FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

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Executive Summary

The increasing frequency of wildfires in Europe's Wildland-Urban Interface (WUI) requires a multi-scale approach to mitigation. This deliverable outlines key strategies, including fire-adapted urban design, strict building codes, community engagement, and advanced technologies. It emphasizes coordinated efforts, policy measures, and post-fire recovery to enhance resilience and establish a harmonized European wildfire management framework.

Summary

The increasing frequency and intensity of wildfires in WUI areas across Europe demand a comprehensive and multi-scale approach to mitigation. This deliverable highlights key strategies to enhance community resilience, emphasizing the need for coordinated efforts at both the urban planning and property levels. Effective wildfire mitigation requires strategic fuel management, fire-adapted urban design, and strict building codes that prioritize fire-resistant materials and defensible spaces. Community engagement plays a crucial role, with education, incentives, and collective action proving essential in reducing risk. Evacuation planning and shelter-in-place strategies must be strengthened to protect vulnerable populations, while emerging technologies, such as satellite monitoring and AI-driven risk assessments, can significantly improve early warning systems. Policy measures, including financial incentives for fire-resistant construction and cross-border collaboration, are key to establishing a harmonized European framework for wildfire resilience. Additionally, post-fire recovery efforts must integrate long-term strategies to rebuild safer, more resilient communities. The guidelines in this deliverable provide a roadmap for enhancing fire resilience through proactive planning, risk-informed decision-making, and sustained investment in prevention, preparedness, and adaptation.

Key take away messages

- **Fire-adapted urban planning**: Urban design should incorporate wildfire mitigation measures, including reducing fuel continuity, managing vegetation, and creating defensible spaces around buildings.
- **Fire-resistant construction and materials**: Implementing strict building codes that prioritize fire-resistant materials and designs can significantly reduce ignition risk. International standards like NFPA 1144 and AS 3959 serve as useful references.
- **Community engagement and governance**: Effective prevention requires collaboration among homeowners, local authorities, and communities. Homeowners' associations and collective risk management plans can greatly enhance wildfire resilience.
- **Evacuation and shelter-in-place strategies**: Planning should include efficient evacuation protocols as well as shelter-in-place strategies for scenarios where evacuation is not feasible, ensuring safe refuge locations and proper protocols.

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List of Acronyms

ABCB	Australian Building Codes Board
BAL	Bushfire attack level
CBD	Crown bulk density
CBH	Crown base height
CFD	Computational fluid dynamics
CSN	Citizens-scientists networks
DA	Demonstration area
DS	Defensible space
FDI	Fire danger index
FEMA	Federal Emergency Management Agency
FZ	Flame zone
GDPR	General data protection regulation
GIS	Geographical information system
HIZ	Home ignition zone
ICF	Insulating concrete forms
LiDAR	Light detection and ranging
LPG	Liquefied petroleum gas
NASCC	National Adaptation Strategy to Climate Change
NGO	Non-governmental organization
NFPA	National Fire Protection Association
PS	Pilot site
OECD	Organisation for Economic Co-operation and Development
RIA	Research and innovation action
ROS	Rate of spread
RRF	Recovery and resilience facility
SMS	Short message service
SSD	Structure separation distance
TH	Total height
VBRC	Victorian Bushfires Royal Commission
WWTP	Wastewater treatment plant
WUI	Wildland-urban interface
WUIX	Wildland-urban interface index

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1 Introduction

Wildfires in recent years have been exhibiting increasingly extreme behavior, both in terms of their initiation and development, as well as their impact on populated communities. Wildland-Urban Interface (WUI) areas are those regions where urban developments coexist with or abut natural environments. They are typically considered mixed or transitional zones with vegetation and urban structures.

The development of wildfires brings with it the spread of a potentially powerful flame front, the emission and dispersion of smoke, and the production and projection of flying embers over long distances. All these hazardous components can seriously affect populated areas, impacting both people and buildings, as well as the associated infrastructure.

In the most complex cases, hybrid events can occur, where a pure wildfire impacts a perimeter area with a transitional urban zone (interface area), leading to conflagrations that spread exclusively through urban fabric. In these situations, the threat to the population is much greater due to the higher density of inhabitants per square kilometer, as well as the destruction of buildings and infrastructure. Additionally, during conflagrations, the structures themselves become sources of heat (from the combustion of materials and objects), smoke (often toxic), and flying embers. The phenomenon of ember wash plays a very active role in conflagrations, igniting multiple secondary fires and accelerating the spread of fire through the urban fabric.

In the face of these threats during extreme wildfire events, it is critical to prepare communities, urban areas, and properties to minimize the adverse effects. This principle is further reinforced by the fact that first responders, agencies and stakeholders are often overwhelmed by the scale of the threat and, subsequently, its aftermath, making the active participation of communities and property owners increasingly important.

1.1 Purpose of the document

The primary objective of this deliverable is to review some of the strategies for the prevention and protection of communities against wildfires and to explore the design of codes and best practice guidelines that help mitigate the effects of these events in WUI areas.

Although there have been developments, research efforts, and analytical tools created over several decades, many of these results pertain to realities in other parts of the world, particularly the United States, Canada, and Australia, where residential buildings are typically constructed with different materials and methods than those found in Europe, especially in Mediterranean Europe. This is why it is necessary to study, review, and adapt existing codes and guidelines to the realities of our communities and in accordance with the threats and types of destruction observed in our European latitudes.

The target audience for this document includes, on one hand, local governments and homeowner associations representing developments, towns, and cities that may be threatened by wildfires. On the other hand, it also targets individual property owners, who are ultimately responsible for their homes and everything within them. Therefore, it is necessary to implement this document at two levels: the community level and the property level, both of which are closely linked. It is also important to emphasize the significance of collaboration among property owners within communities: it is of little use for one property owner to make every effort to prepare their lot if their neighbors do nothing. This is why this document must be analyzed and shared by the stakeholder groups involved in wildfire prevention and adaptation.

1.2 Structure of the document

This deliverable is divided into the following chapters:

- Introduction
- The two scales of implementation
- Strategies for an adapted urbanism
- Building fire codes
- Gardening design and irrigation
- Fuel treatments and mitigation
- Sheltering methods and protocols
- Evacuation
- Technical solutions
- Working with population and involved stakeholders
- Post-fire recovery

As seen, the first section focuses on the community scale, providing guidance and tools to help identify hazard factors (such as fuel) and prepare the surroundings of urban developments, towns, and cities. On the other hand, there is a second, broader section that spans several chapters and addresses the homeowner scale. Here, the attention is centered on existing building codes for housing protection, the design of fire-resistant gardens and plots, as well as some techniques and technologies that can enhance their protection.

The third section deals with protocols and recommendations for evacuation and shelter in place, both of which are necessary in the complex fire scenarios that are emerging. Finally, the document reviews FirEUrisk activities carried out with communities to improve risk perception and implement good practices, as developed in other tasks within this project. Additionally, some reflections and methods for post-fire recovery are outlined, particularly in urban areas affected by wildfires. However, this topic—at least regarding the social and economic aspects—is addressed in other FirEUrisk deliverables.

2 The two scales of implementation

Wildland-urban interface environments are highly complex. Several components interact within them during wildfire emergency events, including the population, homes, services, and infrastructure. One of the defining characteristics of interface fires is that, once the main wildfire flame front impacts and passes through these areas, the combustion of materials and objects continues, sometimes burning for long periods. This combustion latency in interface areas influences how these emergencies are managed and is directly related to the arrangement of both vegetation and all objects and materials present on individual properties.

Fire can impact and penetrate urbanized areas through existing vegetation, whether it is forest vegetation or garden plants (ornamental plants). Additionally, it can spread via flying embers, creating multiple ignitions in vegetation, objects, materials within properties, and even the homes themselves. Finally, WUI and urban fires can spread even in the absence of much vegetation cover, via structure-to-structure ignition if building materials are highly flammable and neighboring structures are close enough.

To address the preparation of these complex scenarios, two scales of action are proposed:

- the **community** scale and
- the **property** scale

At the community scale, homes, infrastructure, gardens, and forest vegetation are considered a single entity, along with the surrounding forested environment. A community is not just a group of people; it is also a complex network of buildings, vegetation, infrastructure, and services that are interrelated and can be dynamically threatened during a wildfire event. Furthermore, the community is situated within a forested environment, which is also considered part of the scenario and plays a crucial role in determining how the flame front approaches urbanized areas.

At the property scale, the focus is on an individual building and its immediate surroundings, such as the yard or garden. This scale is well-defined in residential developments consisting of individual lots and single-family homes. However, it is less clearly applicable to other common construction patterns in Europe, such as condominiums (apartment towers) or row houses and townhouses, which include shared landscaped areas that must be maintained collectively by the homeowners' association. Moreover, the size of the properties where buildings are located varies significantly—from just a few square meters to several hectares. This high variability makes it difficult to propose standardized prevention measures for homeowners, as recommendations must be adapted to each country and regional context.

3 Strategies for an adapted urban environment

The initial design and development of residential areas are approached from a utilitarian and aesthetic perspective, focusing on the layout of lots and common areas. While shared-use infrastructure—such as road networks, electricity distribution grids, gas and water pipelines, telecommunications antennas, transformers, and wastewater treatment plants—as well as community green spaces like parks and gardens are outlined in urban development plans, it is much more difficult to design and plan the contents of each private lot, particularly regarding the type and arrangement of vegetation.

Rarely is a unified vegetation design planned for all properties, leaving the selection of plants up to individual homeowners. However, from the perspective of wildfire penetration, the resulting vegetation patterns are crucial, particularly the vegetative structures that emerge as property enclosures, such as green hedges, which are often shared by multiple neighbors. These vegetation patterns provide continuous fuel loads that facilitate fire spread and can significantly contribute to wildfire penetration into residential areas.

Given this, urban planning adapted to wildfire risk—especially considering the evolving fire regimes of recent years—must account for the collective distribution of vegetation across all properties and propose measures to prevent or mitigate fuel continuity and load. However, this presents a major challenge: securing agreement among property owners. Thus, just as important as proposing vegetation fuel mitigation measures is the establishment of governance structures for managing urbanized areas within the WUI, particularly homeowners' associations that can discuss and implement prevention and fire defense strategies for the entire community. Implementing these measures also requires an annual budget for prevention and maintenance work, which should be funded collectively by affected property owners.

When assessing a residential area's vulnerability to wildfires, two key aspects emerge: fuel (vegetation) continuity and **friction** with homes, corresponding to the presence of vegetation near to or touching the structures. The continuity of vegetation determines how easily fire can traverse an urban zone, while friction refers to the potential exposure of homes to burning vegetation. In essence, fire-adapted urban planning must address both of these elements in one way or another.

Fuel continuity and wildfire spread

It is important to note that when discussing fuel continuity, all vegetative elements capable of transferring the flame front effectively must be considered. In many cases, the presence of cured grass alone is enough to propagate fire into and through a residential area, even if its relative fuel load is low. Indeed, when calculating the linear intensity of a flame front, both the heat release per unit area (which depends on fuel type) and the rate of fire spread (which is also influenced by topography and wind) must be considered. If a vegetation structure has high linear intensity, it is because one or both of these factors are high. In the case of cured grasses, the primary factor is the rate of fire spread.

A key strategy for fuel mitigation within residential areas—and one incorporated into fire-adapted urban planning—is the control and removal of fine dead fuels, including but not limited to cured grass, dry shrubs, pruning debris, and pine needles and dry leaf litter. It is crucial to highlight that tree cover within urban areas generates, among other things, significant amounts of fine dead fuel, such as pine needles, which accumulate on rooftops, terraces, gardens, hedges, vehicles, roads, and access streets. Fire-adapted urban design must take this factor into account, as it requires a commitment to systematic and periodic removal of these materials.

Management of vacant lots and grasslands

Vacant lots often accumulate cured grass, dry brush, and other vegetation containing large amounts of fine dead fuel. These areas must be maintained systematically and periodically as part of wildfire prevention plans to ensure they do not become ignition points or contribute to secondary fires within populated areas. Effective control methods include mechanical removal (brush cutters), the use of livestock (such as grazing sheep or goats), and prescribed burns, all of which are highly effective for controlling cured grass right before fire season.

Creation and maintenance of green areas

Another alternative is maintaining green grasslands throughout the dry season using prescribed irrigation, which can transform highly flammable areas into non-combustible zones that help protect the rest of the community. Maintaining green spaces within urban areas is therefore a valuable strategy, particularly when combined with livestock grazing, which helps regulate fuel accumulation. However, despite its undeniable effectiveness in fire prevention, using livestock (such as sheep or goats) in residential areas is not widely accepted due to concerns over waste and odor.

Vegetation selection and climate adaptation

As climate conditions evolve, plant communities are adjusting their structures (species associations), densities, and even physiological cycles. The same applies to vegetation used in urban landscaping, including parks, gardens, and private properties. The selection of plant species for green areas should prioritize adaptation to new climatic conditions, particularly in terms of temperature fluctuations and water availability.

Key strategies for fire-adapted urban design include the use of fire-resistant plants and the irrigation of green areas with reclaimed water. One current trend is the increased use of succulents and cacti for ornamental purposes, as they are more drought-tolerant, resistant to high temperatures, and have lower fuel loads in the event of a fire.

Understory management and vertical fire transmission

The management of understory vegetation, or the plant layer beneath tree canopies, plays a critical role in wildfire transmission within urbanized areas. Neglected lots or lack of vegetation management can significantly increase fire penetration, even in low-intensity surface fires, and facilitate the spread of flames into tree crowns.

There are two main strategies within fire-adapted urban planning to mitigate this risk:

- Controlling the density, height, and species composition of the understory shrub layer.
- Systematic application of prescribed irrigation to maintain plant moisture levels, making vegetation more fire-resistant and applying specific techniques for regions with water scarcity, such as use of reclaimed water.

Additionally, previously mentioned strategies—such as reducing fuel continuity and load across vegetation layers—must also be implemented. The advantage of urban environments is that understory vegetation can generally be easier to manage, particularly by creating firebreaks using streets, roads, property lines, homes, and common areas such as sports facilities, parks, gardens, and golf courses, which help prevent fire spread within residential areas.

Water supply and hydrant networks

Urban planning must also include the installation of secondary or tertiary water supply networks to support a system of hydrants and water access points for irrigation and fire suppression, ensuring adequate water flow during peak demand periods—especially in regions where fire season coincides with prolonged droughts.

Future projections of water availability for both residential consumption and emergency services must be integrated into urban design. Consequently, the construction and maintenance of water reservoirs—such as tanks, ponds, irrigation canals, and swimming pools—should be planned to ensure continuous water supply.

Accessibility and evacuation routes

A critical aspect of fire-adapted urban planning is accessibility, which refers to the road network that facilitates both fire suppression operations and emergency evacuation during a wildfire.

Urban design must account for population density, vehicle presence, and traffic needs, resulting in a road network geometry tailored to these factors. Additionally, as specified in wildfire prevention and defense regulations, the street network should provide multiple entry and exit routes, enable rapid evacuation through several pathways, and include horizontal and vertical signage adapted for low-visibility conditions (such as those caused by heavy smoke).

3.1 Estimation of fuel load in communities

3.1.1 Characterization of vegetation fuels in the WUI

The characterization of wildland fuels involves field sampling techniques in representative plots and can also involve remote sensing methods that automatically or semi-automatically extract key vegetation structure variables, particularly tree density, height, and, in some cases, species identification. Using allometric equations, it is also possible to estimate the biomass contribution of individual trees, which in turn allows the calculation of the biomass available for combustion in wildfires.

The use of fuel model catalogs—which are idealized representations of vegetation structures with specific fire behavior characteristics studied in laboratory settings—facilitates the modeling of wildfire ignition and spread, particularly for surface fires. Examples include the BEHAVE catalog and the Scott & Burgan fuel models. Within the FirEUrisk project, procedures have been established for identifying and mapping fuel models at various scales, including European-scale mapping (coarse scale), pilot sites (PS; moderate scale), and demonstration areas (DA; fine scale).

3.1.2 Vegetation characterization in the WUI

A detailed characterization of vegetation distribution in WUI zones, where vegetation intermingles with residential areas, is now required. This makes automated mapping more challenging, especially when using remote sensing products such as satellite imagery, orthophotos, or LiDAR telemetry. The fragmented nature of vegetation in these areas, along with the presence of non-native ornamental species—commonly found in gardens and communal green spaces within residential developments—complicates the process. Additionally, analyzing fuel load and distribution in residential areas requires significantly higher spatial resolution, such as 5 m, 2 m, or even 1 m, to capture all relevant details and their spatial relationship with buildings.

The objective of this high-resolution mapping is twofold:

- To identify vegetation fuel continuity, meaning how connected vegetation patches are and their potential capacity to transmit fire across the residential area.
- To quantify fuel load (expressed in kg/m^2), meaning the amount of biomass available for combustion at each location.

Given the high level of detail, it becomes necessary to consider the third dimension—vertical distribution. A 3D characterization and mapping of fuels provides insight into vertical fuel continuity, the potential for fire to spread into tree canopies, and the impact of canopy fires on nearby structures. This three-dimensionality is essential not only for airflow modeling (fluid dynamics) but also for assessing the effects of radiation and convection on buildings.

3.1.3 3D Vegetation mapping techniques: LiDAR and photogrammetry

To achieve 3D vegetation mapping, it is necessary to use tools and techniques such as LiDAR telemetry and photogrammetry.

LiDAR technology is widely used in forestry and enables precise identification of individual trees and key parameters describing their geometry, such as height and crown size (particularly crown diameter).With the latest pattern recognition techniques and the increasing use of artificial intelligence (AI), it is now possible, under certain conditions, to identify tree species and their health status. These descriptors serve as a baseline for enhancing field sampling analysis and extracting key vegetation variables, such as Crown Base Height (CBH) – the height at which tree crowns begin, total height (TH) and Crown Bulk Density (CBD) – the apparent density of foliage in the canopy. This last parameter (CBD) is particularly important for assessing the biomass distribution in tree canopies, which may participate in wildfires. In WUI zones, LiDAR data can also be used to estimate building heights and even generate simplified 3D models of structures.

Photogrammetry utilizes large sets of aerial images captured in both orthogonal and oblique projections to generate point clouds that characterize all objects in a WUI landscape in 3D. The increasing availability of drones makes this characterization more technically accessible and cost-effective. Specialized 3D restitution software processes these images, integrating aircraft positioning data (in the case of drones, high-precision RTK positioning).Because color information is also obtained for each point, the same pattern recognition techniques (e.g., neural networks) can be applied to identify individual plants and species. It is important to highlight that photogrammetry is limited to relatively small areas, but it is highly applicable to residential developments and scattered populated areas.

To further refine vegetation distribution mapping, high-resolution orthophotos are used to analyze radiometric responses, which help delineate patches of different vegetation types. This is particularly useful for mapping continuous low-height fuel models, such as cured grass and ground cover species.

3.2 The WUIX index

When analyzing vegetation-house patterns in WUI zones, two key factors must be characterized:

- Vegetation **continuity** – which determines the fire transmission potential across the urban area.
- **Friction** with buildings – which quantifies the potential impact on structures.

To assess these factors, two indices have been proposed, along with a third index that combines them into a final value. This index (WUI Index or WUIX) can serve as a baseline metric for characterizing interface typologies and assessing potential wildfire risk in these areas.

The Wildland-Urban Interface Index (WUIX) (Caballero, 2006) originates from the concept proposed in the WARM project (Caballero et al., 2003), which aimed to classify land based on two landscape aspects directly related to building exposure to wildfire risk in the Wildland-Urban Interface (WUI):

- Vegetation continuity
- Vegetation friction with buildings

The WUIX index is purely topological, meaning it analyzes the relative positioning and spatial relationships between objects in the landscape (vegetation and buildings) in two dimensions. Since no fire behavior modeling is performed, topography and wind are not included in the calculations. Similarly, fuel load and other fuel model parameters are not considered.

Calculation methodology

Both components—continuity and friction—are estimated using a cellular automaton model applied to a fine-resolution square grid with a resolution R_f (in meters). The calculations are then aggregated to a coarser-resolution grid, with a resolution R_g (also in meters), which is a multiple of the fine resolution.

Vegetation continuity calculation

The continuity calculation follows a straightforward mechanism: for each fine-resolution vegetation cell, a value of 1 is assigned if the adjacent north (N), east (E), south (S), or west (W) cells also contain vegetation. A value of 0.5 is assigned if the diagonal neighbors (NE, SE, SW, NW) contain vegetation. The resulting value, ci, represents the unitary continuity of the cell (independent of R_f), with a maximum possible value of 6. This process is repeated for all vegetation cells in the fine grid. The results are summed within each coarse grid cell, multiplied by R_f, and assigned to the coarse-grid continuity value (C_g).

Urban fabric continuity calculation

Similarly, the continuity of the urban fabric can be calculated, but this time considering the cells classified as houses. This results in a unitary continuity value (u_i) for each cell in the fine grid by analyzing the eight neighboring cells, which are then used to compute the total continuity in the coarse grid (U_g). This urban fabric continuity value is useful for classifying WUI typologies, as will be explained later. It is evident that the index can be improved by incorporating other elements that contribute to urban ground sealing, such as streets, other facilities, and infrastructure that are not necessarily residential buildings. In this regard, and within this methodology, considering only residential buildings provides a default measure of urban fabric continuity.

Building-vegetation friction calculation

The friction calculation follows a similar approach: starting from building cells, the model assigns 1 if the adjacent N, E, S, or W cells contain vegetation; 0.5 if the cell is at a convex building corner and surrounded by vegetation; additionally, 1 is added for each building cell covered by vegetation (see the following section).The resulting value, fi, represents the unitary friction, with a maximum possible value of 7. As with continuity, this process is repeated for all fine-grid cells within each coarse-grid cell, summed, multiplied by R_f, and assigned to the coarse-grid friction value (F_g).

The term "friction" may not be the most technically precise, but it has recently been adopted to describe the dynamic spatial relationship between vegetation and houses. In fact, the concept immediately evokes the idea of plants making direct contact with building facades, in which case there is indeed physical friction. However, this consideration has at least two relevant aspects in its computation:

In the calculation of the WUIX interface index, cells in a raster map are classified as either vegetation or houses, followed by a topological analysis. Here, the term "friction" refers to the contact between two adjacent cells, one classified as vegetation and the other as a house. However, in this approach, it is important to consider that if the raster map's cell resolution is too coarse, it may obscure the fact that there is actually a separation between vegetation and the building—one that is smaller than the selected resolution. This results in a "fictional" friction, but one that remains relevant, provided that the raster grid resolution corresponds to a distance where the fire's impact is significant.

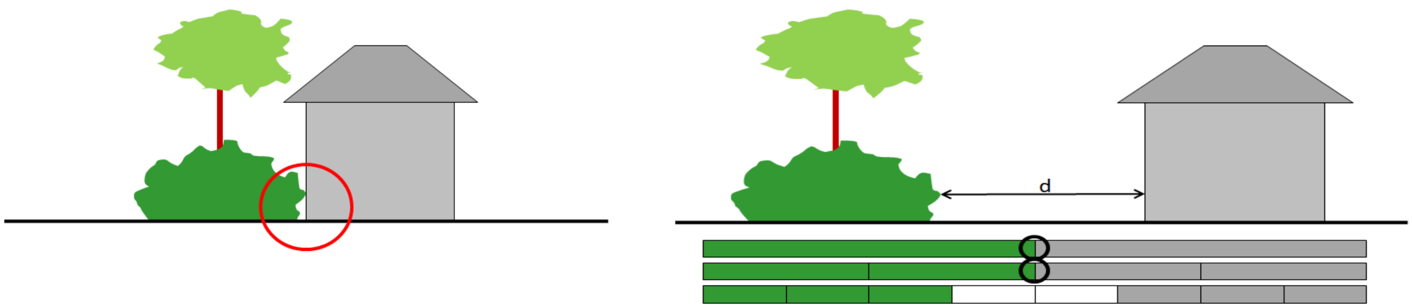


Figure 1. Conceptualization of friction between houses and vegetation. While direct contact between plants and houses is counted as friction in the real world (left), in a digitized grid (right) of cells classified as vegetation (green) or houses (gray), this friction depends on the grid resolution, capturing real separations if the resolution is at least half of the reference distance d. In the example on the right, a resolution of 8 m does not capture the separation distance d of 5 m, nor does a resolution of 4 m; in both cases, friction is considered to be present. However, a resolution of 2 m is able to identify this gap.

This leads to the second consideration: "thermal friction," which refers to the presence of vegetation within a threshold distance where the thermal impact of flames is significant. Current literature cites 40 kW/m² as a reference threshold incident radiant heat flux above which a structure may sustain damage. This value will be used as a reference to determine the distance, and therefore the resolution, that best reflects the concept of friction between houses and vegetation.

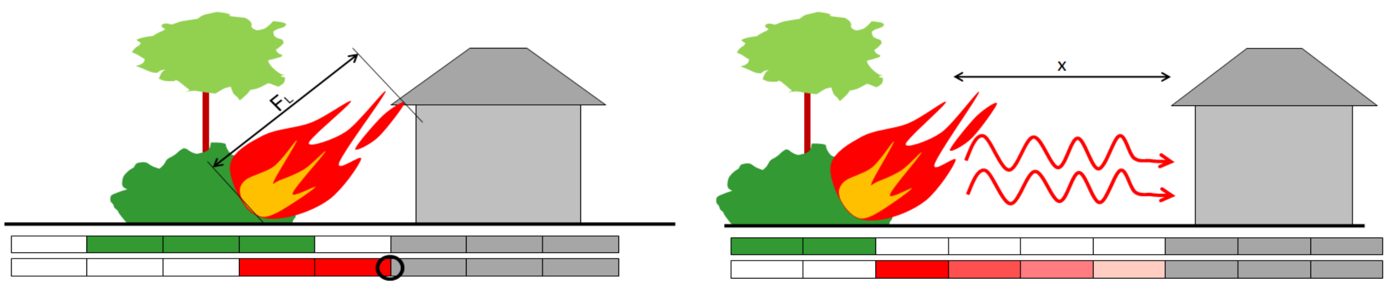


Figure 2. The inclusion of the thermal effect from the presence of nearby flames redefines the concept of friction, considering a distance equal to the flame length (FL) or/and a threshold distance x, below which the heat flux on facades is equal to or exceeds 40 kW/m². In the example, in both cases, although there is a separation between the vegetation and the house, the presence of the flame under these conditions creates "thermal friction", either through flame impingement (left) or radiation (right).

However, considering the effect of flames already involves integrating other factors that influence their geometry, such as wind, topography and also the consideration of shape factor and threat direction, among others. This means that the derived interface index is no longer independent of weather conditions, unlike the WUIX index, which only considers the topological relationships between vegetation and buildings. Nevertheless, this second approach is a useful tool for analyzing specific cases or linking it to a building code, closely aligned with the BAL (Bushfire Attack Level) index of the Australian code, as will be discussed later.

As seen, the selection of the calculation grid resolution used for WUIX is crucial in integrating the distances that account for the potential effects of flames (both contact and radiation) on building facades. If the resolution is too coarse, it will mask separations that are actually relevant. Conversely, if it is too fine, even small gaps will prevent friction from being registered, even if the flames envelop and touch the facade or if the radiant heat flux exceeds the mentioned threshold.

Final WUIX calculation

The final WUIX value (expressed in m²) is obtained by multiplying the total friction (F_g) and continuity (C_g) values found in each coarse grid cell:

$$WUIX = C_g \cdot F_g$$

Handling overlapping tree canopy and buildings

In many WUI areas, some or all buildings are covered by tree canopy. In these cases, each overlapping cell is classified simultaneously as both building and vegetation. Since WUIX does not perform comparative vertical (Z-axis) analysis, such as measuring the distance between tree crowns and rooftops, the model assumes vertical friction is always present in cases of overlap. To address this, the friction value is increased by 1 in all cells where vegetation overlaps with buildings. The final calculation adds R_f meters of friction for each overlapping cell.

Conceptual limitations and 2D assumptions

While the calculation provides acceptable results, this approach has conceptual inconsistencies, as it mixes length-based analyses (friction, continuity) with surface area-based analyses (e.g., the area of buildings covered by vegetation). However, the same principle is applied to friction calculations, which inherently occur on surfaces (building facades), reducing the three-dimensional nature of the problem to a 2D approximation. In essence, each voxel facing a building facade does not account for its vertical depth, only its contact length. This is one of the main limitations of using 2D algorithms to model a fundamentally 3D phenomenon.

Effect of tree canopy over buildings on vegetation continuity

Buildings covered by tree canopy also contribute to higher vegetation continuity values because the model assumes that structures do not disrupt fuel continuity. However, this assumption is not entirely correct since there may be horizontal continuity (e.g., through overlapping canopies) but not vertical continuity (e.g., pruned trees with raised crowns separated from the understory). Alternatively, horizontal continuity may exist in tree crowns but not in the understory, due to disruptive elements like roads and pathways. To improve accuracy, it is recommended to apply stacking techniques—a method that integrates continuity and friction analysis for multiple vegetation layers. This approach, explained in later sections, provides a more realistic multi-strata characterization. By default, the algorithm assumes all vegetation layers are vertically connected in cases of overlapping tree canopy and buildings.

3.3 Measurement of fuel continuity

Continuity reflects in a simplified way the ability of the territory to propagate fires, particularly indicating the degree of fire penetrability within the mesoscale of a populated area. High continuity is therefore interpreted as a high capacity of the territory to develop and sustain consolidated flame fronts and generate fire runs of significant magnitude. Low continuity may be associated with areas where fire encounters difficulty advancing as a flame front. However, low continuity can still be vulnerable to the reception of flying embers and the generation of secondary ignitions, thereby causing fires that, even if they do not progress as consolidated flame fronts, can locally develop intense combustion and flames.

The analysis of continuity patterns is particularly useful for identifying fuel corridors or pathways that may facilitate the penetration of fire fronts into populated areas, especially if their main axis aligns with the most adverse dominant winds. It is also interesting to compare continuity in the exterior, perimeter, and interior of urban developments and observe to what extent they increase, remain stable, or decrease along the potential trajectories of an approaching fire front.

As explained above, a vegetation structure with multiple layers (for example, understory shrubs and tree canopies) may have different continuity patterns; in such cases, it is necessary to conduct a stacked analysis of the various continuities, emphasizing the significance of tree canopy continuity, under the assumption that crown fires may develop. In situations where vertical continuity exists, stacking procedures can double the maximum unitary value (originally 6, but 12 when stacking two layers), thereby reinforcing the importance of this dual continuity (horizontal and vertical). These increased maximum values should be considered in the calculation of normalized magnitudes and in the establishment of ranges, following a similar procedure to the one previously described.

Since continuity is a topologically consistent magnitude (analyzing vegetation points with vegetation points), it is in perfect alignment, for example, with canopy cover fraction in the territory (considering all vegetation layers) or other measures of vegetation cover. Therefore, continuity ranges can follow a linear rule in any of the four aggregation modes. It is suggested to consider four equidistant range classes in any of the modes (for example: 1-25, 25-50, 50-75, and 75-100 for normalized values). The obtained continuity allows for the evaluation of the Home Ignition Zone (HIZ) at medium and long distances (influence radius of 10 m or 30 m), highlighting the importance of nearby forest vegetation (on parcels at the edge of urban developments) and neighboring yards and gardens.

Continuity can also be used to identify areas where it is low or very low, meaning zones of partial or total discontinuity. It is particularly useful to analyze the role of the urban fabric in the distribution of discontinuities (buildings, roadways) in each vegetation stratum and in an integrated manner, as well as other structures and facilities that create gaps or separations in the vegetation continuum (including perimeter fuel breaks and other fire prevention infrastructures and treatments). In clusters of houses or residential groupings, this continuity is typically reduced, providing better opportunities for fire defense and even for considering shelter-in-place strategies, as long as the surrounding environment is adequately prepared for such measures.

If the vegetation map used for the analysis includes such data, it is highly valuable to assess to what extent landscaping elements contribute to vegetation continuity within residential areas, particularly hedges. As previously mentioned, it is especially useful to identify the longest hedge alignments that coincide with the most adverse dominant wind directions. The calculation of continuity depends on the quality and content of the vegetation (fuel) map used as input. In the examples included in this text, grasses, pine needles, debris, and other combustible elements that could contribute to fire spread in real-world conditions have not been considered. It is up to the analyst's discretion to include these components in the calculation if deemed relevant to the analysis.

3.4 Measurement of urban fabric continuity

Just like vegetation continuity, specific urban continuity represents the degree of housing clustering within a given area, in this case, the area of the coarse-grid cell. Strictly speaking, it should also consider the space occupied by other elements of the urban fabric, such as courtyards, plazas, streets, and infrastructure, which are generally considered non-combustible. However, in this case, the WUIX program only incorporates the building perimeters and therefore the area occupied by them.

In this sense, specific urban continuity does not fully account for urban soil sealing, only part of it. The specific urban continuity (U_o) metric helps identify clusters of houses that could be potential candidates for shelter-in-place strategies in cases where evacuation is compromised in a wildland-urban interface (WUI) zone. However, it is also necessary to analyze specific friction (F_o) and specific vegetation continuity (C_o) to estimate whether the homes could be exposed to fuel. The specific WUIX index confirms this (through low values) since it incorporates both continuity and friction.

One might expect that the specific urban continuity map would be the exact opposite of the specific vegetation continuity map, but this is not always the case. In areas dominated by vegetation, vegetation continuity is generally higher; in areas with urbanized nuclei, urban continuity will be higher. However, there is a range of intermediate combinations that precisely reflect the highest friction zones, and therefore, the greatest exposure of buildings. In these areas—where both vegetation continuity and urban continuity are moderate—the highest WUIX index values appear. Thus, analyzing both continuities separately provides limited information unless friction is also considered.

It is also important to highlight that if a relatively small coarse-grid resolution (R_g) is used (e.g., 5 or 10 meters), urban continuity in the housing area will be high, and consequently, vegetation continuity in the same locations will be low—as the calculation would only include the closest surrounding vegetation, which is generally scarce in more urbanized areas. Therefore, it is recommended to conduct continuity analyses for both urban and vegetation continuity using higher R_g values, such as 30, 50, or even 100 meters, to incorporate more information about the surrounding vegetation near buildings.

It is also essential to remember that a predominantly urban area may be covered by a tree canopy, meaning that continuity differs between surface-level vegetation and the overhead stratum. In such cases, it is advisable to perform stacked analysis techniques, as previously explained.

3.5 Estimation of house exposure

As mentioned, friction is interpreted as the physical contact between vegetation cells and building cells (contiguity). This definition is quite limiting in terms of accurately characterizing the actual impact of fuel around a building, as it requires vegetation to be within a distance equal to or less than the resolution of the fine-grid mesh to be considered in contact. In reality, it is not just the vegetation adjacent to a building that poses a risk, but rather the thermal effects of nearby combustion—including flame contact, radiation, and convective movements—which do not necessarily have to occur directly against facades or rooftops to cause some degree of impact. In this sense, friction can be interpreted as the potential effect of the nearest heat sources to buildings, which, with near certainty, could at least result in flame contact. Observations indicate that a large extent of friction is not necessary for a structure to be significantly affected, but higher friction values increase the likelihood of impact from any direction in which the fire threat approaches.

Unlike continuity, maximum friction values correspond to a worst-case, idealized scenario: a checkerboard distribution where 1-meter-wide building structures alternate with 1-meter-wide vegetation cells. Since this is a theoretical assumption, it does not directly correlate with any real-world magnitude (unlike continuity, which aligns well with canopy cover fraction). As a result, defining extreme values and categorical ranges for friction is more challenging. Instead, observing and studying different real-world interface patterns allows us to determine maximum values and significant ranges through calibration using realistic relative values.

The obtained friction values allow for short-distance analysis of the HIZ (influence radius of 0 to 10 meters), emphasizing the role of immediate vegetation in potential housing impact as well as in the adequacy of the defensible space (DS). In a typical residential area (a neighborhood with trees in gardens), it is common to find specific friction values ranging between 300 and 1000 m/ha, exceeding 2000 m/ha in cases where housing density is higher and tree canopies fully cover rooftops. This significantly increases friction values, just as larger average building sizes do. From a friction perspective, one of the worst WUI scenarios could be an area with small cabins (typical vacation homes) completely covered by the tree canopy and embedded within the surface vegetation structure.

In general terms, friction is classified as follows:

- Low (L) if $F_o < 0.25\ m^{-1}$,
- Medium (M) if $0.25 < F_o < 0.5\ m^{-1}$,
- High (H) if $F_o > 0.5\ m^{-1}$.

The specific friction values (F_o) can be expressed interchangeably in m^{-1} or in m/ha, simply by multiplying by 10,000.

It is important to remember that the calculation of both unitary and total friction values is affected by taxigeometric artifacts (Caballero 2006), which overestimate the total length of facades and rooftops exposed to vegetation. This may require the calculation and subsequent application of a correction factor depending on the required level of precision.

3.6 Metric of the WUIX index

The WUIX index is a modulation of the observed friction based on the local continuity of vegetation. In a way, the WUIX index not only indicates the presence of friction but also whether this friction is embedded within a vegetation structure that is more or less prone to transmitting a wildfire flame front. The WUIX index map allows for a more nuanced assessment of the potential risk generally associated with interface typologies or patterns (see Annex 3) by incorporating the friction between buildings and vegetation structures. Thus, the WUIX index can be understood as a complementary tool that refines and enhances the analysis of potential wildfire risk, serving both in the planning and prioritization of preventive actions (to reduce friction, continuity, or both) and in the development of defense operation protocols in wildland-urban interface (WUI) zones.

The calculation of the friction-continuity index (WUIX) and its components provides a simple method for evaluating the relative positioning effect between vegetation and buildings in wildland-urban interface (WUI) zones. The proposed algorithms are easy to understand and integrate into spatial analysis and require relatively simple input data to obtain. The results can be normalized for comparison against maximum values or referenced to different analysis areas for relative studies across various parts of the territory. Since topography and wind are not considered, the analyses remain independent of specific fire scenarios, making them topologically comparable. Additionally, because this process is conducted in a two-dimensional space, its integration into GIS platforms is greatly simplified, as both the input data and output results are stored as raster layers with a given resolution. The unitary values obtained for continuity, friction, and the WUIX index can be easily reused within GIS platforms for further analysis and spatial aggregations by simply applying layer algebra operations.

The WUIX index distinguishes four possible scenarios within each interface typology:

- **Low friction, low continuity**. A scenario with scattered vegetation and little proximity to homes. This can occur in dense urban areas (cities, urban centers) or in rural areas with low vegetation presence and dispersed houses.
- **Low friction, high continuity**. A scenario with dense, continuous vegetation capable of sustaining consolidated flame fronts and fire runs, but with separation from buildings. This may be due to perimeter fuel breaks adjacent to urban areas (cities) or isolated buildings separated from forest vegetation, such as the "Galician model", where less flammable grasslands surround individual homes.
- **High friction, low continuity**. A scenario where homes are surrounded by vegetation in direct contact, but arranged in islands that break continuity. Although fire front propagation is unlikely, this interface pattern remains vulnerable to flying embers. Such patterns are more relevant in wildfire-prone areas rather than within the main fire front's propagation perimeter.
- **High friction, high continuity**. A scenario with dense, continuous tree cover where isolated houses or intermix developments are in direct contact with vegetation. Conceptually, this represents the worst interface pattern.

3.7 The classification of WUI patterns

For the systematization of the classification of interface typologies, the following classes of urban continuity U_o (m^{-1}) are considered:

I	Undeveloped	$U_o = 0$
II	Isolated	$0 < U_o \leq 1,5$
III	Scattered	$1,5 < U_o \leq 3$
IV	Intermix	$3 < U_o \leq 4,5$
V	Urban	$U_o > 4,5$

Likewise, the following classes of vegetation continuity C_o (m^{-1}) are considered:

A	No vegetation	$C_o = 0$
B	Sparse vegetation	$0 < C_o \leq 1,5$
C	Average density	$1,5 < C_o \leq 3$
D	High density	$3 < C_o \leq 4,5$
E	Very high density	$C_o > 4,5$

With these values, the 25 generic interface classes can be identified according to the following table (the descriptions correspond to 1-hectare cells, with Rg = 100):

	n	Cod	Equivalent description (1 ha)		n	Cod	Equivalent description (1 ha)
	1	IA	Empty		14	IIID	Scattered with dense vegetation
	2	IB	Sparse vegetation		15	IIIE	Scattered with very dense vegetation
	3	IC	Medium vegetation		16	IVA	Intermix (no vegetation)
	4	ID	Dense vegetation		17	IVB	Intermix with sparse vegetation
	5	IE	Very dense vegetation		18	IVC	Intermix with medium vegetation
	6	IIA	Isolated (no vegetation)		19	IVD	Intermix with dense vegetation
	7	IIB	Isolated with sparse vegetation		20	IVE	Intermix with very dense vegetation
	8	IIC	Isolated with medium vegetation		21	VA	Urban (no vegetation)
	9	IID	Isolated with dense vegetation		22	VB	Urban with sparse vegetation
	10	IIE	Isolated with very dense vegetation		23	VC	Urban with medium vegetation
	11	IIIA	Scattered (no vegetation)		24	VD	Urban with dense vegetation
	12	IIIB	Scattered with sparse vegetation		25	VE	Urban with very dense vegetation
	13	IIIC	Scattered with medium vegetation				

Class 16 is technically a dense scattered settlement, but the term intermix is used to maintain class consistency and simplify the table, as intermix inherently implies the presence of vegetation. It is also recommended to add a friction identifier to the interface typology code, based on the following criteria according to the specific friction value F_o (m^{-1}):

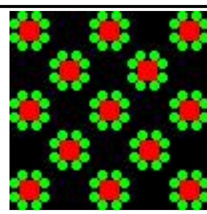
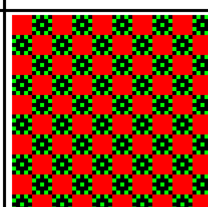
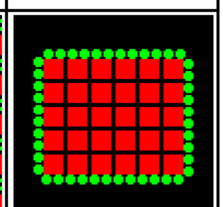
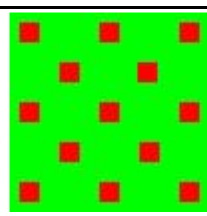
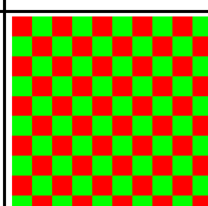
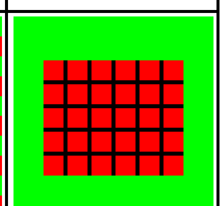
- Low (L) if $F_o < 0.25$
- Medium (M) if $0.25 \leq F_o \leq 0.5$
- High (H) if $F_o > 0.5$

In this way, the resulting code that identifies each interface typology will consist of:

- A Roman numeral referring to urban fabric continuity
- A capital letter indicating vegetation continuity
- A slash (/) followed by a code representing the friction range between buildings and vegetation within each cell

For example, the code IVC/H represents an intermix scenario with medium vegetation and high friction.

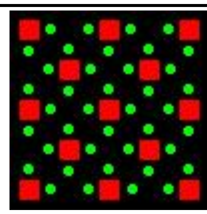
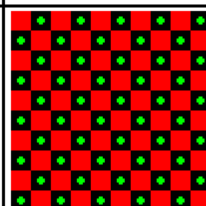
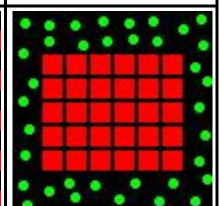
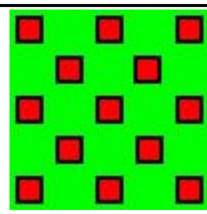
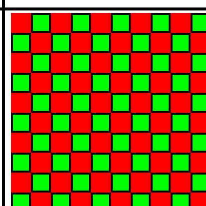
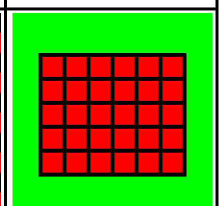
The values of vegetation continuity and urban fabric continuity can be used to classify and categorize WUI patterns. Additionally, these patterns will show cases of high friction or low friction.

High Friction	Low U_o	AverageU_o	High U_o
Low C_o	 H1 (IIA, IIB, IIIA, IIIB)	 H2 (IVA, IVB)	 H3 (VA, VB)
High C_o	 H4 (IID, IIE, IIID, IIIE)	 H5 (IVD, IVE)	 H6 (VD, VE)

Green = vegetation. Red = buildings. Black = unburnable. In brackets WUI classes

All **high friction** (H) cases pose a potential threat to buildings, as they involve fuel in direct contact with structures. Therefore, these cases should be modified to reduce or eliminate this exposure. Cases with low vegetation continuity

(Co) will not sustain flame front propagation, but they will be prone to secondary ignitions from flying embers and localized ignitions near homes. As a result, all such cases may be at risk in wildfire influence zones. Cases with medium or high vegetation continuity (Co) represent the most hazardous WUI scenarios, as they can develop flame fronts capable of directly impacting homes. **H4** corresponds to scattered housing in a forested area. **H5** represents a checkerboard intermix pattern (the worst case). H6 refers to a city with a well-defined urban fabric surrounded by forested terrain. Protection in all three cases requires separating homes from surrounding vegetation, so they transform into their low-friction counterparts (L4, L5, and L6). Although WUIX considers "separation" as a fuel-free strip with a width equal to the fine-grid resolution (Rf), in reality, it should be at least twice the predicted flame length in the direction of maximum fire spread.

Low Friction	Low U_o	AverageU_o	High U_o
Low C_o	 L1 (IIA, IIB, IIIA, IIIB)	 L2 (IVA, IVB)	 L3 (VA, VB)
High C_o	 L4 (IID, IIE, IIID, IIIE)	 L5 (IVD, IVE)	 L6 (VD, VE)
Green = vegetation. Red = buildings. Black = unburnable. In brackets WUI classes			

Low-friction (L) cases represent a simplified model of protection structures for each urban fabric pattern. Cases with low vegetation continuity (C_o) correspond to interface scenarios with minimal wildfire exposure, as they neither sustain flame front propagation nor generate significant secondary ignitions that could affect homes. Cases with high vegetation continuity (C_o) represent situations where homes may be surrounded by a spreading flame front or secondary ignitions, but upon reaching the buildings, a separation reduces their impact. It is essential to emphasize once again that this actual safety distance is not equivalent to the fine-grid resolution (R_f)—which is what WUIX considers—but rather, for example, at least twice the predicted flame length in the direction of maximum fire spread. **L4** indicates that in scattered housing areas, a buffer must be created around each home. **L5** indicates that in an intermix, vacant lots must be treated, creating auxiliary fuel breaks along their boundaries. **L6** highlights the need to establish a perimeter fuel break enclosing the entire urban fabric. These represent, theoretically, the target structures into which the equivalent high-friction (H) typologies must evolve. The unitary friction value (f_i) at each point provides a metric for the necessary linear fuel treatment, which must be multiplied by the required width to obtain the total treatment area. If referring to the perimeter surface of each building, the specific friction value (F_{op}) indicates the length of treatment needed around each home. These values are particularly useful for protecting isolated homes and scattered housing, as such scenarios lack community-based defense structures. In the real world, large areas with a single, pure interface typology are rare. Instead, blended patterns will appear, forming a continuous mix of the described classes, each with its associated characteristics.

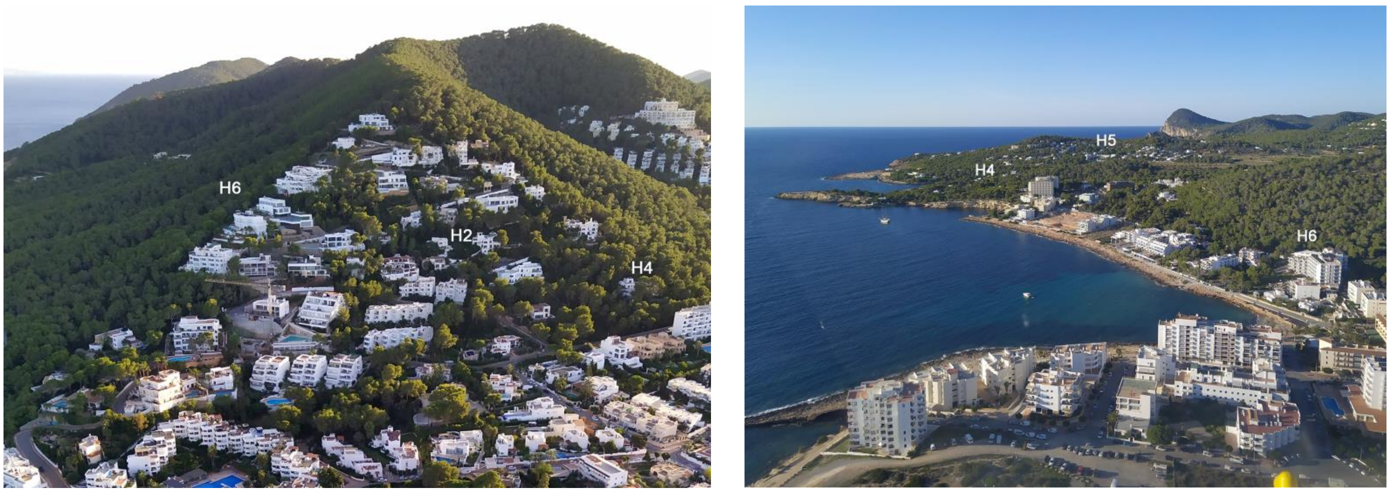


Figure 3. Some examples of WUI types classification as identified in the landscape.

The use of this classification, based on vegetation continuity, urban fabric continuity, and the expected friction between houses and vegetation, provides a systematic approach for an initial landscape assessment. It is important to consider that pure typologies are rarely found in the territory, as they are typically a mixture of different types.

This preliminary identification of typologies also enables the planning of necessary transformations, shifting from a more exposed and vulnerable typology to a more fire-resistant one. This process is an integral part of the strategic adaptation and urban design planning for populated areas facing wildfire risk.

3.8 Urban design and transformation strategies

These tools and metrics that allow us to characterize the different WUI typologies in detail, at the urbanization scale, and associate them with wildfire risk scenarios are very useful for designing urban planning strategies for adaptation to these risks. Indeed, the transformation of WUI typologies in the landscape should be approached using both quantitative characterization (surface area of each class) and qualitative characterization (typologies and associated risk) at the local level (municipality).

As previously discussed, some WUI typologies present higher risk due to greater continuity – which translates into an increased ease of fire spreading through the urbanized area – and friction – which increases the exposure of buildings. Both factors are integrated into the WUIX index, which stratifies the territory. Thus, urban planning for WUI transformation could focus on transitioning from high-friction WUI classes to their equivalent lower-friction classes.

This, as expected, involves separating homes from surrounding vegetation, although this can be difficult to implement in reality, especially in highly fragmented areas, such as intermix typologies. In these cases, collaboration among property owners is necessary, ensuring a shared prevention objective, including the selection of plant species, the organization and ornamental design of their plots, as well as policies and strategies for land transformation and maintenance. For adaptation to be successful, these aspects should be included in self-protection plans and in the statutes for the formation and maintenance of communities in developed urban areas.

Some specific transformations that are suggested include:

- For **isolated houses** in forested areas, the creation of defensible spaces around the structures to reduce friction. In these cases, self-protection methods and measures are particularly important.
- For **intermix** urban developments, increasing the density of the urban fabric until creating pure interface models, and reinforcing the separation from vegetation at the perimeter with firebreak zones.
- For **cities, towns**, and other developments with well-defined urban fabric, reinforcing the perimeter with firebreak zones, improving accessibility, and equipping the transition zone with water points (hydrants) and active defense infrastructure (rainguns).
- For developments with **clusters of buildings** but with intermediate vegetation patches, increasing the network of roads and streets, increasing the sealing of the urban fabric, managing these vegetation areas to reduce the presence of highly flammable fuels (such as cured grass), and implementing a controlled irrigation strategy to maintain moisture levels. The introduction of livestock to control fuel biomass production is also recommended.

4 Building fire codes

4.1 The Australian Standard AS 3959-2009 of building construction in fire-prone areas

The document AS 3959-2009, which regulates the construction of buildings in bushfire-prone areas in Australia, covers the following chapters:

- Objective and scope of the standard
- Classification of fire risk (**BAL** - **B**ushfire **A**ttack **L**evel)
- Construction requirements based on risk level
- Methods for assessing fire risk
- Recommended materials and designs
- Mitigation strategies and protective measures
- Regulatory aspects and possible improvements

Objective and scope

The objective of AS 3959-2009 is to enhance the resilience of buildings located in high wildfire risk areas, protecting both structures and occupants during fire events. Some key aspects considered in the standard include:

- Reducing the risk of ignition in homes.
- Addressing fire threats from embers, radiant heat, and direct flame contact.
- Using fire-resistant materials and specific design measures.
- Not guaranteeing structural survival in all fire events, due to the variability and severity of wildfires.

Fire risk classification (BAL – Bushfire Attack Level)

The standard introduces six levels of fire exposure (BAL), defined by the radiant heat flux received by the structure. These are referred in the following table:

Table 1. BAL Levels and Their Characteristics

BAL	Exposure Level	Characteristics
BAL-LOW	Insignificant risk	No additional Construction measures required
BAL-12.5	Low	Protection against **embers** and mild radiant heat
BAL-19	Moderate	Increased resistance to radiant heat and better control of openings
BAL-29	High	Stricter protection against radiant heat, enhanced resistance in facades and roofs
BAL-40	Very high	Protection against **direct flame attack**, more robust structures
BAL-FZ	Flame zone	Extreme risk, **direct contact with fire**. Highly fire-resistant materials required

The code does not explicitly reference the type of housing, year of construction, or maintenance condition of existing buildings. This suggests that the standard is more focused on new constructions and building requirements to reduce wildfire risk, without specifically addressing retrofitting (adaptation of existing buildings) or their classification based on age and structural condition.

Critical structural points

Each level has specific construction criteria, including the use of non-combustible materials, sealed openings, and reinforced structures. The standard establishes differentiated requirements based on the BAL risk level, considering the following key elements:

- **Foundations and floors**: The use of concrete slab foundations in direct contact with the ground is recommended. Exposed wooden structures should be avoided.
- **Exterior walls**: Must be made of fire-resistant materials (masonry, concrete, fiber cement). Wood usage is restricted at higher BAL levels.
- **Windows and doors**: Heat-resistant glass (tempered or double-glazed). Sealed openings against embers and metal shutters for higher BAL levels.
- **Roofs and coverings**: Must prevent ember accumulation through continuous metal roofing and protected drainage systems. Flammable materials such as wooden shingles are prohibited.
- **Ventilation systems**: Metal mesh screens to prevent the entry of embers. Protection of vents and ducts at higher BAL levels.

- **External structures** (Porches, Terraces, Pergolas, etc.): Fire-resistant materials should be used for balconies and platforms. In BAL-40 and BAL-FZ levels, external structures must be non-combustible.
- **Gas and water pipes**: Must be underground to avoid direct heat exposure.

Methods for assessing fire risk

The standard proposes two main methods to determine the BAL for a given location:

Simplified method (Method 1), a step-by-step procedure based on:
- Regional Fire Danger Index (FDI)
- Classification of surrounding vegetation
- Distance between the building and classified vegetation
- Terrain slope in relation to vegetation
- Determination of the BAL level

Detailed method (Method 2), used for more precise evaluations, incorporating:
- Advanced heat flux models
- Exact measurements of fuel load and fire spread
- Consideration of the effects of barriers and structures

Recommended materials and designs

The standard emphasizes the use of specific building materials and house designs to enhance fire resistance:

- Recommended Materials
- Masonry, concrete, brick, and fiber cement for walls
- Metal roofs with sealed joints to prevent ember intrusion
- Tempered or fire-resistant glass windows
- Fire-resistant coatings on balconies and external structures
- Strategic Designs
- Separation between houses and vegetation to reduce ignition risk
- Creation of fire barriers (retaining walls, gravel pathways)
- Sprinkler systems to moisten facades and roofs in extreme risk areas

Mitigation strategies and protective measures

The standard not only focuses on construction but also on preventive strategies, in particular:

- Immediate Environment Management
- Reduction of flammable vegetation around the home

- Garden maintenance and removal of dry leaves
- Use of low-flammability plants in landscaping
- Active Defense Systems
- Automatic sprinklers to cool the structure
- Water storage tanks and independent pumping systems
- Safe and accessible evacuation routes

Regulatory aspects and possible improvements

The standard is a dynamic document, updated based on recent wildfire research. Some of the potential future improvements proposed are:

- Incorporation of high-protection shelters and bunkers
- Evaluation of fuel loads in unmanaged vegetation
- Use of new fire-resistant materials such as bale construction and treated wood
- Studies on the fire resistance of steel roofs and tiles

Use of the code for the design of a European code

The AS 3959-2009 standard provides a solid technical foundation for developing similar regulations adapted to the European region and further to design a European code, incorporating the following aspects:

- Adjusting the BAL classification to fit European wildfire conditions
- Consider the different regions of Europe and their specific construction characteristics
- Integrate the age, materials, and maintenance condition of buildings
- Incorporating fire resistance regulations specific to European materials
- Developing landscape mitigation strategies suitable for European vegetation and climate

4.2 The NFPA 1144 Standard for reducing structure ignition hazards

The NFPA 1144-2018 standard establishes criteria to assess and reduce the ignition risk of structures in the wildland-urban interface. Unlike AS 3959-2009, which focuses on the construction of new buildings, NFPA 1144 includes strategies to evaluate and mitigate risks in **existing** structures. NFPA 1144-2018 is a more flexible standard than AS 3959-2009, as it addresses both new constructions and existing structures. The integration of active mitigation strategies modification of vegetation fuel is key to reducing vulnerability in WUI areas.

The code is divided into the following key chapters:

- Administration: Definition of the scope, purpose, and application of the standard
- Referenced Publications: List of standards and documents used as a basis

- Definitions: Explanation of key technical terms
- Fire hazard assessment in the structure ignition zone
- Design, location, and construction of buildings
- Fuel modification around structures
- Informative Annexes: Include fuel models, Type IV construction, and additional references

Ignition risk Assessment for structures

The standard introduces a structural assessment based on several factors

- Immediate environment: location in relation to slopes, predominant winds, and terrain characteristics
- Building materials: evaluation of roof type, walls, windows, ventilation, and flammable materials in the structure
- Landscape conditions: presence of flammable vegetation near the building
- Access infrastructure and water supply: assessment of roads, evacuation routes, and availability of water sources
- External structures: such as decks, sheds, and other attached constructions

Design and construction requirements

The construction requirements in NFPA 1144 are mostly aimed at reducing the ignition of structures. They are divided into:

- Materials and design
- Use of non combustible or fire resistant materials for roofs, walls, and exterior coverings
- Roofs with continuous structures and no accumulation of embers
- Tempered glass windows with seals to prevent the entry of embers
- Chimneys and gas exhaust ducts with spark protection systems
- Ventilations with metal mesh to prevent the entry of embers
- Location and separation of structures
- Minimum separation of 9 meters between buildings and flammable vegetation
- Requirement of buffer zones without vegetation in high risk areas
- Additional requirements in sloped terrains or areas with rapid fire spread conditions
- Attached and exterior structures
- Terraces, pergolas, and balconies must be made of non combustible materials or treated with fire retardants
- Prohibition of untreated wood in exterior structures in high-risk areas

Fuel modification in the building surroundings

NFPA 1144 focuses not only on construction but also on managing vegetation fuel around homes, in particular:

- Reduction of flammable vegetation within a radius of 9 to 30 meters around the structure

- Regular cleaning of dry leaves and combustible materials near buildings
- Use of low flammability plants for landscaping
- Strategic cutting and pruning of trees to prevent flames from reaching roofs and facades

Risk assessment methodology

The standard establishes a methodology for risk assessment through the creation of wildfire hazard severity maps in residential areas. These maps include:

- Location of each home and its proximity to ignition sources
- Levels of surrounding fuel load
- Evaluation of evacuation routes and firefighter access
- Identification of mitigation infrastructure such as water sources and firebreaks

Comparison of NFPA 1144 with AS 3959-2009

Both standards aim to reduce the risk of ignition in wildfire-prone areas, but they have key differences:

Table 2. Comparison between NFPA 1144 and AS 3959-2009 codes.

Aspect	NFPA 1144-2018	AS 3959-2009
Main approach	Risk assessment and mitigation for both existing and new structures	Regulation of new building construction
Risk levels	Based on a structural and environmental assessment	BAL Classification Bushfire Attack Level
Scope of application	Applies to both new and existing buildings, including landscape mitigation strategies	Only applicable to new constructions
Factors considered	Materials, design, separation, accessibility, vegetation fuel	Radiant heat flux, vegetation proximity, terrain slope
Landscape modification	Includes active fuel reduction strategies	Does not focus on immediate environment management

4.3 Structure of a proposed European code

Following the examples of the presented codes, it is suggested to develop a European code for identifying requirements and actions for the construction of homes in forested areas.

A proposed structure for the code is based on the following chapters:

A. Assessment of expected fire level
B. Characterization of buildings
C. Characterization of the site
D. Characterization of the immediate surroundings
E. Defense and protection measures

A code like this will compare the expected fire levels (A) with the type and condition of the building (B), its location relative to the fire front (C), the characteristics of the immediate surroundings, both on the property itself and neighboring parcels (D), and the available means and infrastructure for protection and defense (E). From this analysis, the minimum construction requirements (materials, design), site selection criteria, vegetation fuel mitigation measures, and necessary or recommended defense and protection measures and installations will be determined.

The full development of this code, however, falls outside the scope of the FirEUrisk project and should be considered as one of the future lines of research. Member states will need to join efforts in a coordinated manner to define the final scope and content of the code.

5 Gardening design and irrigation

The design, maintenance, and irrigation of gardens on properties are fundamental factors in creating fire-resistant communities, especially during extreme fire events that we have been experiencing in recent years.

5.1 Principles for fire-resistant garden design

In the design of fire-resistant gardens, several key aspects must be considered regarding vegetation behavior during wildfires:

- **Flammability of plant species**. Not all plant species react the same way to fire. Some are highly flammable (meaning they ignite easily when exposed to a heat source) and/or highly combustible (producing large amounts of heat, often resulting in long-lasting flames). These types of plants should be avoided in garden design.
- **Horizontal and vertical continuity**. The arrangement of plants in the garden must be carefully planned, particularly to prevent plant crowns from touching each other or being placed too close together. Such contact facilitates the rapid spread of fire. The same principle applies to ground-level vegetation in relation to tree canopies—if there is a continuous connection from the ground to the tree canopy, fire can spread more easily. This includes the presence of ladder fuels, which act as wicks, allowing fire to climb from the ground into the tree crowns, leading to crown fires.
- **Moisture content of live vegetation**. In a garden, the moisture level of plants is regulated by the irrigation system used by the owner. This is a major difference from natural, unmanaged vegetation in the wild, which does not receive artificial watering. Proper irrigation, along with thoughtful plant arrangement, helps maintain green and hydrated vegetation, making it less likely to ignite and spread fire. However, it is important to note that frequent irrigation increases biomass production, so it must be complemented with regular pruning and fuel load management to prevent excessive vegetation accumulation.
- **Presence of fine dead fuels**. Cured grass, dry shrubs, plant debris such as dead leaves and pine needles, and dry leaves within ornamental plants often serve as ignition sources and fuel for fire spread within gardens. Fine dead plant material should be viewed as the "gasoline" of the property, as these elements ignite

extremely efficiently, even from small glowing embers. Proper detection and control of fine dead fuels should be a well-implemented part of garden design and maintenance.

5.2 Objectives for garden design

Therefore, the objectives of garden design and maintenance should include:

- Selection of plant species which are neither highly flammable nor highly combustible
- Avoiding horizontal and vertical continuity of vegetation
- Controlling vegetation density to reduce fire spread risk
- Keeping vegetation away from buildings to minimize fire hazards
- Eliminating fine dead fuels such as dry grass, leaves, and plant debris

To achieve these objectives, it is recommended to consult specific garden design and maintenance guides, which have been published in various parts of Europe and provide solutions to these challenges.

5.3 Methods

The suggested basic methods to apply in garden design are:

- Species selection, lower load, higher humidity, less flammable
- Separation of fuel elements (discontinuity) D=2H
- Separation of undergrowth from canopy base
- Separation of residential fuels
- Dead fine fuel mitigation
- Increased humidity of the living part (previous irrigation)
- Temporary increase in the humidity of the dead part (instant watering)
- Water availability for local defense
- Garden structures hardening

5.4 Guides of suitable plants for gardening and garden design

The design of the plot in a single-family home property is a fundamental aspect of protecting homes, increasing their chances of survival, and providing greater capacity to be used as a shelter in the event of a fire. It has been proven that ornamental elements used in landscaping can act as receivers of flames from fire propagation and flying embers, generating new combustion, spreading fire within the property and to neighboring ones, and potentially affecting objects and materials nearby or even impacting the structural components of homes.

Therefore, the selection of plant species, the design of their arrangement in the garden, and their maintenance are critical aspects to consider in protecting properties from wildfires, especially during extreme fire events that have been occurring in recent years. These fires develop large flame lengths, very high rates of spread, and dense smoke clouds with widespread ember wash. These conditions make it necessary to design gardens that are resistant to fire and flying embers, particularly in terms of the placement of ornamental plants.

There are several comprehensive guides that describe the behavior of different plant species used in gardens, providing recommendations on their selection, distribution, and maintenance. Some of these guides are detailed below.

5.4.1 Guide in Catalonia

Gardening practice guide adapted to wildfire prevention (*Guia pràctica de jardineria adaptada a la prevenció d'incendis forestals*). Diputació de Girona, 2020.

https://interior.gencat.cat/web/.content/home/030_arees_dactuacio/bombers/foc_forestal/publicacions_tecniques_i_normativa/guies_tecniques/prevencio_i_extincio/2020_Guia_de_pirojardineria_ca.pdf

The increase in urbanization near forests and rural depopulation has heightened the risk of wildfires. The WUI presents a challenge because fires in these areas require not only forest fire suppression but also the protection of homes and infrastructure. Pyro-gardening is a technique aimed at designing gardens that reduce fire spread and facilitate firefighting efforts. This guide is aimed at preventing wildfires in the WUI through proper garden design and maintenance. The goal is to reduce the vulnerability of buildings to fires by promoting fire-resistant landscaping.

Pyro-gardening is a key tool in wildfire prevention in the WUI. A well-designed and maintained garden not only enhances the surroundings but also acts as a natural barrier against fire spread. The proper selection of plant species, along with continuous maintenance, is essential to reducing the vulnerability of homes and ensuring greater safety against wildfires. By following these guidelines, residents in fire-prone areas can significantly reduce wildfire risk and improve the safety of their homes and communities.

Objectives of the guide

- Reduce fire risk in properties located in the WUI
- Create defensible spaces around homes to aid firefighter protection
- Prevent continuity of vegetative fuel between vegetation and structures
- Design low-maintenance, fire-resistant, and sustainable gardens
- Promote shared responsibility among homeowners and authorities in risk management

Application of the guide

This guide is intended for:

- Homeowners with gardens in the WUI
- Housing developments and neighborhood communities
- Landscaping professionals and landscape architects
- Local governments and emergency response teams

The recommendations can be applied to residential developments, isolated homes, and green spaces within the WUI.

Wildfire risk in the WUI

Considered factors that increase risk are:

- Continuous vegetative fuel without breaks
- Proximity of homes to dense forests or abandoned agricultural land
- Climatic conditions high temperatures, prolonged droughts, and strong winds
- Limited accessibility for emergency vehicles

The guide emphasizes the need to maintain a 25-meter protection zone around buildings to reduce flammable vegetation.

Legislative measures for wildfire protection

Regulations require property owners to keep their land free of dry vegetation and reduce fuel load within at least 25 meters. Technical specifications include:

- Removing flammable vegetation around homes.
- Reducing tree density and pruning lower branches.
- Creating low-combustibility buffer zones in residential areas.

Functions of a garden in the WUI

Well-designed gardens not only enhance the environment but also fulfill environmental, social, and safety functions, in particular:

- Environmental, regulating the microclimate, absorbing rainwater, and increasing biodiversity.
- Social, providing spaces for social interaction, mental well-being, and community cohesion.
- Economic, increasing property value, reducing energy consumption through shading and thermal protection.

Structural elements of homes and their vulnerability

Fires affect homes through:

- Direct flames: contact with flammable vegetation or nearby combustible materials
- Radiant heat: intense heat can melt or shatter glass and plastics
- Convection: hot air currents can carry burning embers firebrands over long distances

Some key elements to reinforce are:

- Roofs and gutters: prevent accumulation of leaves and flammable debris
- Windows and doors: use tempered glass and fire-resistant frames

- Exterior walls: prefer fire-resistant materials
- Porches and terraces: avoid the accumulation of flammable furniture and climbing plants

Vegetation in gardens and perimeter hedges and garden zoning

The area is suggested to be divided into concentric rings with specific measures to reduce risk:

Zone 1: 0-2 meters

- No flammable vegetation or combustible furniture
- Prohibit the use of fast-burning species like conifers
- Recommended gravel, mineral soil, or well-irrigated grass

Zone 2: 2-10 meters

- Avoid dense vegetation and maintain at least 5 meters between trees
- Prohibit the use of flammable shrubs or species that accumulate dry matter

Zone 3: 10-30 meters

- Maintain a minimum 2-meter separation between tree canopies
- Keep the area free of dry vegetation and combustible debris

Recommended and non-recommended plant species

Low-fire-risk plants:

- Trees: Olive (*Olea europaea*), Cork oak (*Quercus suber*), Strawberry tree (*Arbutus unedo*)
- Shrubs: Lavender (*Lavandula spp.*), Rosemary (*Rosmarinus officinalis*), Boxwood (*Buxus sempervirens*)
- Ground covers: Ivy (*Hedera helix*), Flame vine (*Distictis buccinatoria*)

Highly flammable plants that are NOT recommended:

- Trees Pine (*Pinus spp.*), Eucalyptus (*Eucalyptus spp.*), Cypress (*Cupressus spp.*)
- Shrubs: Broom (*Spartium junceum*), Oleander (*Nerium oleander*)
- Ornamental plants: Dry grasses, reeds, and ferns

Design of perimeter hedges

The integration of green hedges must observe:

- Avoid flammable hedges like cypress and thuja
- Opt for broadleaf species with low combustibility
- Separate hedges at least 2 meters from the house

Maintenance and risk reduction

Essential measures to reduce garden flammability are:

- Regular pruning: remove lower branches and maintain a well-ventilated tree canopy
- Strategic irrigation: maintain soil and plant moisture
- Removal of dry material: fallen leaves, dead branches, and plant debris
- Use of mineral mulch: gravel and rocks instead of pine bark or wood chips

Post-fire evaluation

After a fire, it is recommended to:

- Assess structural and vegetation damage
- Remove charred material to avoid future risks
- Restore the landscape with more fire-resistant species

5.4.2 Guide in France

Fire Prevention Guide for the Forest-Residential Interface(*Guide Prévention incendie interface forêt-habitat*). Valabre, 2016.

https://www.sdis83.fr/internet/_media/guide-resident-foret-prevention-incendie.pdf

This guide provides essential information on preventing wildfires in forested areas, particularly in the Provence-Alpes-Côte d'Azur region of France. It highlights the increasing risk of wildfires due to urban expansion, forest growth, and climate change, and stresses the importance of both governmental and individual actions in fire prevention. The guide underscores the importance of collective action in wildfire prevention. Homeowners, municipalities, and emergency responders must work together to reduce fire risks and improve community resilience. By following the recommended measures, residents can protect their homes, their communities, and the surrounding forests from devastating wildfires.

Wildfires are not a new phenomenon, but their frequency and intensity have increased due to:

- Rising temperatures and prolonged droughts linked to climate change
- Expanding forests and urbanization, leading to more forest-human interfaces
- A shift in fire regimes, with shorter intervals between major fires

The guide emphasizes that no area is immune to wildfires. Some regions experience fires on average every 25 years, while more densely populated areas record one fire per year for every 10 km².

Residents must take personal responsibility for wildfire prevention by:

- Clearing vegetation around their homes
- Adapting construction materials and home design to be fire-resistant
- Regularly maintaining their property to reduce flammable materials

- Understanding fire behavior and preparing for emergency situations

The document warns that fires can spread extremely fast, reaching speeds of up to 5 km/h, and embers can travel more than 6 km, igniting new fires far from the initial fire front.

Defensible space and vegetation management

One of the most effective ways to reduce wildfire risk is creating and maintaining defensible space around homes. This involves:

- Clearing vegetation within 50 meters around homes to reduce fire intensity
- Removing dry brush, dead trees, and low branches to prevent fire spread
- Ensuring proper spacing between trees (minimum 3 meters between crowns)
- Avoiding flammable plant species, such as pine and eucalyptus, near structures
- Regularly pruning and irrigating vegetation to maintain moisture content

The document provides guidelines for homeowners on choosing fire-resistant plants and maintaining a firebreak around properties.

The legal obligation of vegetation clearance

French law mandates land clearing (*débroussaillement*) in areas prone to wildfires:

- Minimum clearance of 50 meters around homes and 10 meters on both sides of private roads
- In urban zones, entire properties must be cleared
- In some high-risk areas, clearance may extend to 100 meters
- Property owners are responsible for these actions, and municipal authorities enforce compliance

Failure to comply can result in:

- Fines starting at 135 Euros, increasing to 30 Euros per day per hectare
- The municipality carrying out the work at the owner's expense
- Legal liability if a wildfire starts due to non-compliance

Fire-resistant construction and home design

The guide emphasizes that home construction materials and design can significantly impact fire resistance. Key recommendations include:

- Using non-combustible roofing materials
- Installing metal shutters and double-glazed windows to prevent heat penetration
- Keeping gutters clean to avoid ember accumulation
- Avoiding wooden fences and decks that can ignite easily
- Ensuring emergency vehicle access with roads that are at least 4 meters wide

- Managing Perimeter Hedges and Fences

Hedges and fences can accelerate fire spread if they are made of combustible materials. The guide recommends:

- Avoiding flammable hedges like cypress or thuja
- Maintaining at least 3 meters distance between hedges and buildings
- Using fire-resistant fencing materials, such as metal
- Firefighting Resources and Emergency Preparedness

Residents are encouraged to have fire suppression tools readily available, including:

- A water source, such as a swimming pool or water tank, with a pump
- Fire extinguishers and hoses long enough to reach all parts of the property
- Clear evacuation routes and emergency plans

The document also stresses the limitations of emergency services in a wildfire situation:

- Firefighters may not always be able to reach every home
- Access roads must be clear and wide enough for fire trucks
- Self-protection measures are essential for increasing survivability

Handling vegetation waste and fire safety rules

To minimize fire hazards:

- Do not burn cut vegetation (this is illegal in most cases).
- Dispose of plant waste at designated facilities or compost it.
- Avoid outdoor fires, especially barbecues near vegetation.

Strict regulations govern the use of fire in wildfire-prone areas, and violations can result in severe fines.

5.4.3 Guide in USA

Fire-Resistant Plant List. Fire Safe Council of San Diego County, 2017.
https://firesafesdcounty.org/wp-content/uploads/2017/05/Comprehensive-Fire-Resistant-Plant-List.pdf

This document presents an extensive list of fire-resistant plants, emphasizing their importance in creating defensible spaces against wildfires. The information focuses on plant species suitable for minimizing fire spread risk in urban areas and the wildland-urban interface.

Definition of fire-resistant plants

Fire-resistant plants do not ignite easily from flames or other ignition sources. Although they may suffer damage or even perish in a fire, their foliage and stems do not significantly contribute to fuel, thereby reducing fire intensity.
Factors influencing a plant's flammability characteristics include:

- Moisture content in the plant
- Age and total biomass volume
- Amount of accumulated dead material
- Chemical composition of leaves and stems

List of recommended plants for defensible spaces

The document includes an extensive list of recommended species, categorized as follows:

Trees

• *Acer spp.* (Norway Maple, Red Maple, Silver Maple, etc.)
• *Arbutus unedo* (Strawberry Tree)
• *Ceratonia siliqua* (Carob Tree)
• *Cercis occidentalis* (Western Redbud)
• *Eriobotrya japonica* (Loquat)
• *Ginkgo biloba* (Fairmount Maidenhair Tree)
• *Juglans californica* (California Walnut)
• *Liquidambar styraciflua* (Sweet Gum)
• *Pistacia chinensis* (Chinese Pistache)
• *Quercus agrifolia* (Coast Live Oak)
• *Umbellularia californica* (California Bay Laurel)

Shrubs

• *Arctostaphylos spp*. (Manzanita)
• *Ceanothus spp.* (California Lilac)
• *Cistus spp.* (Rockrose)
• *Elaeagnus pungens* (Silverberry)
• *Fremontodendron spp.* (Flannel Bush)
• *Rhus spp.* (Lemonade Berry, Laurel Sumac, etc.)
• *Ribes viburnifolium* (Evergreen Currant)

Groundcovers

- *Achillea spp.* (Yarrow)
- *Aptenia cordifolia* (Red Apple Ice Plant)
- *Baccharis pilularis* (Coyote Bush)
- *Drosanthemumhispidum* (Rosea Ice Plant)
- *Lantana spp*.
- *Myoporum parvifolium* (Creeping Myoporum)
- *Vinca minor* (Dwarf Myrtle)

Vines

- *Lonicera japonica* (Hall's Honeysuckle)
- *Distictisbuccinatoria* (Blood-Red Trumpet Vine)
- *Keckiella cordifolia* (Heart-Leaved Penstemon)
- *Solanum jasminoides* (Potato Vine)

Perennials & annuals

- *Coreopsis gigantea* (Giant Coreopsis)
- *Iris douglasiana* (Douglas Iris)
- *Lavandula spp.* (Lavender)
- *Penstemon spp.* (Beardtongue)
- *Sisyrinchium bellum* (Blue-Eyed Grass)
- *Salvia spp.* (Sage)
- *Epilobium canum* (California Fuchsia)

Considerations on the safety and use of fire-resistant plants

- There are no completely fire-proof plants. All plants will eventually burn under extreme conditions.
- Species with higher moisture content and low accumulation of dry material are the most recommended.
- Vegetation should be pruned and kept free of dry debris, especially near homes and structures.
- Landscape design should allow for natural barriers between flammable vegetation and structures.
- The introduction of **native species** in gardens is recommended, as they are adapted to the climate and require less maintenance.

Application in urban and wildland-urban interface areas

The document highlights the importance of landscape planning to:

- Reduce fire spread in vulnerable communities
- Protect homes through strategic species selection
- Create defensible zones around structures, reducing fuel loads
- Ensure ecosystem sustainability by using native species

5.5 Irrigation using water reclamation

Use of Reclaimed Water for Wildfire Defense in WUI Areas has been implemented in the WUI PROTECT® & GUARDIAN Projects. This is an innovative strategy for wildfire prevention and defense in WUI areas using reclaimed water for prescribed irrigation to create green firebreaks. The approach, developed by Medi XXI GSA and AGBAR, integrates multiple components for fire prevention, self-protection, and environmental sustainability. The combination of reclaimed water, prescribed irrigation, and smart fire defense is a game-changer for wildfire prevention in WUI areas. It provides an eco-friendly, cost-effective, and scalable solution that strengthens fire resilience while conserving water resources.

The use of treated wastewater for wildfire defense in urbanized areas is a highly suitable strategy for a future of adverse climate change, where the availability of water for fire protection will become increasingly scarce.

WUI PROTECT® is a fire prevention and self-protection system, rather than an extinguishing solution. It is based on four main pillars:

- Planning – Pre-emergency risk assessments, emergency action plans, and post-emergency restoration
- Forestry & Pyrogardening – Vegetation management through prescribed burning, biomass projects, and irrigation with reclaimed water
- Infrastructure – Sensory networks, smart irrigation, and automated defense systems
- Training & Education – Community awareness, virtual reality training, and operational drills

The system is deployed in three defense levels:

- Collective: Perimeter defense of urban areas and towns.
- Domestic: Protection of individual homes.
- Portable: Support for emergency operations.

Use of reclaimed water for fire protection

The strategy involves using recycled wastewater to irrigate vegetation, creating a green firebreak that reduces fire spread. The GUARDIAN Project (Green Urban Actions for Resilient Defense of the Interface Area; Blanco, 2022) is the largest fire defense system in Europe using this method:

- Wastewater Treatment Plant (WWTP) processes used water
- Tertiary treatment makes it suitable for irrigation
- Water is distributed to WUI areas through a sensor-controlled irrigation system
- Prescribed irrigation ensures vegetation retains moisture, making it less flammable
- Creates wet areas, infiltration zones, and green barriers

The benefits of using reclaimed water are:

- Reduces potable water consumption for fire protection
- Enhances vegetation resilience, reducing fire intensity
- Lowers CO_2 emissions by promoting sustainable forest management
- Improves biodiversity conservation and local ecosystem stability

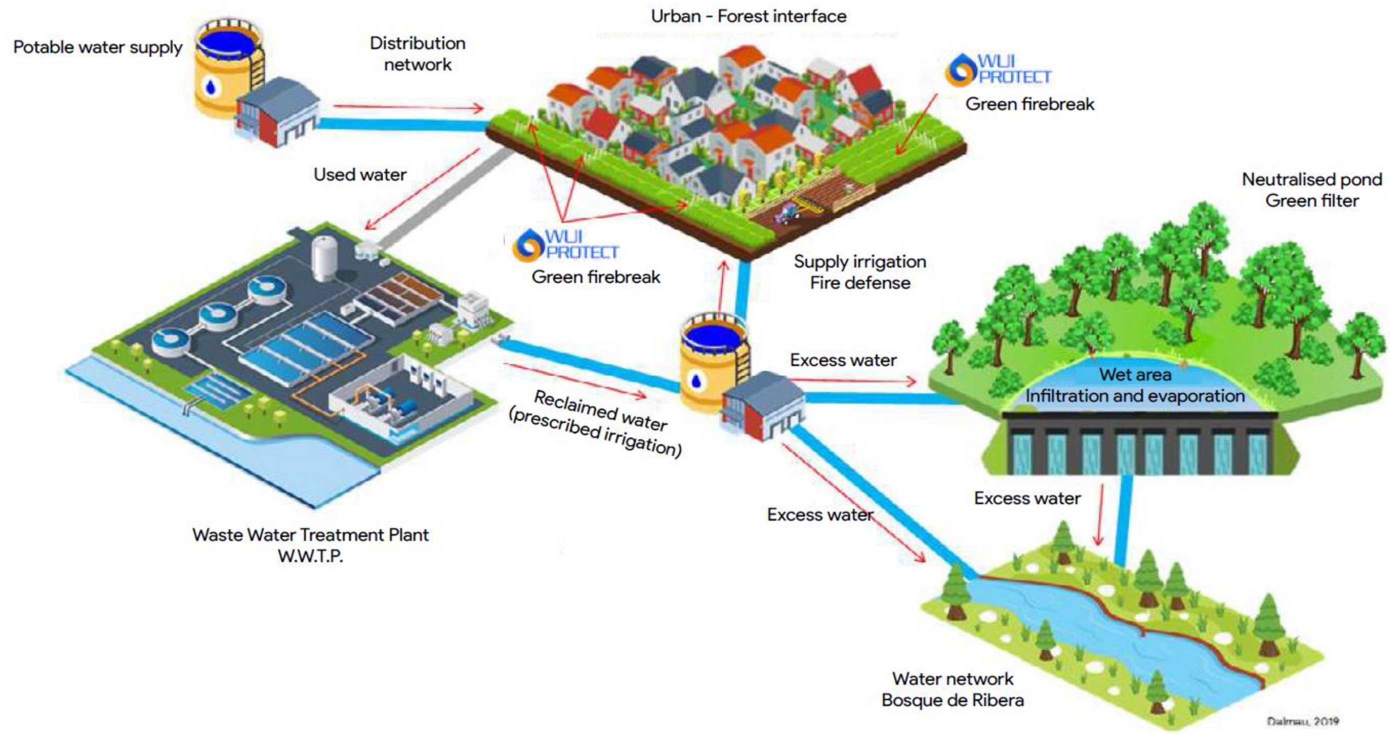


Figure 4. Diagram of the design and development of the GUARDIAN system for the use of reclaimed water in wildfire defense of urbanized areas (adapted from Dalmau, 2019).

Several locations in Spain have implemented the WUI PROTECT® system, such as Carcaixent, Alcoi, Paterna, Torrent, Chiva, Xàbia, and Valencia's Albufera Natural Park. The system successfully prevented house losses in the 2016 Carcaixent wildfire.

Future applications and expansion

- Collaboration with AGBAR enhances water regeneration technologies.
- The strategy aligns with the circular economy model, ensuring sustainable water use.
- Integration with smart technologies (sensor networks, remote monitoring, AI-driven irrigation).
- Potential for expansion to other fire-prone regions globally.

6 Fuel treatments and mitigation

6.1 Treatments in the surrounding areas

The treatments in the areas surrounding the urbanized zone aim primarily to reduce fire activity as it approaches, specifically by decreasing both the rate of spread and flame length, as well as minimizing the generation and projection of flying embers. Some of the proposed actions include:

- Fuel management (reduction, prescribed fire, livestock)
- Soil protection, water reserves
- Live humidity control, prescribed irrigation
- Improve access and penetrability to extinguishing media
- Availability of water for operations

6.2 Treatments in the border plots

The edge of urbanized areas constitutes a zone where fire defense can be highly effective, provided that fire activity is substantially reduced, accessibility is improved, and, ideally, the area is equipped with infrastructure for wildfire defense.

As part of this strategy, it is crucial to distinguish the parcels located along the urban edge, which in many cases are in direct contact with the surrounding forested area, as critical for the defense of the entire community. These parcels must adhere to and implement vegetation mitigation measures with much greater rigor, as they can serve as the entry point for fire into the rest of the development.

Some of the mitigation treatments proposed are:

- Absence of flammable / combustible enclosures
- Absence of fine dead elements
- Absence of flammable materials and objects
- Ideally, presence of wall and/or separation panels
- Accessible from the rear
- Water available
- Adapted homes (glazing, roofing, openings, etc.)
- Separate building on the edge of the mountain (2 times FL)
- Buried LPG tanks

6.3 Treatments in the internal plots

Interior parcels are those that are not located directly on the edge of the forested area. These parcels may be developed (i.e., with a building inside) or undeveloped/abandoned. Undeveloped or abandoned parcels should be considered as potential ignition and consolidation points for fire fronts, especially under the influence of ember wash, which is very common in wildfires.

It is important to remember that a wildfire in an urbanized area often does not propagate as a continuous front; rather, it advances in a fragmented manner and through leapfrogging, mainly due to the production of flying embers. For this reason, the primary strategy for managing interior parcels is the removal of dry vegetation, particularly cured grass and other flammable plant materials, as these are highly effective at igniting fires when exposed to flying embers.

Other strategies for treating interior parcels include:

- Avoiding the accumulation of vegetation and pruning debris in undeveloped parcels.
- Preventing the accumulation of objects and materials in undeveloped parcels.
- Avoiding the use of flammable green hedges as perimeter enclosures.
- Disrupting vegetation continuity with neighboring parcels to prevent fire runs within the urbanized area, particularly if aligned with prevailing winds.
- Implementing fuel load mitigation measures in green corridors and forested passageways, which can act as wicks within urban developments.
- Limiting the use of flammable plant species as ornamental vegetation in recreational areas and green spaces.

For developed interior parcels, the principles of fire-adapted landscaping should be applied.

7 Sheltering methods and protocols

Wildfires are an increasing threat in Europe due to factors such as climate change, land-use changes, and socio-economic alterations that have led to the abandonment of primary sector activities (agriculture, forestry, and livestock). These conditions contribute to the likelihood of larger and more intense fires. Associated with these events are extreme impacts, with the loss of human lives being the most severe consequence, as seen in recent wildfire disasters in Southern Europe, including Portugal, Spain, and Greece (Viegas et al., 2019, 2021; Almeida et al., 2022, 2023). The 2018 Mati wildfire in Greece, which claimed 104 lives, highlighted the urgent need for improved safety measures in fire-prone regions (Mitsopoulos et al., 2023). Greece implemented the AntiNero program with a budget of €72 million for prevention projects in public forests across the country, representing a shift toward more prevention-oriented approaches to wildfire management (Mitsopoulos et al., 2023).

Norway has implemented age-friendly design principles in various projects, such as in Telemark, where multipurpose spaces and universally designed parks accommodate people of all ages with equipment suitable for both older and younger users (Norsk Design, 2021). The Powerhouse Telemark building in Porsgrunn demonstrates sustainable construction with mindful interior design principles (Snøhetta, 2020).

Therefore, the need for standardized fire shelters to be available in fire prone communities is obvious, providing last-resort protection when evacuation is impossible or unsafe.

This standard incorporates lessons from major international wildfire events, particularly the 2009 Victoria fires in Australia, which led to the Victorian Bushfires Royal Commission (VBRC) report. The report emphasized that fire shelters should not be considered a primary response but rather a contingency measure within an integrated fire management strategy. Shelters must complement fire prevention techniques, early warning systems, evacuation plans, and community awareness initiatives.

7.1 Building codes for sheltering

The construction of shelters for the protection of people in the event of a wildfire has not been widely considered until recent years. Indeed, the new wildfire events that exhibit extreme behavior are difficult to predict and, frequently result in people becoming trapped without a safe evacuation to non-exposed areas. The list of wildfire events that have trapped numerous people during evacuation or transit is already long, almost always involving extreme fire behavior.

For this reason, the construction of buildings that serve as shelters and protect people trapped from smoke and fire is being considered. Although there is still much research to be done on methods and construction materials that improve survival in a fire shelter, existing codes and experiences can already contribute to better and more efficient design and construction of these facilities.

7.1.1 The ABCB Standard of private bushfire shelters

The ABCB 2014 - The Design and Construction of Private Bushfire Shelters standard establishes the requirements for designing and constructing private wildfire shelters in Australia. The Australian standard ABCB 2014 is a valuable reference for constructing fire shelters. It provides a performance-based approach, with strict criteria for design, location, and habitability. For its application in Europe, key aspects must be adapted, such as risk classification, integration with local regulations, and consideration of existing structures. This document, along with AS 3959-2009 and NFPA 1144-2018, offers a solid foundation for developing a European wildfire protection code.

Structure of the standard

The document is divided into several key chapters:

Introduction and context

- Developed in response to extreme wildfires in Australia, particularly the 2009 Victoria fires
- Based on recommendations from the Victorian Bushfires Royal Commission (VBRC)
- Highlights that shelters should not be considered the only safety strategy but part of a comprehensive plan

Design standards

- Establishes performance-based requirements instead of prescriptive solutions
- Focuses on providing a habitable environment during the passage of the fire

Design requirements

- Defines acceptance criteria to ensure shelters meet safety standards

- Includes considerations on location, access, materials, and ventilation

Additional considerations

- Discusses psychological factors, occupancy duration, and maintenance
- Considers air toxicity and the impact of nearby combustible materials

Informative annexes

- Provides technical details and additional references
- Includes a fire safety concept tree based on NFPA

Implementation

The standard focuses on protecting human life by designing private fire-resistant shelters. It follows a performance-based approach rather than rigid specifications, allowing flexibility in design while meeting safety criteria.

Purpose of the shelter

- It does not replace evacuation but serves as a "Plan B" when escape is impossible
- Must ensure occupant survival during the passage of the fire front
- Should be integrated into a comprehensive fire risk management strategy

Acceptance criteria

- Establishes strict requirements for BAL-40 and BAL-FZ zones (highest risk areas)
- Shelters must be sealed to prevent the entry of smoke and toxic gases.
- Must maintain habitable conditions for at least 60 minutes.

Location and access

- A minimum distance of 6 meters between the shelter and other structures or fuel sources
- The access path must be safe and easily navigable
- Ensures a safe evacuation after the fire

Structural design and materials

- Construction with concrete or solid masonry, with a fire resistance rating of 60/60/60
- Doors and windows must withstand high temperatures and prevent ember intrusion
- Minimum ventilation required to maintain adequate oxygen levels while avoiding CO_2 buildup

Occupancy duration

- Defines a minimum shelter time of **60 minutes**, divided into:
    - Pre-event: 10 minutes before fire arrival.
    - Fire front passage: 10 minutes of intense exposure.
    - Secondary fires and residual heat: 30-40 additional minutes.

Internal shelter conditions

- Maximum allowable temperature: 45°C, with a thermal discomfort index not exceeding 39°C
- Internal materials must not release toxic gases above 100°C
- Doors and seals must remain functional after the fire

Psychological factors

- Considers the stress and anxiety of occupants inside the shelter
- Recommends prior familiarization with the shelter's use to avoid panic or poor decision-making

Maintenance

- Requires a maintenance manual to ensure the shelter's long-term functionality
- Periodic inspections are necessary to verify the integrity of seals, doors, and ventilation systems

Key considerations for European adaptation

The Australian standard provides a solid technical framework, but for its application in Europe (especially in the Mediterranean region), several factors must be considered:

Differences in climate and vegetation

- The Mediterranean region has different wildfire regimes compared to Australia
- The BAL classification should be adapted to Mediterranean vegetation characteristics

Regulation and standards

- The standard must be integrated with European construction and material regulations
- Consideration of specific regulations in countries such as Spain, France, Italy, and Portugal

Focus on existing structures

- Include strategies for modifying existing buildings, not just new constructions
- Apply retrofitting criteria to improve fire resistance in older homes

Landscape management

- Incorporate active strategies for fuel reduction
- Promote the use of firebreaks and natural barriers in wildland-urban interface areas

Protection of critical infrastructure

- Extend the focus beyond individual homes to include community shelters
- Consider the protection of schools, hospitals, and other critical facilities

7.2 Best practices in sheltering

7.2.1 Foundational design principles for fire-resistant shelters

Shelters in WUI zones must balance structural resilience with habitability during fire exposure. Research supports that concrete and insulating concrete forms (ICFs) provide excellent fire resistance, capable of withstanding temperatures up to 2000°F for up to 4 hours without structural damage (Concrete Network, 2023). ICF walls effectively prevent heat transfer, delaying fire ignition on the cool side of the wall for 2-4 hours (Concrete Network, 2023).

For ventilation systems, shelters require both normal and protective ventilation systems. In shelters, CO_2 levels should not exceed 2%, and O_2 levels should not drop below 19% (FEMA, 2015). When outside air is hazardous, it must pass through appropriate filtration systems before being introduced into the shelter environment (FEMA, 2015).
Regarding materials, non-combustible options like concrete (classified with the highest fire resistance - class AI under EN13501-1:2018), mineral wool insulation, and fire-resistant glazing are essential for WUI structures (Rockwool, 2022). Mineral wool insulation provides both fire resistance and effective thermal insulation with R-values between 3.0-3.5 per inch, making it suitable for buildings that must comply with stringent fire codes (Rockwool, 2022).

Research on prototype fire shelters has shown that heat transfer rates are influenced by temperature differences between shelter exterior and interior, surface area, construction materials, and wall thickness (Frankman et al., 2013). Aluminized exterior layers provide excellent reflection of radiant energy, though they can fail when in direct contact with flames exceeding aluminum's melting point (660°C) (Frankman et al., 2013). This indicates the need for robust fire-blocking layers with low thermal conductivity and stability at high temperatures.

Studies of sheltering practices during bushfires have found that active sheltering significantly improves survival rates, with 84% of people surviving in their first sheltering location (Blanchi et al., 2018). The number of people actively sheltering had the strongest influence on survival probability, emphasizing that shelters require not only appropriate design but also well-informed and capable occupants (Blanchi et al., 2018).

For WUI communities, building codes should address both ember and fire exposures, with consideration for structure separation distance (SSD) in hazard reduction strategies (Maranghides& Mell, 2013). Strategic shelter placement should align with population density and wildfire risk profiles, with buffer zones between structures and vegetation leveraging existing firebreaks (Ribera et al., 2020).

7.2.2 Strategic shelter placement in wildfire risk areas

Strategic spatial distribution of protective infrastructure must align with population density and wildfire risk profiles. The EU-funded GUARDIAN project implements comprehensive solutions for wildfire resilience in WUI zones in Spain, including hydraulic infrastructure and green firebreaks (Ribera et al., 2020).

Buffer zones between structures and vegetation can leverage existing firebreaks, as demonstrated in the GUARDIAN project's fuel management strategies that include 50-60 meter-wide perimeter strips of fire-resistant vegetation (Ribera et al., 2020; Caballero et al., 2021).

Table 3: Shelter Placement Parameters in EU Context

Parameter	Requirement	Source
Shelter density	1 per 50–100 residents in BAL-FZ	ABCB (2014)
Buffer zone width	15 m	NFPA 1144
Accessibility distance	≤500 m	EU Directive 2019/882

7.2.3 Ventilation and air quality management

Proper ventilation and air quality management are critical for fire shelter safety, as smoke inhalation represents a significant risk during wildfire events. Carbon monoxide can lead to unconsciousness or death, making effective ventilation systems essential for survival during sheltering (FEMA, 2015).

For effective shelter ventilation, both normal and protective ventilation systems are required. When outside air is hazardous, it must pass through appropriate filtration systems before being introduced into the shelter environment. Pressurization can be used to keep refuge areas at positive pressure to prevent smoke entry, while ensuring CO2 levels do not exceed 2% and O_2 levels do not drop below 19% (FEMA, 2015).

7.2.4 Occupancy and capacity planning

Emergency shelter planning must consider accessibility and capacity requirements for diverse populations. EU Directive 2019/882 addresses accessibility requirements for products and services, promoting a 'universal design' approach that ensures access for persons with disabilities (European Parliament and Council, 2019). In Greece, regulations require that hotels allocate a minimum of 5% of their rooms for persons with reduced mobility (Hellenic Chamber of Hotels, 2022).

Greece has faced significant wildfire evacuations in recent years, including its largest-ever evacuation in 2023 affecting over 20,000 people across Rhodes, Corfu, and Evia (Mitsopoulos et al., 2023). During these emergencies, the Greek government has provided hotel accommodations for those whose homes were affected by fires (Hellenic Fire Service, 2023).

7.2.5 Maintenance and operational protocols

Regular maintenance and operational protocols are essential components of emergency preparedness. Greece's National Climate Law 4936/2022 establishes a framework for climate adaptation strategies, including the development of the National Adaptation Strategy to Climate Change (NASCC) that covers a ten-year period and is evaluated every five years (Hellenic Republic, 2022).

In Portugal, collaborative networks like Ageing@Coimbra demonstrate how regional stakeholders can build holistic ecosystems in health and social care, taking into consideration the specificities of territories and living environments (Malva et al., 2018).

Emergency preparedness experts recommend practicing drills regularly, as demonstrated in Galicia, Spain, where local authorities organize community workshops to raise awareness about forest fires and emergency procedures. These activities include sharing safety recommendations and posting informational signs indicating safe locations during emergencies (Climate-Adapt, 2024).

7.2.6 Case studies and lessons learned

Recent wildfire events across Europe have provided valuable lessons for shelter and evacuation strategies. The 2024 fire season in Greece demonstrated the importance of understanding and adapting to extreme wildfire behavior, with authorities implementing a significant shift in firefighting strategy—the first major change in 23 years. This approach emphasized immediate deployment of both aerial and ground teams upon fire detection, along with increased frequency of patrols on high-risk days (Civil Protection Knowledge Network, 2025).

In Spain, the Barcelona government's wildfire prevention program has focused on reducing vulnerability in high-risk wildland-urban interface (WUI) areas through comprehensive risk assessments. This included volunteer-led vulnerability assessment of 610 structures in at-risk settlements, with owners receiving informative risk assessment forms with specific recommendations for improvement (European Forest Institute, n.d.).

Table 4: Some shelter performance examples in EU Wildfires

Location	Year	Key Outcome	Failure/Pitfall
Greece	2024	Successful implementation of new firefighting strategy with immediate deployment	Extreme fire behavior with crown fires, rapid spread, and spotting activity
Kythira, Greece	2022	87% of homeowners implemented suggested changes following risk assessments	Community participation required joint effort by experts and local citizens
Barcelona, Spain	2023	Comprehensive risk assessment of 610 structures in high-risk WUI areas	Balancing natural environment with human settlement safety
EU-wide	2024	Deployment of 556 firefighters pre-positioned across France, Greece, Portugal and Spain	Coordination challenges across 12 different European countries

The EU Civil Protection Mechanism has proven crucial in coordinating pan-European assistance during wildfire emergencies. In 2024 alone, the Mechanism was activated 14 times for wildfires across Europe. During Greece's summer fires, the Emergency Response Coordination Centre mobilized aircraft from the rescEU reserve in France and Italy, helicopters from Serbia, and several ground firefighting teams from across Europe (European Civil Protection and Humanitarian Aid Operations, 2024).

7.2.7 Shelter in place during wildfires: strategic considerations and operational protocols

Sheltering in place during wildfires represents a critical contingency strategy for WUI communities when evacuation becomes untenable due to rapid fire spread or compromised escape routes. This approach, validated by post-2009 EU policy reforms, requires rigorous structural preparedness, active occupant engagement, and integration with broader risk management frameworks (European Civil Protection and Humanitarian Aid Operations, 2024). FirEUrisk emphasizes that effective shelter-in-place protocols must be embedded within holistic wildfire management strategies that balance prevention, suppression, and community resilience measures.

Occupancy Planning and Vulnerable Populations

EU Directive 2019/882 addresses accessibility requirements for products and services, promoting a "universal design" approach that ensures access for persons with disabilities, including in emergency situations (European Parliament and Council, 2019). While the directive establishes a framework for accessibility, it does not specify exact space allocations per occupant in emergency shelters.

In Norway, emergency shelter planning includes approximately 20,000 shelters with space for 2.5 million people. These permanent safe rooms were designed to protect the population during acts of war and are primarily located in cities and larger towns (Sikkerhverdag, n.d.). Modular temporary walls can provide flexibility in emergency shelters by creating private spaces for families, meeting diverse needs during crisis situations (DIYversify, 2024).

In Spain, local authorities in Galicia organize community workshops to enhance resilience against wildfires, focusing on raising awareness about emergency procedures. These activities include sharing safety recommendations and posting informational signs indicating safe locations during emergencies (Climate-Adapt, 2024). The municipality conducts drills involving fire brigades, police, and ambulance services, allowing residents to practice emergency protocols. Training incorporates virtual reality simulations that enable citizens to safely experience forest fire scenarios, helping to prevent panic during actual emergencies (Climate-Adapt, 2024).

7.3 Some guidelines for the installation of community shelters

7.3.1 General considerations

Community shelters can be newly constructed or repurposed from existing buildings, with guidelines that should be adapted to local risk conditions and available resources. While shelters may serve additional functions, their primary role as a refuge must not be compromised. Walking is the preferred method of reaching shelters, except for individuals with mobility issues, in which case vehicles should be relocated away from the shelter if time permits.

Before establishing a shelter, critical factors must be evaluated, including the estimated number of users, which may include permanent residents, temporary visitors, or tourists. The history and frequency of wildfires in the region must be assessed to determine the likely demand for the shelter. The local topography, prevailing winds, vegetation, and potential hazards such as industrial facilities should be considered to predict fire behavior. Special accommodations should be made for individuals with specific needs. As shelters are designed for short-term occupancy, typically lasting from a few hours to a day, they should be accessible to all individuals regardless of physical or cognitive abilities or language barriers.

7.3.2 Shelter location

Shelters must be easily accessible, with multiple access routes to prevent isolation in case of road blockages. The site should be in areas minimally exposed to high-intensity fire fronts and firebrands, avoiding locations such as steep ravines or cliffs. Smoke accumulation zones, particularly in areas with poor air circulation like valley bottoms, should be avoided. The ideal location is near the village center, away from high-risk areas such as parking lots and abandoned buildings. While village outskirts may be more vulnerable to fire, exceptions may be made if necessary.

7.3.3 Surroundings of the shelter

The shelter's surroundings should be maintained to reduce exposure to heat, firebrands, and direct flames. Parking should not be permitted near the shelter, though access for dropping off individuals with disabilities and emergency services must be ensured. Access routes should be designed for comfort and safety, with smooth pavements and minimal exposure to heat. Fire-resistant tree barriers can be used for protection, and water mist or sprinkler systems may be installed around the shelter. The shelter and its routes should be well-signposted to guide unfamiliar users. Outside, visible emergency signage and an audible alarm should indicate when the shelter is operational.

7.3.4 Building construction

Whenever possible, shelters should be housed in public-use buildings such as multipurpose halls, churches, or schools. In the absence of suitable public buildings, private structures may be designated as shelters, provided their owners formally agree to this use. Continuous access must be ensured, with designated individuals holding keys if the primary manager is unavailable.

The building materials should be non-combustible and highly resistant to extreme temperatures. Openings, including doors, windows, and ventilation systems, must be sealed to prevent firebrand intrusion. Smoke-tight construction should be prioritized, and an entrance chamber with two doors may be used to mitigate smoke ingress during entry and exit. The structure should accommodate the expected number of users while allowing for a safety margin in emergencies. Sanitary facilities must be adequate and accessible to individuals with disabilities. A designated recovery room with high smoke resistance should be included for injured individuals or those with respiratory conditions, potentially equipped with an oxygen pressurizer. A quiet space for prayer or meditation may be provided. Where possible, the ceiling height should be maximized to improve air quality.

7.3.5 Shelter interior

Flammable materials inside the building must be minimized to reduce fire risks. First aid supplies should be available, including treatments for burns, respiratory issues, and trauma. Medications such as anxiolytics and essential prescriptions for community members, such as diabetes medications, should be stocked. Emergency food and water supplies must be maintained. Designated areas for pets, including cages, should be available. Communication devices such as radios and intercoms should be installed to ensure external contact with authorities or neighboring communities.

To enhance occupant comfort, seating should be provided, with beds or stretchers available in the recovery room. Additional emergency equipment such as power generators, ABC fire extinguishers, and megaphones should be available, along with accessories like internet modems, phone chargers, children's entertainment, and pet leashes. Internal air quality should be maintained through cooling and purification systems to mitigate smoke exposure and CO_2 buildup.

7.3.6 Maintenance and activation

A comprehensive **maintenance plan** must be implemented to ensure the shelter remains in optimal condition, covering structural integrity checks, ventilation systems, fire resistance features, water supply, power backup, and emergency communication equipment. The shelter should undergo quarterly inspections to verify its readiness, and surrounding vegetation must be regularly cleared or treated to reduce fire risk. Access routes should be maintained to ensure safe entry and exit, with clear signage and unobstructed pathways. At least once a year, potential users should participate in community drills or events to familiarize themselves with shelter procedures, including registration, emergency communication, and shelter-in-place protocols.

An **activation plan** must be developed to outline emergency procedures, specifying the authorities responsible for shelter activation, shelter occupancy management, and re-entry coordination. The primary activation authority should be the local Civil Protection Agency, Fire Department, or Emergency Operations Center (EOC), while the secondary activation authority, such as designated shelter managers or municipal emergency officials, may initiate activation in case of communication failures. Clear leadership roles should be assigned to trained individuals capable of maintaining composure and assisting in shelter operations, including occupant registration, resource distribution, and maintaining order. The shelter must have designated spaces for vulnerable individuals, including those with respiratory conditions, physical disabilities, or medical needs, and should be equipped with sufficient supplies to support temporary occupancy.

Once the fire front has passed, an official clearance from fire authorities is required before occupants leave the shelter. Firefighters and emergency response teams must assess the area for residual risks such as secondary ignitions, unstable structures, gas leaks, and electrical hazards. Before departure, all individuals must receive a post-fire safety briefing to ensure they understand potential dangers, including structural instability, falling trees, hidden embers, and gas explosions. Vulnerable individuals requiring assistance should be prioritized for safe transport back home or directed to alternative accommodations if their homes are deemed unsafe. Community members in good physical and mental condition should be encouraged to return home in a controlled manner to monitor their properties for secondary ignitions and assist in the post-fire stabilization process.

8 Evacuation

In the face of a wildfire threat, especially if it is particularly fast-moving and destructive, the widespread protocol in Europe is to evacuate populations to safe locations. However, this general trend is nuanced in some countries, such as France, where staying in homes is considered the first option, or in specific situations where the threat is imminent and does not allow for a safe evacuation. In such cases, a shelter-in-place approach is implemented.

Recent wildfire evacuations have demonstrated the importance of proper planning for vulnerable populations. For example, in Greece in 2023, more than 1,200 children were evacuated from a summer camp in Loutraki as wildfires approached (BBC, 2023). Consequently the Greek government has established protocols for those affected by fires, providing hotel accommodations and compensation for displaced residents.

8.1 Risk-informed evacuation planning frameworks

European wildfire dynamics have evolved substantially over the last decade, fueled in part by climate change, modified land-use practices, and expanding WUI zones (Penney G., and al, 2024). Against this backdrop, risk-informed evacuation planning has emerged as a centerpiece of wildfire management policy, particularly in EU Mediterranean countries involved in the FirEUrisk project like Greece, Portugal, Spain, Cyprus and Italy. The premise is straightforward but essential: wildfires often accelerate faster than traditional evacuation templates anticipate, rendering purely reactive strategies unworkable. Instead, modern approaches rely on continual forecasting, data analytics, and local-scale contingency measures.

A guiding principle of risk-informed frameworks is advanced fire modeling integrated with robust meteorological data. This approach rests on computational fluid dynamics (CFD) simulations that factor in wind patterns, topography, vegetation load, and relative humidity, producing short-term forecasts of likely flame trajectories (Cova et al., 2011; Modeling Evacuate versus Shelter-in-Place Decisions in Wildfires, 2011).

While these models show considerable promise, current CFD applications for wildfires face computational constraints that can limit their real-time operational use in rapidly evolving emergency scenarios. Even with advanced computing resources, the complexity of wildfire behavior introduces inherent uncertainties that evacuation planners must acknowledge when incorporating these predictions into decision frameworks (Cruz and Alexander, 2023).When local authorities have access to these near-real-time models, they can generate "trigger points" for phased evacuation orders or shelter-in-place advisories, tailoring protective actions to the evolving intensity and speed of the fire front.

The table 5 depicts a conceptual overview of how varying wildfire intensities, generally expressed through the rate of spread (ROS), influence evacuation feasibility and the role of community refuges. At lower ROS, communities typically have more time to organize an orderly departure, and additional shelter capacity may serve as an optional fallback. However, as ROS rises, dual-use infrastructures become a more critical life-safety measure—often requiring High-Performance Cooling (HPC) or advanced ventilation to protect occupants from extreme radiant heat and smoke. Actual outcomes depend on multiple factors, including local topography, vegetation load, weather conditions, and the community's preparedness. This table is, therefore, a starting point for planning discussions rather than a definitive prescription.

Table 5: Fire Behavior Scenarios vs. Community Refuge Capacity

Fire Behavior Scenario (ROS)*	Typical Evacuation Feasibility (Time & Route Availability)	Role of Dual-Use Shelters (Fallback, Mandatory, etc.)	Possible Infrastructure Needs (Sprinklers, Ventilation, etc.)
LOW ROS (Slow fire spread)	High feasibility, longer lead time (traffic likely manageable).	Optional fallback if roads become jammed or if certain groups need quick refuge.	Basic sprinklers or external hoses. Minimal HPC** ventilation.
MODERATE ROS (Faster spread in spots)	Moderate feasibility; partial contraflow or staged evac needed. More risk of route saturation.	Strongly recommended as partial fallback, especially for vulnerable. Shelters may fill quickly.	Sprinkler networks, small capacity water storage, improved HVAC.
EXTREME ROS (High wind, crowning)	Low feasibility; roads may close within minutes or become unsafe. Potential chaos in mass egress.	Mandatory last resort if egress routes fail or time is too short. Central evac may be impossible.	Advanced HPC** ventilation, robust fireproofing, large water reserves. Ember-resistant roofing/materials.

For instance, the ENGAGE platform in Greece integrates data from the Hellenic Fire Brigade, the Forest Service, and meteorological agencies, drawing on advanced modeling that flags hazardous intersections or potential choke points along major egress routes (Zikeloglou et al., 2021; Arbinolo et al., 2024).

As shown in figure 5, the escalation from routine fire monitoring to a mandatory evacuation follows a four-phase structure keyed to progressively stricter trigger thresholds. During the initial Green Phase, authorities focus on surveillance of fire and weather conditions. Once preliminary triggers (such as rising wind speed or decreased distance to the fire front) are met, the Yellow Phase activates an "Alert" message, followed by the Orange "Prepare" Phase when fire risk becomes imminent. Finally, the Red Phase denotes a mandatory "Go Now" evacuation, in which road closures, contraflow lanes, and public shuttles swiftly mobilize to clear residents from danger. This schematic visually underscores how local agencies can integrate continuous fire modeling and real-time updates into a tiered communication plan, ensuring communities remain aware, prepared, and able to evacuate in a structured manner if the wildfire intensifies.

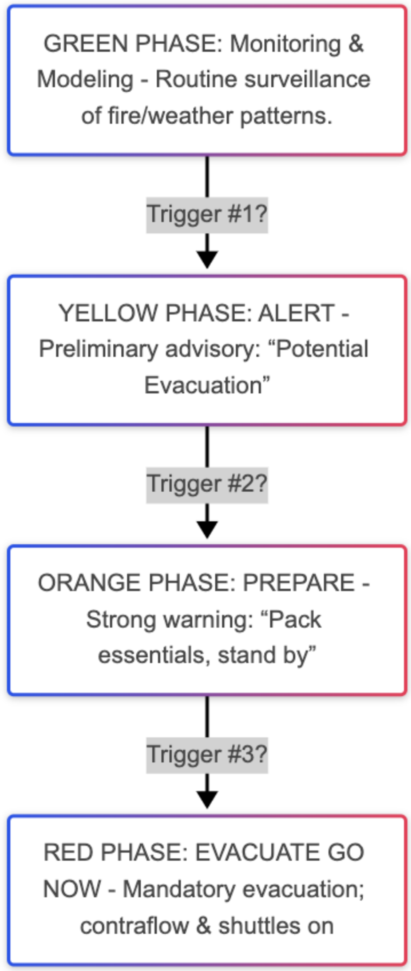


Figure 5. Phased Evacuation Flowchart and Trigger Points.

This data-driven workflow proved particularly impactful during the 2023 Rhodes wildfire, where coordinated evacuation measures helped move thousands of residents and tourists to safety as the fire intensified (OECD, 2024). While precise figures varied across operational reports, the Rhodes evacuation represents a significant case study in managing large-scale population movement during an active wildfire emergency, demonstrating how data integration can enhance evacuation efficiency under challenging conditions. As soon as simulations indicated that the main highway risked closure from encroaching flames, local Civil Protection officials activated contraflow measures on secondary roads and dispatched real-time alerts to drivers via smartphone messaging systems. Had these steps been delayed, large segments of the population might have become stranded on overburdened roads—a factor historically responsible for many wildfire-related fatalities (Forest Fire-Related Deaths in Greece, 2021).

Beyond hazard modeling, risk-informed planning also underscores the importance of systematic training and drills that reflect realistic wildfire scenarios. In many EU regions, multi-agency tabletop and field exercises occur biannually or annually, with explicit goals to identify communication gaps, test phased or zonal evacuation routes, and calibrate the timing of alerts (Planning Considerations: Evacuation and Shelter-in-Place, 2019). Such drills often incorporate multi-disciplinary teams—firefighters, police, medical units, local politicians, and volunteers—to reinforce unity of command and avoid contradictory orders. A prime lesson from the Mati fire (2018) in Greece is that fragmented directives can produce disorganized evacuations with devastating consequences. Post-incident reviews called for a "Common Operating Picture" among emergency agencies to unify guidelines (Kalogiannidis et al., 2024). This unified approach is likewise emphasized in southwestern France's code on WUI evacuations and Italy's newly revised "Piano di Protezione Civile," both seeking to reduce misalignment in instructions given to the public (Best Practices in Wildfire Mass Evacuation Planning, 2019).

Crucially, risk-informed evacuation frameworks reflect a deeper understanding of human behavior under crisis conditions. Empirical studies show that individuals frequently delay evacuating due to complex decision-making processes, including gathering possessions, coordinating with family members, assessing perceived risk versus the discomfort of displacement, and interpreting often conflicting information sources (Nunes et al., 2024). By factoring this multi-dimensional 'protective action decision model' into planning, local authorities can systematically deploy staged communications that address these psychological factors, moving beyond simple directives to encompass the social and cognitive aspects of emergency response. The North Shore Emergency Management example in British Columbia (Canada) highlights how pre-evacuation messaging can persuade residents to prepare their vehicles and essential documents, thus minimizing last-minute confusion (Vespaziani, 2019). These same principles have been adapted in the EU context, often with geo-targeted messages and culturally appropriate translations, bolstering compliance in demographically diverse communities.

As a final point, the synergy of advanced modeling, iterative drills, and behavioral insights is strengthened by cross-border cooperation—particularly relevant in the Alps and the Pyrenees, where wildfires can cross national frontiers. Joint planning exercises, some funded through the EU Civil Protection Mechanism, allow multiple countries to share best practices on corridor management, resource pooling, and mutual assistance protocols (gr_drm_plan, 2021).

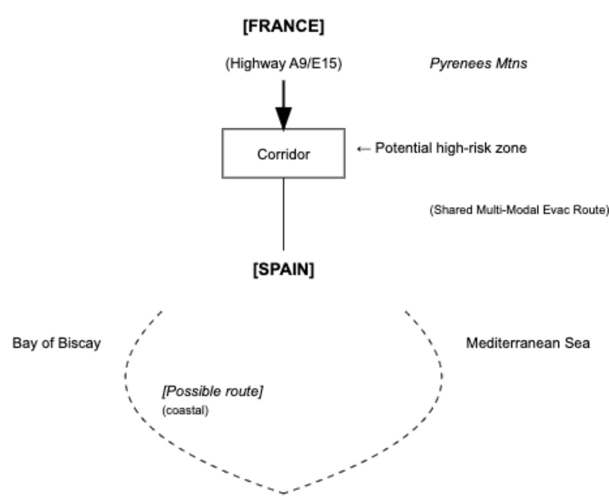


Figure 6. Cross-border fire risk: Conceptual representation for shared evacuation corridors

Ultimately, risk-informed evacuation underscores that effective wildfire management is neither solely about local resources nor about a single blueprint for all communities. Instead, it is a flexible, data-centric paradigm that must adapt swiftly to the scale and speed of unfolding events in synergy with local constraints and vulnerabilities.

8.2 Vulnerable population evacuation protocols

Beyond modeling roads and flame fronts, no evacuation strategy is complete without dedicated protocols for vulnerable populations. The EU's focus on social inclusion has propelled efforts to embed robust "vulnerability mapping" into every stage of emergency planning (ΔΙΑΧΕΙΡΙΣΗ ΚΑΤΑΣΤΡΟΦΩΝ ΚΑΙ ΚΡΙΣΕΩΝ, 2021). Demographic analysis often reveals clusters of older adults, individuals with physical or cognitive impairments, or single-parent households lacking reliable transport. By highlighting these high-risk zones, municipalities can implement specialized measures: pre-evacuation counseling, scheduled pick-up services, or personal phone calls to confirm readiness.

The table shown in figure 7 highlights how different vulnerable population groups in WUI areas face unique risks and require tailored measures during wildfire evacuations. Each row briefly outlines the specific challenges—ranging from mobility issues and language barriers to socioeconomic constraints—and the recommended protocols that authorities or community liaisons can implement. This structured overview provides a quick reference for planning and operational teams who must ensure no segment of the population is overlooked in an escalating wildfire scenario.

OLDER ADULTS / INDIVIDUALS WITH MOBILITY ISSUES

- Key Risks: Physical limitations, slower response, medical aids.
- Protocols: Opt-in registries, buddy systems, priority shuttle buses, pre-positioned medical teams near residences with >30% elderly.

INDIVIDUALS WITH COGNITIVE OR DEVELOPMENTAL DISABILITIES

- Key Risks: Difficulty understanding urgent instructions, extra support needed.
- Protocols: Simplified alerts (pictograms), dedicated shelters with specialized staff, family consultations if forced evacuation is required.

NON-NATIVE SPEAKERS / TOURISTS

- Key Risks: Language barriers, unfamiliar with local roads.
- Protocols: Multi-lingual & pictogram-based alerts, drone loudspeakers in tourist hotspots, translators embedded in emergency teams.

SOCIOECONOMICALLY DISADVANTAGED HOUSEHOLDS

- Key Risks: No private vehicle or limited resources, difficulty in relocating quickly.
- Protocols: Public shuttles along "green corridors," community liaisons to arrange evacuation, local gov't vouchers or short-term shelter/housing.

SEASONAL / MIGRANT WORKERS

- Key Risks: Isolated from official alerts, language or cultural gaps, short-term housing.
- Protocols: Info hubs at worksites, "Am-I-Safe" wristbands for quick tracking, bilingual evacuation drills and materials.

CHILDREN (SCHOOLS, YOUTH CAMPS)

- Key Risks: Depend on adult supervision, reduced situational awareness.
- Protocols: School/camp evacuation plans with buses on standby, buddy systems for older kids, pre-designated reunification procedures.

Figure 7. Vulnerable Populations and Evacuation Measures

At the operational level, centralized registries stand out as indispensable tools. For example, the Safe Village Program in Portugal encourages residents with limited mobility to register for immediate assistance during crises (Nunes et al., 2024). These registries remain GDPR-compliant by requiring explicit opt-in and storing minimal personal data. When a wildfire escalates, local command centers can cross-reference real-time hazard maps with the registry, dispatching pre-positioned minibuses or ambulances for those flagged as having physical constraints. Preliminary evaluations suggest the integrated registry approach substantially improved evacuation performance during a 2022 wildfire drill in the region (building upon methodologies established by Cova et al., 2011). While exact efficiency improvements require further validation across multiple scenarios and conditions, these early results demonstrate the potential of centralized vulnerability tracking when integrated with local response capabilities.

Another key strand is designing inclusive alerts. Populations unable to read or understand standard text messages benefit from pictogram-based or multi-lingual alerts. This approach directly impacted during the 2021 NE Attica fire, when georeferenced SMS texts in over a dozen languages—supplemented by bold pictorial cues—raised compliance among non-Greek speakers (Zikeloglou et al., 2021). In Germany's Ahr Valley area, tested drone-mounted megaphones deliver audible evacuation orders to remote or mountainous WUI communities, a tactic that also doubles as a fallback if phone networks fail (Best Practices in Wildfire Mass Evacuation Planning, 2019).
Ensuring adequate transportation remains a universal challenge for vulnerable populations, especially for those who rely on less flexible forms of assistance (Planning Considerations: Evacuation and Shelter-in-Place, 2019). Some EU initiatives, like the Zones à Risques Incendie program in France, propose "priority shuttle" designs: a dedicated line of buses and small passenger vans that bypass normal traffic in the event of a mass evacuation, often using "green corridors" or temporarily repurposed bicycle paths (OECD, 2024). The success of these shuttle networks hinges on advanced coordination with local law enforcement, who must manage potential disruptions to everyday traffic patterns. To further protect individuals who cannot be promptly moved, these local programs sometimes designate "last-resort" safety zones—open fields, car parks, or hardened structures—where at-risk residents can remain if egress by road is impossible.

Equally vital is the step of post-evacuation support. Many official shelter sites or "megacenters" have specialized staff to help reconnect families, provide immediate medical checks, or continue personal care tasks (Forest Fire-Related Deaths in Greece, 2021). The Mati tragedy reinforced how easily older or cognitively impaired residents can be lost in the chaos unless real-time tracking or photo identification is in place. Thus, advanced wristbands or mobile apps—similar to those used in significant sporting events—are being evaluated in pilot programs across Greece to help care home staff confirm safe arrivals at designated shelters (Arbinolo et al., 2024). These experimental applications show promise for improving accountability during evacuations, though they remain in developmental stages rather than wide-scale deployment, with ongoing assessments of their reliability under crisis conditions.

Finally, ongoing training remains essential. Vulnerable communities, especially older individuals or those with hearing impairments may find technology-heavy solutions daunting. Repeated drills that incorporate local volunteer groups, plus iterative refinements of user-friendly interfaces, help lower the barrier to compliance. Through projects like the Cross-Border Fire Resilience Initiative, regions in southwestern France and northeastern Spain have tested "buddy system" expansions, where bilingual or sign-language-proficient volunteers accompany evacuees throughout the process, ensuring no one is left behind (Wildfire Risk Awareness and Communication: Analysis of Good Practices, 2024). Collectively, these protocols reinforce that protecting vulnerable populations is not a marginal concern but a central pillar of any ethically and operationally sound evacuation plan.

8.3 Community refuge strategies and dual-use infrastructure

As wildfire events intensify, a purely evacuate-centric approach has revealed certain limitations, particularly in fast-moving scenarios where roads become blocked or the fire front encircles entire communities. Recognizing this, European policy and practice increasingly emphasize the creation of dual-use infrastructure that can be rapidly repurposed into community refuges (Fire safety engineering for community resilience, 2024). This shift is influenced by Australian experiences (Handmer and O'Neil, 2016) with 'stay or go' policies and neighborhood refuges—including critical lessons learned following the 2009 Black Saturday fires that prompted significant policy revisions—adapted for the specific climatic, urban planning, and architectural contexts of the EU (Blanchi et al., 2015). These adapted approaches incorporate both the successes and limitations observed in the Australian context, particularly regarding the conditions under which shelter-in-place strategies remain viable.

One prominent example is the reimagining of parks and public squares as multi-functional refuge areas. Typically, these spaces undergo "defensible design," which involves converting flammable materials—like pine needle-laden lawns or dense shrubs—into irrigation-supported greenbelts or non-combustible surfaces such as compressed gravel (Best Practices in Wildfire Mass Evacuation Planning, 2019). Larger parks may include "internal safe zones" with minimal vegetation, perimeter firebreaks, and overhead sprinklers connected to municipal water systems or onsite storage tanks. During normal times, these areas simply serve as recreational green spaces. In an emergency, they become muster points for those who cannot feasibly evacuate in time.

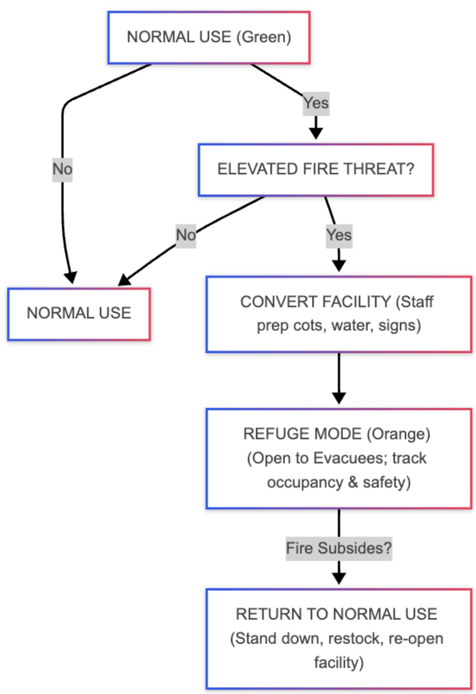


Figure 8. Flowchart of Dual-Use Facility Conversion

As depicted above (Figure 8), once local authorities confirm a rising wildfire threat, staff initiate basic shelter preparations such as setting up cots, finalizing signage, and activating backup water supplies. The facility then shifts to "Refuge Mode," welcoming evacuees and coordinating updates with the municipal operations center. Once officials declare an "All Clear," the venue is systematically cleaned, restocked, and reopened for normal daily activities. This dual-use framework ensures that public infrastructures can rapidly adapt to urgent fire scenarios without requiring separate, dedicated shelters.

Another category of dual-use infrastructure targets large communal facilities. For instance, Spain's Valencia Oasis Program repurposes municipal swimming pools to be used as short-duration shelters. Trained staff can quickly lower pool water levels to specific thresholds, ensuring water reserves remain available for localized fire suppression (Cova et al., 2011). The presence of a water body also exerts a powerful psychological effect—offering a sense of relative safety from heat exposure. A pilot test saw hundreds of evacuees gather in designated 'pool shelters,' and preliminary feedback indicated positive reception of the concept, although lessons on the complexity of operating pumps and filters under crisis conditions have since prompted design tweaks (Nunes et al., 2024). More comprehensive evaluation studies are underway to fully assess user experiences across different demographics and emergency scenarios, particularly examining factors such as thermal comfort, smoke exposure, and psychological well-being in these temporary aquatic refuges.

Urban contexts sometimes pose different challenges, where horizontal space is limited. Consequently, multi-story structures like car parks, transit hubs, or even shopping centers are being engineered for swift conversion into vertical shelters. In Marseille's Bastide Rouge district, for example, an underground parking facility doubles as an emergency refuge, featuring sealed entrances, smoke filtration systems, and a direct link to the local metro line (Arbinolo et al., 2024). Drills indicate that a well-trained staff can shift the facility from normal to refuge mode in under 30 minutes, controlling airflow and marking safe zones for evacuees. Similar initiatives in Athens revolve around multi-level parking garages near central metro stations, harnessing the city's robust public transport grid as a failsafe for large evacuee flows.

To coordinate these conversions swiftly, authorities rely on rigorous standard operating procedures, akin to checklists in the aviation industry (Protective Actions in Wildfires: Evacuate or Shelter-in-Place?, 2009). For instance, local staff in sports arenas receive pre-event training on how to lower mechanical bleachers, isolate electrical panels, and activate sprinklers, transforming the site into a smoke-resistant hall. Once established, the facility must broadcast its availability to the public: dynamic signage, location-based phone alerts, and audible announcements via loudspeakers can point evacuees toward these "safe harbors" (Wildfire Risk Awareness and Communication: Analysis of Good Practices, 2024).

Robust synergy between technology and infrastructure is likewise evident. IoT sensors in refuge sites measure smoke, temperature, and carbon monoxide levels, relaying real-time data to a central emergency dashboard (Fire Safety Engineering for Community Resilience, 2024). Remote triggers can lock certain sections to prevent occupant exposure if sensor readings breach pre-set thresholds. Some research initiatives, particularly in mountainous WUI zones, are exploring concepts such as 'intelligent sprinklers' that could potentially modulate water flow based on thermal camera inputs to direct coverage where embers accumulate (Best Practices in Wildfire Mass Evacuation Planning, 2019). While these technologies remain largely experimental and face implementation challenges related to power requirements, sensor reliability, and water resource management during emergencies, they represent promising directions for technological innovation in refuge design (Sanchez and Marero, 2023).

While dual-use infrastructure can save lives when evacuation is impractical, it also brings new financial and administrative burdens. Costly retrofits—reinforced roofing, integrated water supplies, advanced ventilation—require stable funding sources. The EU's structural funds and resilience grants (notably under the Recovery and Resilience Facility or RRF) can help offset these costs if local authorities craft carefully aligned proposals (gr_drm_plan, 2021). Maintaining such sites in readiness, training staff, and ensuring the public is aware are likewise resource-intensive tasks. However, the overwhelming lesson from incidents across Europe is that these upfront investments pay dividends in catastrophic scenarios when safe egress is no longer possible.

A final consideration is public acceptance. Some residents may fear that encouraging "shelter-in-refuge" fosters complacency or that people might delay evacuation too long in hopes that a refuge is viable. Hence, public awareness campaigns must clarify that dual-use shelters do not supersede prudent evacuation. Rather, they supplement it by offering an emergency fallback if leaving the threat area becomes impossible (Zikeloglou et al., 2021). By educating communities on the continuum of protective actions—from immediate evacuation to short-distance relocation to a refuge—authorities ensure that residents can make informed decisions under rapidly changing circumstances.

8.4 Conclusions and forward perspectives

Throughout Europe, wildfire events are intensifying under the twin pressures of climatic shifts and expanding WUI development. In response, contemporary wildfire management strategies increasingly transcend simple evacuation orders, converging on robust, proactive planning anchored by risk modeling, inclusive protocols for vulnerable groups, and the strategic development of dual-use infrastructure. These frameworks thrive on high-resolution data, advanced computational simulations, and dynamic communication channels that keep both authorities and the public informed.

The shift toward proactive evacuation strategies reflects the realization that narrowly missing the ideal evacuation window can lead to chaos, as has been evident in repeated fire disasters across Greece, Portugal, and Spain (Forest Fire-Related Deaths in Greece, 2021; Mati 2018 reviews). Adopting risk-informed triggers and phased evacuation orders paves the way for more orderly traffic management and fewer last-minute escapes. Meanwhile, multi-lingual, multi-channel alerts reduce confusion for tourists and local ethnic minorities alike—a priority given that many EU coastal and highland regions attract seasonal visitors (Wildfire Risk Awareness and Communication: Analysis of Good Practices, 2024).

No less important is the recognition that certain population subsets remain at elevated risk. Older adults, children, individuals with disabilities, and those lacking private vehicles require specialized care. Geospatial vulnerability registries, combined with designated pick-up points, buddy systems, and inclusive messaging, have shown promise, but they demand continuous updates and concerted local engagement. The more systematically these measures are tested through scenario drills, the greater the likelihood they will function effectively during an actual fire (Planning Considerations: Evacuation and Shelter-in-Place, 2019).

Lastly, the pivot to community refuge strategies addresses the sobering reality that not all evacuations will succeed within the limited time windows that increasingly characterize Europe's severe fire events (Cova et al., 2011). By repurposing public facilities, water bodies, and even multi-story structures to serve as last-resort shelters, local governments offer a critical second line of defense. The process is resource-intensive, demanding thoughtful design, training, and financial support, yet successful experiences in places like Valencia, Marseille, and certain Greek islands illustrate how dual-use sites can dramatically reduce casualties.

Looking ahead, several themes beckon further advancement. First, cross-border data sharing and collaborative planning exercises appear poised to multiply, given that certain Alpine and Mediterranean fire regimes span multiple nations (OECD, 2024). Second, the next wave of technology—merging big data from phone carriers with real-time fire perimeter mapping—may enable even finer control of evacuation traffic flows and refined updates for in-place shelters. Third, emerging breakthroughs in building materials (e.g., flame-resistant cladding) and landscaping techniques (like living walls irrigated by gray waters) could expand the resilience of shelters-in-place. Fourth, it is imperative that more research delve into social acceptability, ensuring that expanded refuge solutions do not inadvertently erode the sense of urgency around early evacuation.

In sum, Europe is at a crucial juncture in its wildfire management evolution. By balancing the "evacuate or shelter" question with nuanced, data-driven answers, by foregrounding the needs of vulnerable residents, and by systematically embedding the concept of dual-use infrastructure, public authorities can set a high standard of protection and resilience. The lessons gleaned from the Mati fire, the 2023 Rhodes evacuation, and allied events in Portugal and Spain collectively illustrate that progressive, proactive measures stand the best chance of minimizing future tragedies—thereby safeguarding human life, economic assets, and the natural heritage that so profoundly defines Europe's landscapes.

9 Technical solutions

9.1 Creating and maintaining a Defensible Space

It has been demonstrated that managing vegetation and other combustible elements around the home, particularly within the first 30 meters immediately adjacent to the façade, is a decisive factor in the survival of a structure in the event of a wildfire. This factor is even more critical than any action taken at the perimeter of the development, such as low-combustibility perimeter firebreaks. Maintaining this defensible space, meaning the area around the home where defense actions will take place in case of fire, reduces the impact of direct flame contact on the most vulnerable points of the structures, such as glazing and roofing.

The defensible space has been divided into zones in the form of concentric rings, with specific mitigation measures proposed for each zone that have proven highly effective.

- **Zone 1**, from 0 to 2 meters, must be completely free of materials and objects that could ignite locally and result in direct flame contact with the façade, glazing, or roof. No garden furniture, ornamental vegetation, or abandoned objects or materials should be present. Additionally, attached structures such as storage sheds or garages, where objects and materials susceptible to ignition due to flames or flying embers are stored, should be avoided.
- **Zone 2**, from 2 to 10 meters, should be carefully managed to allow for ornamental vegetation while avoiding highly flammable species and controlling the spacing between plants. The presence of combustible objects and materials, including vehicles, must also be controlled to prevent flames exceeding 5 meters in length. It is especially important to avoid fast-burning vegetation such as cured grass, coniferous species, and other plants that accumulate fine dead material, as these are highly prone to ignition by flying embers.
- **Zone 3**, from 10 to 30 meters, must be free of dense surface vegetation, including ornamental elements. Trees should be spaced at least 2 meters apart at the crown level, and the presence of combustible objects and materials should be limited. The primary objective in this zone is to prevent the sustained combustion of larger vegetation, including forest vegetation, which could generate flame lengths exceeding 5 meters. As a general rule, the distance between the home and vegetation should be at least twice the height of the plants. Additionally, this area must remain accessible to facilitate defense operations for the structure. Ideally, a water refill point should be available within this defensive operations zone. In some residential developments, a well-irrigated lawn has been maintained, ensuring the grass remains green during periods of high wildfire risk. This has proven highly effective, but the availability of water must be secured to sustain these lawns.

One of the biggest challenges in maintaining defensible spaces is that they often span multiple properties owned by different neighbors, requiring collaboration among them, particularly regarding parcel enclosures such as hedges and fences made from combustible materials. Furthermore, garden design must be coordinated to ensure compliance with the different defense zones, regulating plant species, density, and height to prevent canopy continuity in trees and ornamental plants.

Another major challenge, especially in residential areas built under tree cover, particularly in pine forests, is the systematic removal of dead pine needles and other plant debris that accumulate on rooftops, ornamental plants, hedges, and objects and materials present in the garden.

9.2 Passive fire protection

In a passive system, stationary materials are designed to help prevent the spread of fire or smoke, keeping the fire to its original area and stopping it from spreading through the building.

Some of the components considered in passive fire protection are:

- Roofing, gutters, eaves
- Glazing, shutters, blinds

- Openings
- Siding
- Decks
- Fire doors, walls, floors
- Flame shields
- Ignition-resistant building materials
- Fire curtains (www.smokeguard.com)
- Treatments and fire protection paint for wood, fire resistant insulation, intumescing paint, mortar coating, mineral fiber matting

In addition to the mitigation of both vegetative and non-vegetative fuels, it is necessary to have a series of protective elements and components for the home, whether passive or active.

9.3 Active fire protection systems and methods

An active fire protection system means that action of some kind is taking place. This action can be manual, meaning that a person or people may activate it, or it may be automatic, deploying once fire, smoke or heat are detected.

Some of the components considered in the design and implementation of active protection systems are:

- Sensing, domotics, smoke detectors
- Exterior sprinkler systems, fire extinguishers, other suppression systems
- Ventilation systems
- Hypoxic environments
- Water cannon (rainguns)
- Automated fire doors
- Fire suppression systems

10 Working with population and involved stakeholders

10.1 Introduction

The involvement of communities and stakeholders is key for effective wildfire risk reduction. The FirEUrisk project promotes the complementarity between traditional top-down approaches to fire risk management and participatory strategies that empower local communities, enhance resilience, and improve coordination among key actors.
This chapter presents findings from activity A2.4.3, which, within a citizen's science approach, explored participatory engagement in wildfire risk reduction through the FirEUrisk Participatory Model.

The FirEUrisk Participatory Model builds on existing frameworks for civil participation, particularly those developed by the Council of Europe to foster structured engagement in wildfire risk reduction. The model has been implemented in two Pilot Sites (Portugal and Greece) and in on Demonstration Area (Italy). The implementation involved: assessing different variables (e.g., social, economic, political, risk awareness and perception, political capital, etc.), identifying the overall propensity towards participation of the community, its awareness and perception with regards to the wildfire risk, mapping of the most relevant stakeholders to be engaged at local level, development of context specific engagement strategies.

Furthermore, through the results achieved by implementing the Model, three different community profiles have been conceptualized: Informative Engagement Communities, Consultative Engagement Communities, and Collaborative Engagement Communities.

The findings contribute to this deliverable by providing practical recommendations for working with local communities and stakeholders to enhance preparedness and mitigation efforts.

Community-based information dissemination

Effective wildfire management relies on timely and accessible information dissemination to at-risk communities. Community-based information dissemination fosters collaboration between local stakeholders, emergency responders, and the general public, ensuring that preparedness, response, and recovery efforts are well-coordinated.

Community-based information dissemination requires adopting best practices to ensure community engagement and preparedness. Key strategies applied in FirEUrisk Pilot Sites include:

- **Multi-Channel Communication**: Combining digital tools, social media, in-person meetings, and printed materials to reach diverse audiences.
- **Two-Way Communication**: Encouraging community feedback, participation in preparedness drills, and integration of local knowledge.
- **Culturally Relevant Messaging**: StoryMaps tailoring content and creation of translated handbooks to address the unique needs, languages, and cultural backgrounds of community member.
- **Collaboration with Local Authorities**: Working closely with emergency services, government agencies, and non-profits to enhance information accuracy and credibility.

Leveraging Story Maps for Wildfire Communication: The Role of FirEUriskStoryMaps in Community Engagement

FirEUriskStoryMaps, which have been developed (for the Pilot Sites), provide an interactive and visually engaging platform for disseminating wildfire-related information. By integrating maps, multimedia, and narrative text, StoryMaps enhance community understanding and facilitate informed decision-making among residents, policymakers, and emergency responders.

FirEUriskStoryMaps were designed to serve multiple functions in wildfire preparedness, offering a dynamic and interactive platform to enhance understanding, assessment, and future planning for fire risks. These StoryMaps provide:

- **Raising Awareness**: Educating communities on wildfire risks, prevention strategies, and historical fire patterns through visually engaging and data-driven storytelling.
- **Improving Accessibility**: Offering location-based information in an interactive format, ensuring that diverse audiences—from policymakers to local residents—can easily access and interpret critical wildfire-related data.
- **Assessing Current Conditions**: Presenting up-to-date maps of fuels and fire-related data, helping stakeholders monitor wildfire hazards and landscape vulnerabilities .
- **Risk Assessment and Mapping**: Showcasing the FirEUrisk Risk Assessment Scheme, including hazard evaluation, exposure analysis, and vulnerability assessments, to support informed decision-making and mitigation strategies.
- **Projecting Future Fire Risks**: Providing advanced estimations of future wildfire risks based on climate trends, land use changes, and other environmental factors, aiding in long-term resilience planning and adaptation strategies."

Collaborative Resilience Planning

Collaborative resilience planning is a fundamental approach to enhancing community preparedness and response to wildfires by integrating diverse stakeholders in a structured decision-making process. Rooted in the FirEUrisk Participatory Model, this approach recognizes the importance of both quantitative and qualitative analyses to assess local vulnerabilities, strengths, and opportunities for resilience-building.

By engaging community members, scientists, policymakers, and emergency responders in a participatory process, collaborative resilience planning ensures that local knowledge, social dynamics, and institutional capacities are effectively leveraged. The process begins with a comprehensive assessment of the resilience ecosystem, identifying key context features and stakeholders, followed by the establishment of Citizens-Scientists Networks (CSN) to foster knowledge exchange and collective action.

Stakeholder Engagement Strategies (SES) and tailored action plans are then developed to promote participatory governance, improve risk communication, and implement adaptive strategies for wildfire resilience. Through ongoing monitoring and evaluation, this approach ensures that resilience efforts remain responsive to evolving environmental and social conditions, ultimately strengthening the community's ability to mitigate, prepare for, and recover from wildfire events.

10.2 FirEurisk participatory model

10.2.1 FirEurisk participatory model – conceptual and operational frameworks

An accurate understanding of community resilience requires the combination of quantitative and qualitative methods of analysis. To strengthen community resilience vis-à-vis hazards such as wildfires, it is necessary to involve local communities in a process starting from the assessment of the current situation and leading towards the implementation and monitoring/evaluation of resilience strategies.

Community involvement, indeed, provides a valuable help in understanding the complex dynamics and relationships among actors, interacting in different ways and contributing to the strengthening (or disruption) of resilience at a local level.

For this reason an operational model was proposed so to support the integration of different tangible and intangible resources coming from a wide range of stakeholders.

Such model, the FirEUrisk Participatory Model, develops through:

- A **Conceptual Framework** (i.e., Resilience Ecosystem) – allowing for the visualization of the components of the overall resilience processes within a specific context. The Conceptual framework builds on, and adapts to the topic of community resilience, the Institutional Development Framework (Ostrom, Gardner, and Walker, 1994).
- An **Operational Framework** (i.e., a three-phased application approach) – by means of which the model is applied in a specific context. The Operational framework builds on, and adapts to the topic of community resilience, the methodology proposed by the Council of Europe's Toolkit for Civil Participation in Decision-making processes (ISIG/CoE, 2017;2020).

FirEUrisk Participatory Model, in fact, aims to operationalize a participatory framework for the overall engagement activities in the field of community resilience, ultimately allowing to:

- Analyze the components of local Resilience Ecosystem in terms of
- Overall context features (i.e., community assessment focused on context variables fostering or hindering resilience at local level, such as citizens' awareness, social bindings, etc.).
- Relevant stakeholders of the Resilience Ecosystem (so to identify potential members of Citizens-Scientists Networks).
- Set-up Citizens-Scientists Networks (CSN) – participatory research-action mechanisms/platforms composed by identified stakeholders.
- Develop context-based Stakeholders' Engagement Strategy (SES) and Action Plans tailored to the specific needs of every local context, to make CSN work effectively.

10.2.1.1 Conceptual Framework

Ecosystems can be defined as networks of interactions between organisms and their environment. For the purpose of these Guidelines, the FirEUrisk Participatory Model proposes to interpret the process of production and disruption of resilience at a community level by considering the local community itself as an ecosystem; this solution allows for highlighting key issues, networks, as well as the complex interactions taking place between local community actors and their context. A similar approach was taken by Ostrom, Gardner, and Walker (1994) in developing the Institutional Development Framework to explain the management of common-pool resources. The Institutional Framework is composed by the following components:

- **The Context features**, i.e., the characteristics of the environment in which interactions take place, the way in which the environment influences those interactions, and the connections between the environment and the wider area of reference. Context features are subcategorized as attributes of the physical world, attributes of the community and rules-in-use within the local context.
- **The Action arena**, which is shaped by the network of stakeholders that populate the ecosystem and their Action situations. Action situations, which can be understood as the opportunities for stakeholders to interact, exchange resources, share knowledge etc., are shaped by, and in turn influence, the above-mentioned Context features.
- **The Patterns of interaction**, i.e., the mutual relationships of involvement among stakeholders which result from what takes place within the Action Arena. Such Patterns of interaction contribute, to generate an Outcome, i.e., a certain arrangement in terms of community resilience, which can, in turn be monitored and evaluated throughout time by means of Evaluative criteria.
-

The figure 9 aims to illustrate the original Institutional Development Framework applied to the analysis of common-pool resources management. This framework is here adapted for the purpose of outlining the FirEUrisk Participatory Model. In this sense, Context features and Action Arena allow for the exploration of the Conceptual Framework (i.e., the Resilience ecosystem), while the Patterns of Interaction-Outcome–Evaluative criteria constitute the theoretical basis for the models' Operational framework.

For what concerns the Context features, the elements represented within the Institutional framework should be understood as follows in the case of the Resilience ecosystem:

- Attributes of the physical world – are intended as the physical and geographical characteristics of a local community, which needs to be, first, defined in its boundaries. The first layer of analysis is constituted by the physical and geographical characteristics of the targeted area. Features which play a relevant role in fire dynamics are of particular attention in this analysis.
- Attributes of Community – are intended as the characteristic of the Local Community which constitutes the FirEUrisk context of action. These can be summarized by using the capitals approach, thus understanding the features attached to the community of reference as encompassed by the categories of: Social capital, Economic capital, Human capital, Institutional capital.

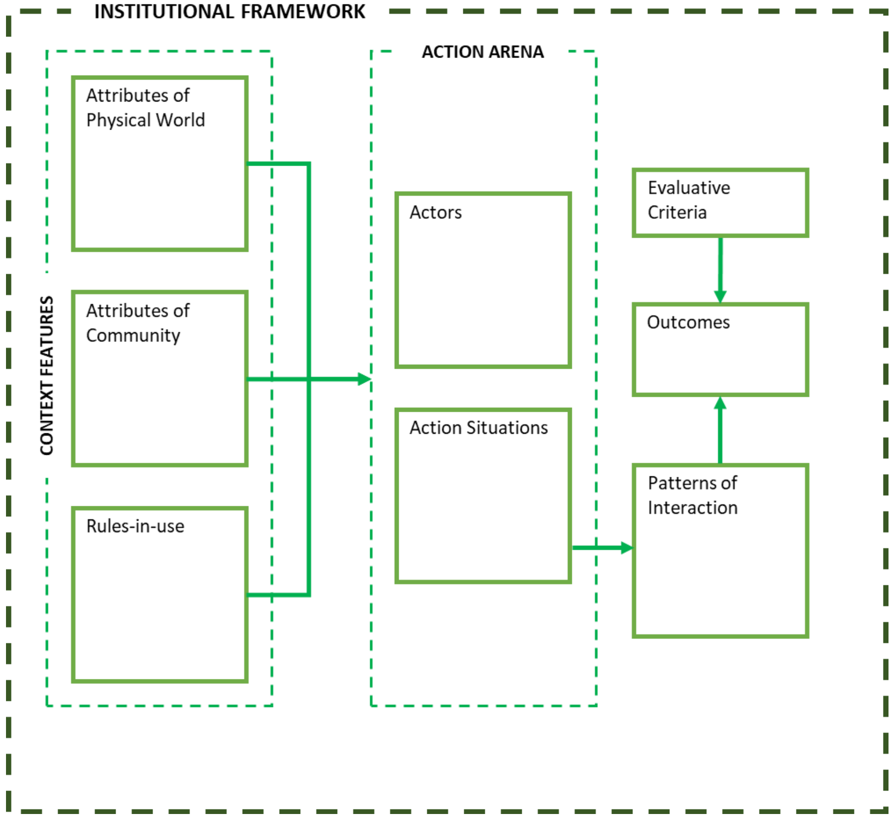


Figure 9. Institutional Development Framework applied to the analysis of common-pool resources management (adapted from Ostrom, Gardner and Walker, 1994).

- Rules-in-Use – are intended as the set of measures, procedures and praxes related with the issue of community resilience, including for instance prevention or emergency procedures, risk communication channels etc., which are in place in the inquired local context.

For what concerns the Action arena, the elements highlighted by the Institutional Development Framework can be further detailed for the specific case of Resilience Ecosystems, as follows:

- **Actors** – FirEUrisk Participatory Model distinguishes among two categories of actors that interact and potentially collaborate within a Resilience Ecosystem:
    - **Scientific stakeholders** – broadly intended as both scientific operators *strictu sensu* (i.e., researchers, academics, data operators etc.) and practitioners involved in the field of territorial resilience (such as first responders, infrastructure managers etc.) which possess technical and professional knowledge relevant for the issues at stake. In the light of CSNs, scientific stakeholders are all those actors which are directly involved in the definition and implementation of resilience measures, from a technical and/or scientific standpoint.

  - **Civil society stakeholders** – i.e., all other actors which, in different ways, actively and consciously or implicitly contribute to the enhancement/disruption of resilience at a local level.

- **Action situations** – similarly to interaction occurring in natural ecosystems, the Resilience Ecosystem is shaped by the unique interaction among actors representing different viewpoints and roles. These interactions set the frame for the chain of Action situations characterizing the resilience enhancement/disruption process in which stakeholders are involved – both explicitly and intentionally, for instance when participating in an emergency scenario simulation, and unintentionally, for instance as they perform their daily lives activities.

Stemming from the above-illustrated adaptation of the Institutional development framework, the following figure aims to summarize the main components of the Conceptual framework of the FirEUrisk Participatory model (i.e., Resilience Ecosystem):

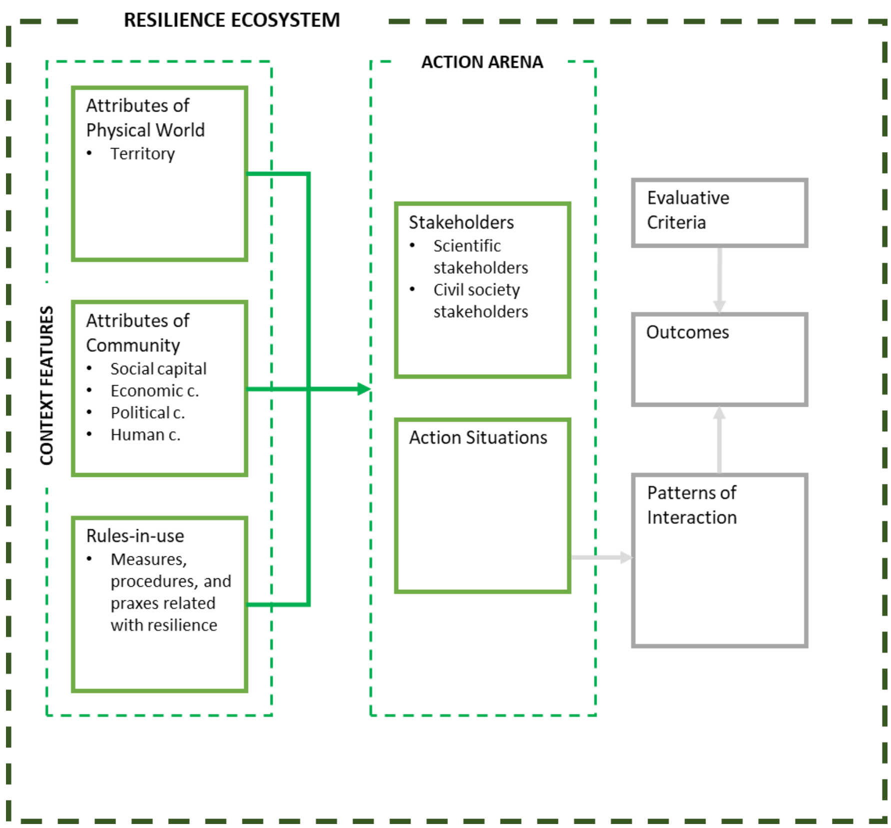


Figure 10. FirEUrisk Resilience Ecosystem – the FirEUrisk Participatory Model Conceptual framework

10.2.1.2 Operational Framework

A three-phased model was piloted in different settings to assess how engagement strategies function in diverse socio-political and environmental contexts. Activity A2.4.3 findings underline that participation must be incentivized, as some stakeholders require institutional backing before engaging actively.

The following paragraphs summarize the steps of the three phases, as follows:

Phase 1 – Assessment: Understanding community dynamics, stakeholders, and risk perceptions through surveys, interviews, and participatory workshops.

- **Context analysis** –involves analyzing the overall action arena and relevant actors within a specific context from the perspective of the Resilience Ecosystem at stake. This includes both community and stakeholders' network analysis. The phase is performed through data collection activities (such as surveys, focus groups, in-depth interviews).
- **Stakeholders' analysis**– focuses on mapping and selecting relevant stakeholders to partner with relevant institutions and disaster management operators. This is performed through facilitated workshops with partners at pilot site and preliminary identified relevant stakeholders.

Phase 2 – Contextualization: implies interpreting the assessment data to tailor engagement strategies to the local context. This includes forming citizens' scientist networks and identifying key actors.

- Sense-making workshops–aiming to interpret the results collected during the assessment phase to adapt the FirEUrisk participatory model to the specific characteristics and needs of the context at hand.
- Establishment of Citizens Scientist Network core group – forming a core group of stakeholders.
- Identification of the community profile – determining the level of propensity towards participation.

Phase 3 – Implementation: implementing engagement activities based on the community's propensity for participation, ranging from basic awareness campaigns to structured co-creation initiatives.

- Low propensity: suggested activities for promoting engagement are surveys and information campaigns focusing on public meetings, brochures, posters, and local media campaigns.
- Medium propensity: suggested activities for promoting engagement are dialogue and consultations through surveys, community panels, suggestion boxes, and town hall meetings.
- High propensity: suggested activities for promoting engagement aim at fostering partnerships and co-creation activities through citizen committees, joint training sessions, community-led projects, and monitoring teams.

To summarize, the diagram in Figure 11 aims to illustrate comprehensively the model's phases and steps as follows.

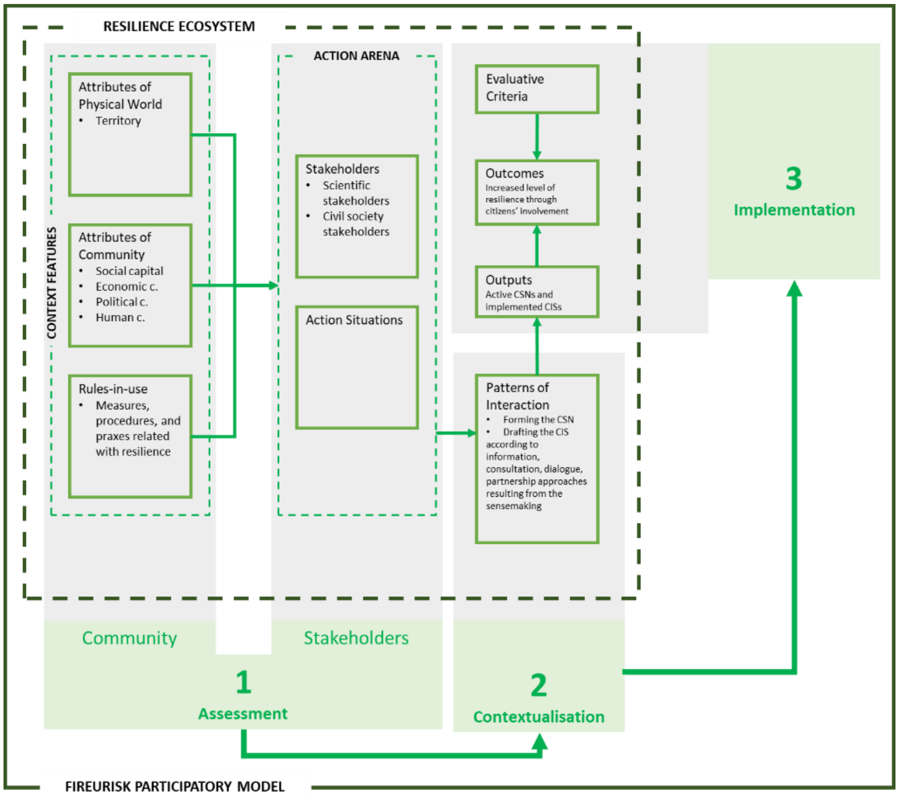


Figure 11. FirEUrisk Participatory Model - Phases

10.2.2 Citizen science and community resilience as foundations for the FirEurisk participatory model

Activity A2.4.3 aimed to analyze the potential for participatory approaches to involve citizens in wildfire risk reduction and enhance social resilience through preparedness.

Citizen-scientist networks serve as a bridge between local communities and scientific research, enabling a collaborative approach to data collection, validation, and outreach. This model fosters trust between local actors and researchers while empowering communities with knowledge and decision-making capabilities in fire risk management.

Citizen science initiatives contribute to community empowerment by enhancing social awareness, fostering collective action, and bridging the gap between experts and non-experts. A good example is constituted by CitieS-Health, a Horizon 2020 project which demonstrated that citizen science enhances research outcomes while making scientific findings more accessible and relevant to policymaking (Creus, 2022).

This approach has been found to have "transformative effects" across three key dimensions:

- **Emerging issues**: citizen science increases awareness of social and environmental challenges, allowing local concerns to be addressed through research.

- **Participant transformation**: individuals engaged in citizen science initiatives develop a sense of shared purpose, leading to shifts in behavior and engagement with their local environment.

- **Institutional impact**: by integrating citizen input, research institutions and policymakers benefit from diverse perspectives, resulting in more inclusive and practical policy solutions.

In this sense, citizen science often embeds an action-research approach, as citizens are involved in research activities starting from their daily life as the practical setting where to not only collect data but also experiment potential solutions to open issues by putting them in action.

It is such an approach that the work around 'Citizens involvement in wildfire risk reduction' has taken.

Furthermore, community resilience is central to effective disaster risk reduction. As defined by Fuchs & Thaler (2018), resilience encompasses the ability of communities to withstand, adapt, and recover from hazards, while learning from past experiences. Over the years, the policy discourse has shifted from vulnerability-based models to resilience-based approaches, emphasizing proactive risk management over reactive disaster response (Cutter, 2018).

It is possible to state that the enhancement of community resilience is the result of a complex social process within which the implementation of citizens-scientists' networks might positively contribute. The foreseen contribution of citizens-scientists' networks is not limited to the assessment of community resilience as an holistic concept, as it extends to the elaboration of actions and strategies to reinforce those community features which contribute to a higher level of community resilience.

The FirEUrisk Participatory Model incorporates these principles by positioning communities as active participants in fire risk reduction rather than passive recipients of top-down interventions.

This shift aligns with the Council of Europe's frameworks for civil participation, including the Civil Participation in Decision-Making Toolkit (2020) and the Code of Good Practice for Civil Participation (2019), ensuring that engagement strategies are grounded in established participatory governance practices.

10.3 Key findings from Task A2.4.3 and case studies

10.3.1 Implementation context and key findings

10.3.1.1 Aveleira - Portugal

- Context: Aveleira is a small village in Central Portugal with a mix of local and foreign residents. The community has recognized the need for a structured response to wildfire risks, particularly in light of past experiences with wildfires.

- Actions: the FirEUrisk model was implemented through preliminary meetings, a focus group, and the development of a community communication plan. The community was engaged in co-creating a fire emergency plan, integrating local knowledge, and participating in regular drills.
- Key findings: the community showed strong cohesion and a willingness to participate in collective efforts, which are crucial for enhancing resilience. The focus on communication and continuous training was identified as essential for effective preparedness.

10.3.1.2 Bravo Mundo Network - Portugal

- Context: Bravo Mundo is a virtual network of foreign residents spread across the Centre Region of Portugal. The network has been proactive in wildfire preparedness, creating guidelines and conducting awareness campaigns.
- Actions: the participatory model was adapted to the network's dispersed structure, focusing on virtual engagement and participatory reviews of their wildfire action plan. Workshops and webinars were conducted to gather feedback and improve the plan.
- Key findings: the network's decentralized structure posed challenges, particularly in maintaining consistent engagement and dialogue with authorities. The need for better coordination and dissemination strategies was highlighted.

10.3.1.3 Rafina-Pikermi - Greece

- Context: Rafina-Pikermi, located in a fire-prone region of Attica, Greece, has a history of devastating wildfires. The community includes both urban and rural areas, making it an ideal case for testing comprehensive fire resilience strategies.
- Actions: the engagement strategy focused on analysing the community's vulnerabilities, promoting dialogue between citizens and formal actors, and engaging schools in fire risk reduction activities.
- Key findings: the community's responsiveness and willingness to engage were strengths, but challenges remain in improving communication between citizens and institutions.

10.3.1.4 Suni, Sardinia

- Context: Suni is a small municipality in central Sardinia, where controlled burning activities have been reintroduced to manage wildfire risks. The community has a strong tradition of involvement in fire prevention activities.
- Actions: FirEUrisk model facilitated the collaboration between local stakeholders, including farmers and the Sardinia Forest Service, to enhance prescribed fire practices.
- Key findings: the community's involvement in traditional fire management practices was a significant asset, but there is a need for ongoing education and adaptation to new challenges.

10.3.2 Summary of activities in each case study

This section summarises the key activities structured)in each pilot site (designed and/or implemented to illustrate how engagement strategies were tailored to different community profiles and local conditions. The activities followed a structured approach, culminating in the application of the FirEUrisk Participatory Model to strengthen community participation in fire risk reduction.

10.3.2.1 Sardinia, Italy

- Established citizen committees to discuss fire prevention strategies.
- Conducted joint training sessions with emergency responders and local volunteers.
- Implemented community-led fire prevention projects, including controlled burning exercises.
- Facilitated meetings between residents and local authorities to strengthen trust and collaboration.

10.3.2.2 Rafina-Pikermi, Greece

- Organised community workshops on fire risk awareness and emergency response.
- Developed school engagement programmes, integrating wildfire education into curricula.
- Designed and piloted a co-created evacuation plan in collaboration with residents.
- Strengthened communication between local institutions and citizens to improve risk perception.

10.3.2.3 Aveleira& Bravo Mundo, Portugal

- Conducted policy-brokering activities to enhance collaboration between residents and policymakers.
- Structured stakeholder meetings to improve wildfire prevention governance.
- Established a Citizen-Scientist Network, formalising volunteer efforts in risk reduction.
- Designed training sessions for residents on fire safety measures and preparedness.

10.3.3 Highlights from pilots

Sardinia, Italy (Suni community): A highly engaged community with strong trust in local authorities and experience in controlled burning practices. Activities included citizen committees, joint training sessions with emergency responders, and community-led fire prevention projects.

Rafina-Pikermi, Greece: A proactive community with high motivation but varying trusts levels in authorities. The engagement strategy focused on improving communication channels, integrating schools into awareness programmes, and co-designing evacuation plans with residents.

Aveleira& Bravo Mundo, Portugal: These communities showed an interest in wildfire risk reduction but needed more structured involvement. Engagement efforts included policy-brokering activities, structured stakeholder meetings, and formalizing volunteer efforts into a Citizen-Scientist Network.

Wildfire risk reduction requires the collaboration of multiple stakeholders, including local governments, fire services, environmental agencies, NGOs, and community organisations. Effective coordination mechanisms include:

- **Stakeholder mapping** to identify key actors and define their roles in risk reduction efforts.
- **Multi-actor governance structures** to facilitate cooperation between authorities, scientific experts, and community representatives.
- **Communication and transparency mechanisms** to ensure that all stakeholders have access to up-to-date information and decision-making processes.
- **Capacity-building initiatives** to equip stakeholders with the necessary skills and resources to contribute effectively.

The findings from activity A2.4.3 highlight that successful stakeholder engagement depends on sustained interaction, trust-building, and the integration of local knowledge into decision-making processes.

10.4 Community profiles and engagement strategies

The community profiles identified in this study emerged as a direct result of the implementation of the research and engagement activities conducted under activity A2.4.3. Through structured participatory assessments, stakeholder workshops, and pilot activities, different levels of engagement and community responses were observed. These insights informed the development of the following community profiles, each representing a distinct level of participation in wildfire risk reduction:

- **Informative Engagement Communities**: these communities have limited experience with participatory processes and require awareness-raising initiatives. Suggested activities include public meetings, brochures, social media campaigns, and accessible educational materials.
- **Consultative Engagement Communities**: these communities are open to dialogue but lack well-structured participatory mechanisms. Engagement strategies should focus on structured consultations, stakeholder panels, and town hall meetings to gather input and foster dialogue.
- **Collaborative Engagement Communities**: these communities demonstrate a high level of engagement and willingness to co-create risk reduction strategies. The best approach involves forming citizen-led committees, community monitoring groups, and implementing co-designed fire prevention projects.

Activity A2.4.3 introduced a decision tree framework to guide engagement approaches based on community readiness. This framework, illustrated in the figure below, presents the key steps for determining suitable engagement strategies.

The diagram in Figure 12 summarizes the key steps and activities associated with each phase and community profile:

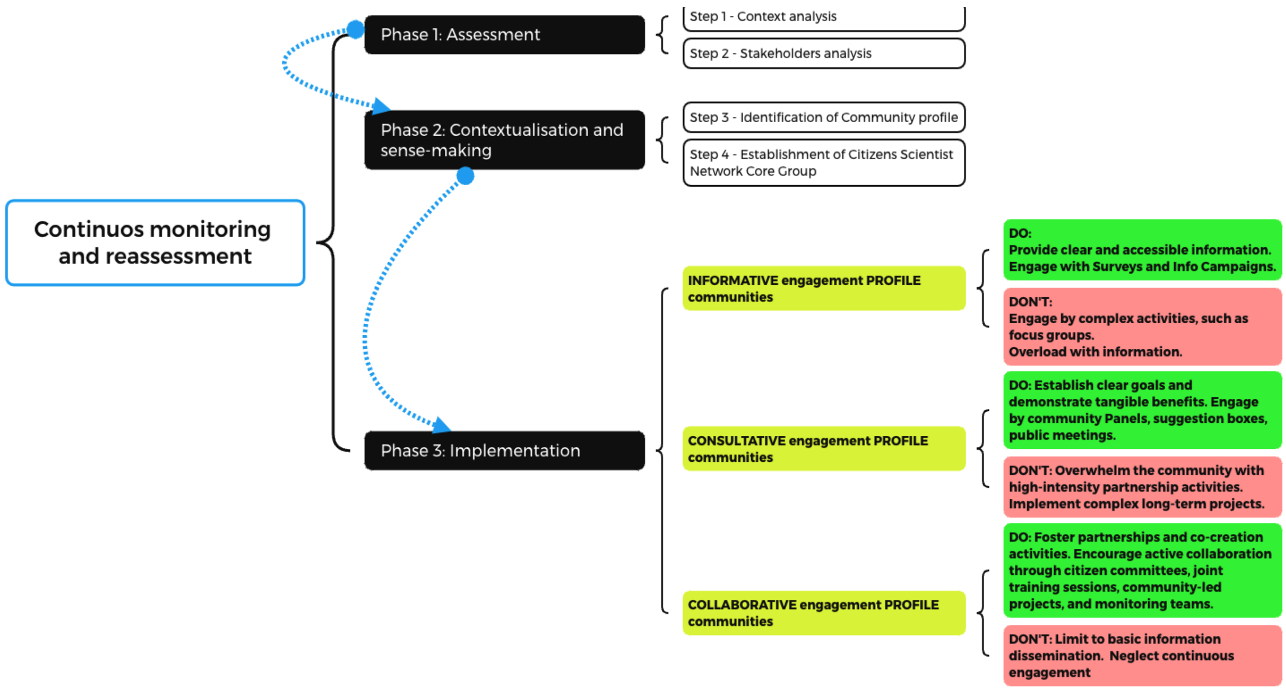


Figure 12. Recommendation for setting up engagement activities at local level

10.5 Recommendations

The findings from the activity A2.4.3 highlight that successful wildfire risk reduction hinges on sustained participation, trust-building, and cross-sector collaboration. The engagement strategies piloted across different contexts reveal a set of overarching lessons that can be applied beyond the FirEUrisk project.

10.6 Recommendations

10.6.1 Key lessons learned

- **Building trust and legitimacy**: communities are more likely to engage when they trust both the institutions and the process. Trust-building requires consistent communication, transparent decision-making, and meaningful participation opportunities.
- **Institutional commitment is crucial**: while community engagement is essential, institutional backing ensures longevity and structural integration of citizen-led initiatives. Support from local governments, civil protection agencies, and fire services strengthens engagement outcomes.
- **Local knowledge enhances resilience:** effective risk reduction strategies should leverage local expertise, particularly in communities with a history of wildfire experiences. Citizen-scientists play a crucial role in data collection, risk assessment, and co-developing mitigation plans.
- **Diverse stakeholder involvement matters**: engagement must extend beyond residents to include NGOs, academic institutions, emergency responders, and private sector actors. Multi-stakeholder collaboration fosters knowledge exchange and strengthens community-based resilience networks.

- **Adaptability and context-specific approaches**: one-size-fits-all engagement strategies are ineffective. The FirEUrisk Participatory Model demonstrated that interventions must be tailored to community profiles, taking into account social, economic, and institutional variables.

10.6.2 Recommendations for scaling and sustainability

- **Institutionalise participatory mechanisms:** ensure that community engagement is not limited to project cycles but is embedded within long-term disaster risk governance frameworks. This requires policy commitment, structured funding, and permanent coordination mechanisms.
- **Develop training programmes for stakeholders**: capacity-building initiatives should target both citizens and institutional actors. Training materials should focus on fire risk literacy, emergency preparedness, and community-based resilience planning.
- **Enhance multi-level coordination:** establish governance platforms where local communities, municipal authorities, and national agencies collaborate in decision-making. Structured dialogue can prevent fragmentation and promote cohesive wildfire risk reduction strategies.
- **Promote digital and social innovation:** digital tools, such as mobile applications, participatory GIS mapping, and online knowledge-sharing platforms, can enhance engagement and enable communities to monitor fire risks in real-time.
- **Foster transnational knowledge exchange:** establish regional and international networks for exchanging best practices on community engagement in wildfire risk reduction. EU-wide initiatives can help scale participatory models and encourage cross-border collaboration.
- These guidelines serve as a roadmap for policymakers, practitioners, and local actors seeking to implement participatory wildfire risk reduction strategies beyond the FirEUrisk project. By institutionalising engagement practices and fostering multi-stakeholder collaboration, long-term resilience can be strengthened across diverse socio-environmental contexts.

11 Post-fire recovery

11.1 Introduction

One of the most defining aspects of post-wildfire scenarios in the WUI is their complex social, economic, and environmental impact, which persists over long periods. Post-wildfire recovery in populated areas with economic activity requires a thorough analysis and planning across different levels of urgency, similar to methods applied in other natural disasters. The pre-design of post-disaster recovery plans facilitates their swift and effective implementation in the chaotic and confusing situation that follows such events. For this reason, a post-disaster recovery plan is an essential component of wildfire preparedness strategies.

Post-incident studies are crucial for improving the scientific understanding of WUI fires. Gaudet et al. (2020) analyze past technical reports and expert interviews to establish best practices for safe and effective field data collection. It identifies three key stages of WUI post-fire studies, compiling methodologies, data attributes, and logistical insights to enhance future research efforts.

In a post-disaster scenario, it is crucial to identify the different phases of intervention based on needs and urgency, categorizing them into short-term, medium-term, and long-term actions.

11.2 Stabilization of burned wildland-urban interface areas

After a wildfire has affected a populated area, there are latent risks that must be identified, located, and stabilized before allowing the return of the population (figure 13). These risks include:

- Unstable buildings due to fire damage, risk of falling debris, glass, etc.
- Broken and unstable glazing
- Smoldering combustion of objects and materials, releasing toxic smoke
- LPG tanks affected by the fire
- Damaged electrical installations, fallen power poles
- Small gas canisters hidden among the debris
- Presence of fibers and other hazardous components (e.g., asbestos)
- Spillage of toxic substances
- Hydrological risks such as soil movement and rockfalls
- Fallen or weakened trees
- Blocked access roads

Figure 13. Some examples of latent risks inside a WUI area after the pass of fire include unstable buildings, broken and falling glazing, laying electrical installations or damaged LPG tanks among others.

A stabilization protocol for latent risks must be applied, involving trained personnel with the appropriate equipment and methods who will enter the affected area (ground zero) to assess and stabilize the site.

Hydrological response of burned slopes

The study on post-fire watershed response in the some WUI areas (Wohlgemuth et al., 2008) highlights critical lessons on hydrological impacts and erosion control following wildfires, in particular that soil water repellency significantly increases after fires, leading to higher runoff and sediment transport. Immediate post-fire rainfall can cause extreme runoff and sediment displacement, emphasizing the urgency of implementing erosion control measures before the rainy season begins. These studies also revealed that sediment yield is highest in the first post-fire year, depleting easily mobilized material, which reduces subsequent erosion even during record rainfall events. This indicates that post-fire watershed stabilization depends not only on vegetation recovery but also on the depletion of transportable sediment. Despite differences in pre-fire vegetation types, the overall fire effects and hydrological responses were similar, suggesting that regional factors like topography, soil characteristics, and rainfall patterns play a more significant role than fire behavior alone. These findings underscore the need for preemptive management strategies, including vegetation treatment, erosion control, and infrastructure reinforcement, to mitigate post-fire flood risks and protect downstream communities.

De-contamination of soil and water

Wildland-Urban Interface fires are increasingly frequent and have severe consequences on water distribution systems. Some of the recent fires revealed harmful contamination in water networks due to volatile organic compounds (VOCs) like benzene and naphthalene. Contamination is hypothesized to result from plastic degradation in pipelines, back-siphoning of pollutants, or smoke and ash infiltration during system depressurization. In this line, the Fire Safety Research Institute (FSRI) is collaborating with universities to analyze post-fire water contamination by studying suppression runoff and smoke condensate in different fire scenarios. Understanding the sources of these contaminants is crucial for enhancing community resilience and improving post-fire water safety.

11.3 Post-wildfire recovery strategies

Post-wildfire recovery strategies follow different time scales for implementation:

- Short-term
- Medium-term
- Long-term

The objective is to restore normalcy to community life and business activities while rehabilitating the natural environment to prevent cascading risks (such as hydrological hazards, pest outbreaks, etc.) and to support the recovery of agricultural and forestry activities in rural areas.

a. **Assessment of the Scope and Intensity of Damage**

- Environmental impacts
- Social impacts
- Economic impacts

b. **Integrated Recovery Planning**

- Analysis of needs and urgency of implementation

- Identification of limitations and constraints
- Access to insurance providers (insurance companies, specific recovery funds)
- Design of financial aid and funding plans
- Development of participation and capacity-building strategies
- Implementation and monitoring plan

Some key takeaways and lessons learned extracted from recent fires regarding post-wildfire recovery in the WUI, and that can serve as guidelines, are:

- **Community-led recovery and engagement**: a successful post-fire recovery strategy must be community-driven rather than imposed by external organizations. Local community services, which already have deep-rooted trust and established relationships, play a crucial role in bridging the gap between affected populations and recovery resources. Effective recovery efforts should focus on empowering local organizations to lead the response rather than relying solely on large, external entities unfamiliar with the community's needs.

- **Holistic recovery planning and support networks**: recovery efforts should not be limited to immediate relief but should include long-term recovery plans that integrate disaster preparedness, mental health services, and economic rebuilding. Multi-sector collaboration is essential, bringing together municipal authorities, social services, NGOs, and emergency responders to create a resilient recovery network.

- **Addressing socioeconomic and psychological Impacts**: post-fire recovery is not only about rebuilding infrastructure but also about addressing the severe mental health and socio-economic impacts on the population. Trauma counseling, mental health programs, and community engagement activities should be a core part of recovery strategies, especially for vulnerable groups like children, the elderly, and marginalized communities.

- **Integrating preparedness into service delivery**: recovery and preparedness must be integrated into everyday community services to ensure continuous support. Emergency preparedness should be embedded into social service programs, schools, and local governance to enhance resilience ahead of future disasters.

- **Sustainable funding and capacity building**: short-term, emergency-based funding is inadequate for long-term recovery. Funding models should prioritize sustainable, long-term financial support to ensure that local organizations can continue their efforts beyond the immediate aftermath of a disaster. Additionally, financial assistance should include direct support for local organizations, recognizing their role in capacity-building and their ability to scale recovery efforts effectively.

- **Infrastructure and asset mapping for better recovery coordination**: A structured asset mapping process should be conducted early in the recovery phase to identify available resources, skills, and infrastructure. This would help optimize resource allocation, avoid duplication of efforts, and ensure that local assets are effectively utilized. It would also improve coordination between government agencies and NGOs.

- **Lessons for Disaster Recovery Implementation**: disaster recovery efforts should be customized to the unique needs of each affected community, rather than applying a one-size-fits-all approach. Best practices should include clear contractual obligations for community consultation, ensuring that affected residents have a say in decision-making. Disaster response organizations should work in partnership with local entities, mirroring successful international development models that emphasize local empowerment and collaboration.

12 Conclusions

The increasing frequency and intensity of wildfires in WUI areas across Europe require the development and implementation of comprehensive mitigation strategies. This document presents a set of guidelines aimed at reducing community vulnerability by addressing fire risk at multiple scales, from urban planning to individual property-level measures. The conclusions drawn from this work highlight key areas where intervention and policy implementation can significantly improve resilience.

A fundamental finding of this report is that effective wildfire mitigation requires a dual-scale approach. On one hand, community-level measures involve urban planning strategies, fuel management, and infrastructure improvements that reduce fire spread and enhance suppression efforts. On the other hand, property-level measures rely on individual homeowners maintaining defensible spaces, using fire-resistant materials, and implementing appropriate landscaping and irrigation practices. Both scales are interconnected, and success depends on coordinated action among municipalities, community organizations, and individual property owners.

This deliverable underscores the critical role of urban planning in mitigating wildfire risks. Strategies such as reducing fuel continuity, modifying urban layouts, and enforcing stricter building codes can significantly lower the probability of structural ignition. Key recommendations include designing urban areas with defensible spaces and strategic fuel breaks, encouraging the use of fire-resistant building materials and architectural designs, and ensuring that road networks facilitate both emergency response and community evacuation. In this regard, the adoption of a European Fire-Resilient Building Code is proposed as a necessary step to standardize construction practices across different regions.

Vegetation management is identified as a crucial element in reducing fire intensity and preventing fire spread in WUI areas. Effective strategies include reducing fuel loads through controlled burns, mechanical removal, and strategic grazing; breaking vegetation continuity between forested areas and urban developments to limit fire penetration; and managing ornamental vegetation in gardens and green spaces to minimize fire hazards. The deliverable emphasizes that vegetation management must be continuous and adapted to changing climatic conditions to remain effective.

Community participation is also essential in fire prevention and preparedness efforts. The deliverable highlights the need for educational programs to inform residents about fire risks and best practices, incentives for property owners to implement fire-resistant measures, and community-based fire prevention networks, where residents collectively work on mitigation efforts. Case studies show that communities with higher levels of engagement and awareness tend to have better wildfire resilience.

The increasing unpredictability of wildfire behavior necessitates robust evacuation plans and shelter-in-place strategies. Thus, this document recommends developing risk-informed evacuation frameworks that prioritize vulnerable populations, identifying designated community shelters that are fire-resistant and equipped with essential resources, and implementing dual-use infrastructure that serves as both everyday public spaces and emergency shelters. A well-prepared evacuation strategy can significantly reduce fatalities and injuries during extreme fire events.

It is also stressed that new technologies and policy measures must be integrated into wildfire management strategies. Key recommendations include expanding fire monitoring and early warning systems using satellite imagery, LiDAR mapping, and AI-driven risk assessments, developing financial mechanisms such as insurance incentives for fire-resistant home modifications, and encouraging cross-border collaboration among European nations to share best practices and resources.

A final aspect of the report focuses on the importance of post-fire recovery, emphasizing that rebuilding efforts must prioritize resilience. This includes stabilizing burned areas to prevent secondary hazards such as landslides, supporting affected communities through financial aid and reconstruction plans, and implementing long-term recovery strategies that integrate lessons learned from previous fires.

Reducing the vulnerability of communities to wildfires requires an integrated approach that combines scientific research, policy implementation, and active community participation. The guidelines outlined in this document provide a comprehensive roadmap for enhancing wildfire resilience in WUI areas. However, their success depends on a multi-stakeholder commitment, where governments, local authorities, emergency services, and residents work together to implement best-practices. The findings presented in this deliverable serve as a foundation for future research, policy development, and practical applications aimed at mitigating the ever-growing threat of wildfires in Europe. Continued investment in education, infrastructure, and fire prevention technologies will be essential in ensuring the long-term safety and sustainability of communities at risk.

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