fire

Article

Wildfire-Residential Risk Analysis Using Building Characteristics and Simulations to Enhance Structural Fire Resistance in Greece

Dimitrios Menemenlis [1,*], Palaiologos Palaiologou [2] and Kostas Kalabokidis [1]

1 Department of Geography, University of the Aegean, 81100 Mytilene, Greece; kalabokidis@aegean.gr
2 Department of Forestry and Natural Environment Management, Agricultural University of Athens, 36100 Karpenisi, Greece; palaiologou@aua.gr
* Correspondence: menemenlis@aegean.gr

Abstract: Urban areas adjacent to wildlands are very dangerous zones for residents and their properties during a wildfire event. We attempted to connect wildfire simulations with field inventories and surveys to create a framework that can be used to enhance the fire resistance of residential structures located in the wildland-urban interface (WUI). Legal restrictions and the lack of economic incentives for WUI residents greatly limit the potential to appropriately intervene to enhance their property's fire resistance. By studying in situ the resilience of building materials and combining them with exposure metrics produced from wildfire simulations, we created an index that helps to assess fire risk at the property level. The proposed index can support property owners to optimally manage the vegetation near or inside their property. State agencies can use our proposed index to estimate with a consistent methodology which properties are more exposed and with higher risk from fire damage so that specific fuel and vegetation management practices on and around them can be suggested or enforced.

Keywords: WUI; settlement resilience; fuel treatments; home-ignition zone; structure fire exposure

Citation: Menemenlis, D.; Palaiologou, P.; Kalabokidis, K. Wildfire-Residential Risk Analysis Using Building Characteristics and Simulations to Enhance Structural Fire Resistance in Greece. *Fire* **2023**, *6*, 403. https://doi.org/10.3390/fire6100403

Academic Editors: Fang Liu, Longxing Yu and Shengzhong Zhao

Received: 7 September 2023
Revised: 11 October 2023
Accepted: 16 October 2023
Published: 19 October 2023

1. Introduction

Residing in the wildland-urban interface (WUI) of fire-prone regions has become a major source of concern to the people who live or work in them since each fire season every fire event near or inside the WUI carries the risk of entrapment, injury, death, or property damage or loss [1–3]. Human activities increase the probability of fire occurrence, enhanced by the abundance of wildland fuels near urban areas that expose a large number of values to risk [4].

The "home-ignition zone" (HIZ) is defined as the area that includes the home and its surroundings within a radius of 30 to 60 m [5]. The potential for ignition depends on the home's exterior materials and design, and the amount of heat radiated from the flames within the HIZ [6–8]. Firebrand ignitions are also affected by the conditions of the HIZ either by igniting the home directly or igniting adjacent materials [9–11]. The structure arrangement and location within the WUI, the density, type, and condition of the road network, the firefighting potential and suppression opportunities for each community, and the presence of vegetation or other type of fuels inside the HIZ are all important factors that define whether a structure will be lost or saved [12,13].

Structures made of hard building materials (stone or concrete with resistant door and window frames) reinforce their fire tolerance, preventing the spread of fire within them, as long as all construction codes, standards, and regulations are applied [14,15]. In many areas of the US [16–18], Canada [19,20], Australia and New Zealand [21–24], and also in Europe [25], different codes and regulations define how the construction of new structures in fire-prone areas should be built. Additionally, they provide guidance on how existing structures can increase their resistance to fire, either from the effect of direct contact or spotting [17,26], focusing on preventing structural ignitions, preparing adequate defensible space around the structure, and improving the firefighting capacity of the property [17,27,28].

The investigation of the 1983 "Ash Wednesday" in Victoria/Australia fires by Ramsey et al. [29] studied elements such as wall and roof cladding, type of window glass, elevation, and vegetation type. In the 2000 Los Alamos fire (US), it was observed that in areas where the fire burned with low intensity, many homes were destroyed from structure-to-structure spread due to their non-fireproof construction materials [6]. In 2008, The Federal Emergency Management Association (FEMA) of the US issued the Home Builder's Guide to Construction in Wildfire Zones to provide information about wildfire behavior and recommendations for building design and construction methods in the WUI that can greatly increase the chances of a building's survival in a wildfire [28]. In 2010, the California Building Standard Commission issued the California Building Code [16], providing an extensive analysis of the minimum standards for the protection of life and property by increasing the ability of a building to withstand and survive a wildfire. Similarly, the Australian Standards issued in 1991 the AS 3959 (revised in 2009 and 2018), provide guidance on the construction of buildings in bushfire-prone areas, aiming to improve their resistance to bushfire's burning embers, radiant heat, and flame contact or any combination of the three [23].

In September 2017, the National Fire Protection Association in the US issued the Standard for Reducing Structure Ignition Hazard—NFPA 1144, providing a methodology for assessing wildfire hazards around existing structures in the WUI, setting the minimum requirements for new construction to reduce the structure ignition probability [30]. In August 2020, the International Code Council issued the International Wildland-Urban Interface Code for 2021, referring to the importance of using ignition-resistant construction materials based on the hazard severity of the building site [17]. The construction features that were regulated include the under-floor areas, roof coverings, eaves and soffits, gutters and downspouts, exterior walls, doors, window ventilation openings, and accessory structures.

Alexandre et al. [31], analyzed two devastating wildfires that burned in the WUI (San Diego, CA, USA and Boulder, CO, USA) and concluded that vegetation connectivity and ladder fuel presence were more important than vegetation type. Ganteaume et al. [32] performed a fire risk assessment at a small-scale WUI of SE France considering the area surrounding the HIZ that corresponds to its ornamental garden. The fire risk was assessed by estimating the flammability of the main ornamental species, the type of vegetation adjoining the environment of the house, the fence type, the structure of the hedges, and the implementation of regulations regarding brush-clearing.

The almost-exclusive use of concrete, coupled with the strict requirements of different seismic codes (1959, 1985, 2000), led to the creation of reinforced concrete constructions in Greece [33]. Despite the above, many communities consist of very old buildings belonging to settlements without a modern urban plan, with roads of width less than the required for the passage of heavy vehicles (e.g., fire trucks), and extensive areas without fire hydrants [34]. In many European countries, regulations and guidelines have been issued to ensure the management of wildland fuels in a 50 m radius around a building, and 100 m around communities [35], with variations depending on vegetation conditions and building location. The Greek WUI safety problem comes from the combination of poor building construction, lack of urban planning, and practically no vegetation management of their surrounding areas. Moreover, the anarchy in urban expansion is attributed to the lack of official urban plans and cadasters. The administration of vegetation management in the WUI is the responsibility of the Greek local authorities (i.e., regions and municipalities), who lack fundamental knowledge of forest management, and their collaboration with the competent Forest Service does not always happen in an efficient manner, as the latter is also responsible for forest fire prevention and fuel management across all forest areas of the country [2,3]. In May 2023, the Greek Government issued a Ministerial Decision by three Ministries (Environment and Energy, Interior, Climate Crisis and Civil Protection) titled "Regulation for Fire Protection of Properties within or in proximity of forest areas" [36]. This regulation aims at establishing a unified and mandatory framework of measures and means of fire protection for properties located within or near forest areas. It sets forth preventive fire protection measures, as well as minimum requirements for passive and active fire protection, both for newly constructed and existing buildings and their surrounding environment, in order to enhance the fire safety level of the property, reduce its vulnerability to fire and limit its contribution to fire spread [36]. Finally, in the context of preventing wildfires from entering urban areas, Green [37] defined that fuel breaks can provide safe access for quick construction of fire control lines. Low-volume fuels, especially flammable grass, can be fired out quickly to widen a fire-line under conditions where backfiring would be impossible for locations with heavy fuels and high heat output. Oliveira et al. [38], Pereira et al. [39], Aubard et al. [40], and Aparicio et al. [41] have investigated and implemented plans for the creation and construction of a fuel break network (FBN) at national and regional levels.

In this paper, we combined fire simulation modeling with in situ inventories in the WUI to assess the fire risk of each individual building, as well as the WUI as a whole. First, we analyzed wide areas to assess their ignition and wildfire spread potential. Then, at a smaller scale, we considered the area surrounding the home ignition zone that is usually covered by ornamental gardens. To achieve the above, we studied the 2021 wildfires in Attica/Athens, Greece, and their effects on buildings to infer which of their characteristics were affected the most and how. We recorded several indicators that can enhance or mitigate the fire risk for these buildings, estimating the role of construction materials on building survival, and the hazards originating from the surrounding vegetation. As a case study, we chose a high-amenity/high-value region of Rhodes Island in Greece to apply our proposed Wildfire Risk Evaluation Index for Structures (WREIS), aiming to assess at the property level how each structure can be affected by future wildfires and what the necessary steps to increase its fire resilience are.

2. Materials and Methods

2.1. Study Area

During the summer of 2023, Greece experienced the most adverse fire season in recent years, both in terms of the daily number of forest fires and the total burned area. To put it into perspective, the fire in Evros alone consumed almost 100,000 ha, the largest wildfire in Europe ever [42]. Amidst this devastating scenario, the Dodecanese region, and specifically the island of Rhodes, faced the largest wildfire in its history. This catastrophic event lasted for 10 days (from 18 to 28 July 2023) and ravaged a total of 17,629 ha of mixed forests, grasslands, agricultural lands, as well as WUI areas [43]. Our study site of Rhodes Island is a semi-mountainous island covered by dense conifer forests and shrublands. It has all the characteristics of a typical Mediterranean ecosystem and during the last 45 years, more than 1300 fires burned approximately 68,000 ha (Figure 1A,B).

Due to the Mediterranean climate, the habitats found throughout the island belong mainly to the Euro-Mediterranean vegetation zone with evergreen woodlands. Most characteristic species include *Pistacia lentiscus*, *Arbutus unedo*, *Quercus coccifera*, *Corydothymus capitatus*, *Sarcopoterium spinosum*, *Origanum* spp., *Asphodelus* spp. and *Phlomis fruticosa*, as well as coniferous forests consisting of *Pinus brutia* and/or pure and mixed forests with *Cupressus sempervirens* var. *horizontalis*. These mixed forests are also found in other parts of Greece (e.g., Dodecanese Islands and Crete), but in Rhodes, they exist in one of their best and most representative form [44]. The main ornamental plants used for planting in coastal areas of Greece are trees such as *Araukaria arauca*, *Cedrus libani*, *Cupressus macrocarpa*, *Phoenix dactylifera*, and *Chamerops humilis*, shrubs such as *Viburnum tinus*, *Thuja orientalis*, and *Pyracantha coccinea*, and climbing ornamental plants such as *Lonicera japonica*, *Jasminum nudiflorum*, and *Hedera helix* [45].

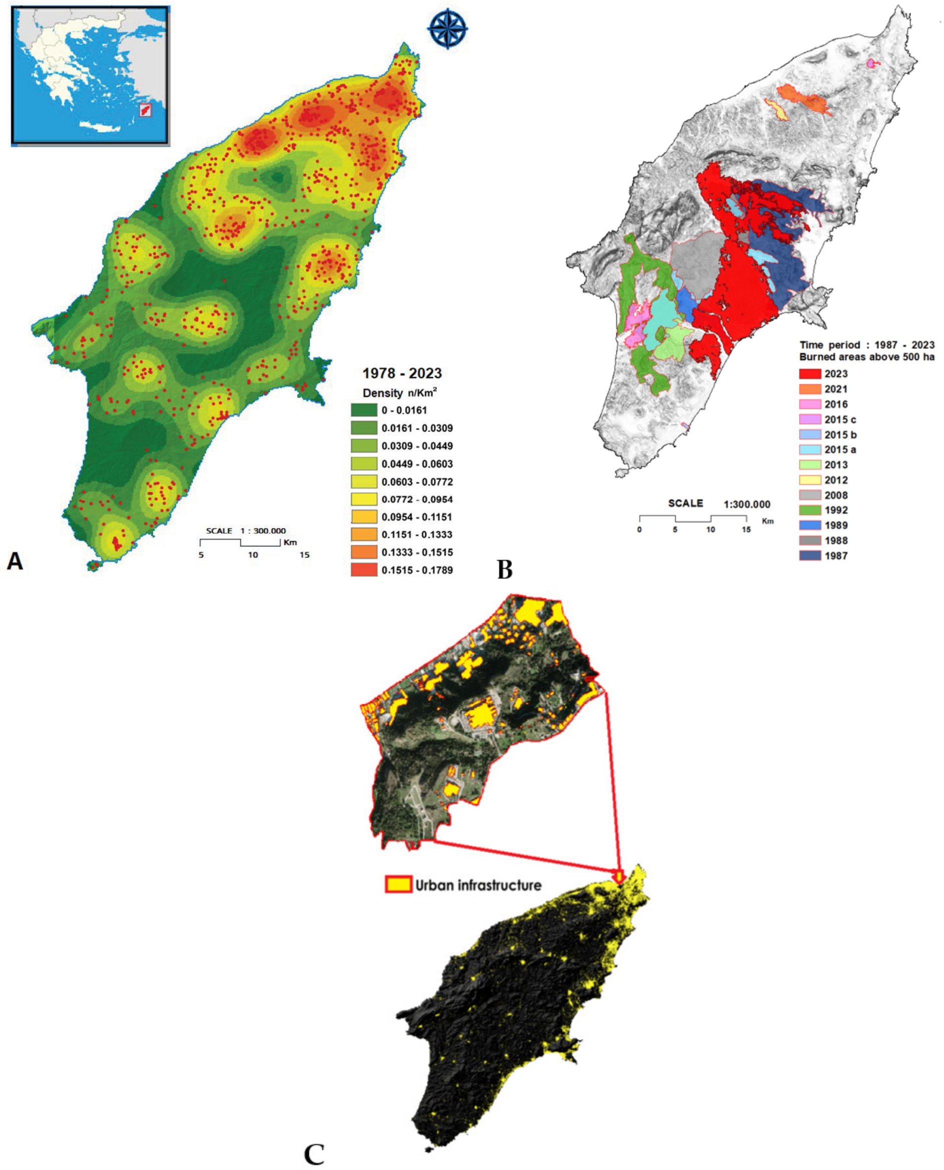

Figure 1. (**A**) Density of wildfire ignitions on the island of Rhodes, for the period 1978–2023, (**B**) burned areas over 500 ha including the major wildfire of 2023, and (**C**) boundaries of the study area and building locations (in yellow).

In Rhodes, several areas are characterized as interface or mixing zones, i.e., areas where houses and other structures meet or mix with forests and other types of vegetation. The type of construction of buildings is no different from the rest of Greece, with the overwhelming use of concrete compared to other construction materials. From a dataset of almost 50,000 buildings, 35,500 were made of reinforced concrete with steel, 9400 of stone, 2900 of brick or cement blocks, 645 of metal, 150 of wood, and 400 of other type of materials [46].

Rhodes is inhabited by 125,000 permanent residents, increasing considerably during the summer with approximately 3 million arrivals each season. The study area is called Ixia (with an area of 135 ha) and is located in the northeastern part of the island, covered by conifer forests mixed with Mediterranean shrublands. There are many different land uses there, including critical infrastructures such as the General Hospital of Rhodes, schools, hotels, resorts, and houses. In Figure 1C, the boundaries of the study area and the existing location of structures are shown.

2.2. Classification of Buildings' Fire-Resistance

Empirical data from the 2021 wildfires around Athens of 152 damaged houses were recorded and examined to assess the durability of reinforced concrete structures and the role of vegetation at various distances from these buildings. The inventory was performed by one person who recorded all the qualitative features of the buildings that sustained any kind of damages (minor or extensive), as well as those without any damages, used as control samples. In total, the 2021 fire around Athens caused minor damage to 72 structures (47.4%), moderate damage to 44 structures (29%), and major damage to 36 structures (23.6%).

The literature that supported this approach was designed for buildings in WUI areas of the US [18], Canada [19,20], Australia [21], and New Zealand [22]. More specifically, based on evidence presented in previous studies [14,47] associating certain structure attributes to their fire susceptibility, we recorded the following data:

1. Wildfire Incident History: information on past wildfire incidents that occurred in that specific WUI and the actions taken to mitigate the risk of future wildfires.
2. Building Characteristics: information on the building occupancy type (e.g., residential, temporary accommodation, commercial use), age, construction materials of the building frame, as well as specific critical structural parts that can be affected by wildfires (i.e., roof, windows, doors).
3. Vegetation Characteristics: wildland vegetation distance from the buildings, vegetation type, as well as the species of ornamental plants that are in proximity to the building.
4. Fire Protection Features: information on fire suppression systems and other fire protection features that are in place.
5. Community WUI Infrastructure: distance from the nearest Fire Station, road width, the existence of hydrants and/or fire extinguishing water tanks, and presence of fuel breaks near the settlement.

There are various ways to categorize the destruction or damages suffered by a building from a wildfire, and the categorization can be subjective and varies based on the wildfire intensity and the specific building codes and standards of the study area. We chose to divide the damages into three categories, as seen in Figure 2:

1. Minor damage: This category includes buildings that have sustained relatively minor damages, such as charring of the exterior walls or damaged roof materials. The frame of the structure is still intact and can be repaired (Figure 2A,B).
2. Moderate damage: This category includes buildings that have sustained moderate damages, such as collapsed roofs, partial wall collapse, and major structural damage on the frame. Significant repairs are required, but the building can be occupied again upon completion (Figure 2C).
3. Major damage: This category includes buildings completely destroyed and are no longer viable as structures. These buildings need to be demolished (Figure 2D,E).

Figure 2. (**A**) Minor damage to a structure made of reinforced concrete, with double-glazed windows and aluminum shutters that were closed during the fire. The roof is tiled and there are no openings or gaps between the roof and the main building. (**B**) The vegetation at a zone of 10 m radius from the structure is <10 cm high without trees or shrubs. No damage occurred to the surroundings of the residence. (**C**) Moderate damage to the exterior of the structure (walls, shutters, etc.), without damage to the building itself. The reason for these damages is attributed to the existence of a pine tree at a distance <5 m from the building. (**D**,**E**) Major damages to the interior and exterior of the buildings. In both cases, trees were in contact with or within 2 m of the structure. Both structures are in steep ground inclination.

2.3. Wildfire Risk Evaluation Index for Structures

The Wildfire Risk Evaluation Index for Structures (WREIS) is created by information and assessments related to the risk of structures for sustaining damages or destruction from a wildfire. This information includes various fire risk factors such as the proximity of the structure to a wildfire-prone area, the type and condition of the vegetation in proximity to or near the structure, the construction materials, the age and condition of the structure, the presence of protective features such as fire-resistant roofs and walls, the presence of fire protection features, such as sprinklers and water hoses, and the existence of appropriate community infrastructure in the specific study area.

The proposed WREIS assessment system for Greece was conceptualized from referenced related platforms around the world such as FireWise USA [18], FireSmart CA [19,20], FireReady AU [21], and FireSmart NZ [22] that provide guidelines for constructing new structures in fire-prone areas and upgrading the safety of existing buildings. These international assessments also deal with how the surrounding environment of a building, specifically the type and density of forest vegetation in relation to the distance from the building, affects the vulnerability of the structures to wildfires. They provide checklists for homeowners and residents in WUI areas, focusing on managing flammable materials around houses and reinforcing vulnerable construction elements.

More specifically, FireSmart of Canada [20] offers a comprehensive scoring system that divides the hazard score level into four categories: <21, 21–29, 30–35, and >35 as well as the defensible space into three different zones and assigns varying weights to different categories. For instance, the characteristics of the home and its attachments contribute to approximately 34% of the total score, while the different zones (0–1.5, 1.5–10, 10–30, and 30–100 m) contribute to 7, 29, 15, and 15% of the total score, respectively, based on the latest version of the Home Ignition Zone assessment scorecard from 2020 [20]. FireSmart of New Zealand [22] also offers a comprehensive scoring system that divides the hazard score level into four categories: <14, 15–22, 23–30, and >31. This system also divides the hazards and risks and assigns varying weights to different categories. For instance, the characteristics of the home and its attachments contribute to approximately 43.83% of the total score, while the surrounding vegetation zone contributes to 27.40% and the historical fires and weather conditions 28.77% of the total score.

Our WREIS index is divided into 5 sub-indices, and the weight of each index in the final building hazard score is derived from both the post-fire characteristics of the buildings in the previous subchapter 2.2 and an early assessment of buildings affected by the July 2023 wildfire in Rhodes. More specifically, in 32 out of the 36 buildings (88.8%) that exhibited major damages, it became evident that the key factors were the presence of forest vegetation entering the building courtyards, followed by the building materials and the construction methods themselves. Additionally, in areas where moderate damage prevailed, 11 out of 72 buildings (15.3%) that ultimately sustained minor damages had a simple independent water tank with a hose, covering the entire perimeter of the building. This deployment was evidently used for watering home gardens, which firefighters and local residents used to extinguish small fire outbreaks on roofs and building openings, actions which proved to be crucial for the sustainability of the buildings. Finally, there were neighborhoods where, as the wildfire approached, heavy firefighting vehicles could not approach due to narrow roads, and the firefighting hydrants did not work because of a widespread power outage. These events posed additional challenges to the sustainability of the buildings at risk in those areas during the fire. Therefore, in selecting the criteria contributing to building hazard assessment in WUI areas in Greece, we created the 5 Sub-indices of WREIS, each with different weights. Specifically, sub-index 1 consists of one factor with a weight of 7.6%, sub-index 2 consists of seven factors with a weight of 26.4%, sub-index 3 consists of 11 factors with a weight of 41.5%, sub-index 4 consists of three factors with a weight of 11.3%, and sub-index 5 consists of four factors with a weight of 13.2% in the final index assessment, taking into consideration the role played by each sub-index of the WREIS due to the Mediterranean-type of vegetation and the unique characteristics of Greek building materials compared to those in Canada, USA, Australia, and New Zealand. Furthermore, the WREIS index can range from a minimum of 0 to a maximum of 73 points.

Within this scheme, the final WREIS index score is grouped into four classes, with up to 20 points representing buildings with the lowest damage likelihood (LDL), 21 to 30 points representing buildings with moderate damage likelihood (MDL), 31 to 35 points representing buildings with high damage likelihood (HDL), and over 35 points representing the highest/extreme damage likelihood (EDL). It is based on the cumulative impact of multiple aggravating factors that can occur simultaneously in a building. Specifically, we observed that in buildings with extensive major damages, several of the aforementioned aggravating factors coexisted simultaneously, and it became evident that when the index approached the threshold of 30 points, the addition of another factor resulted in significantly more destructive outcomes in the building than if it were the sole factor present. Therefore, we defined the threshold of 30 points as HDL, signifying the presence of major damage in the building. We added the threshold of 20 points as the start of MDL above this (21–30), and transition to LDL below this (0–20). Finally, we added the threshold of 35 points as EDL because, as previously mentioned, beyond HDL, any additional aggravating factor can lead to the complete destruction of the building (Figure 3).

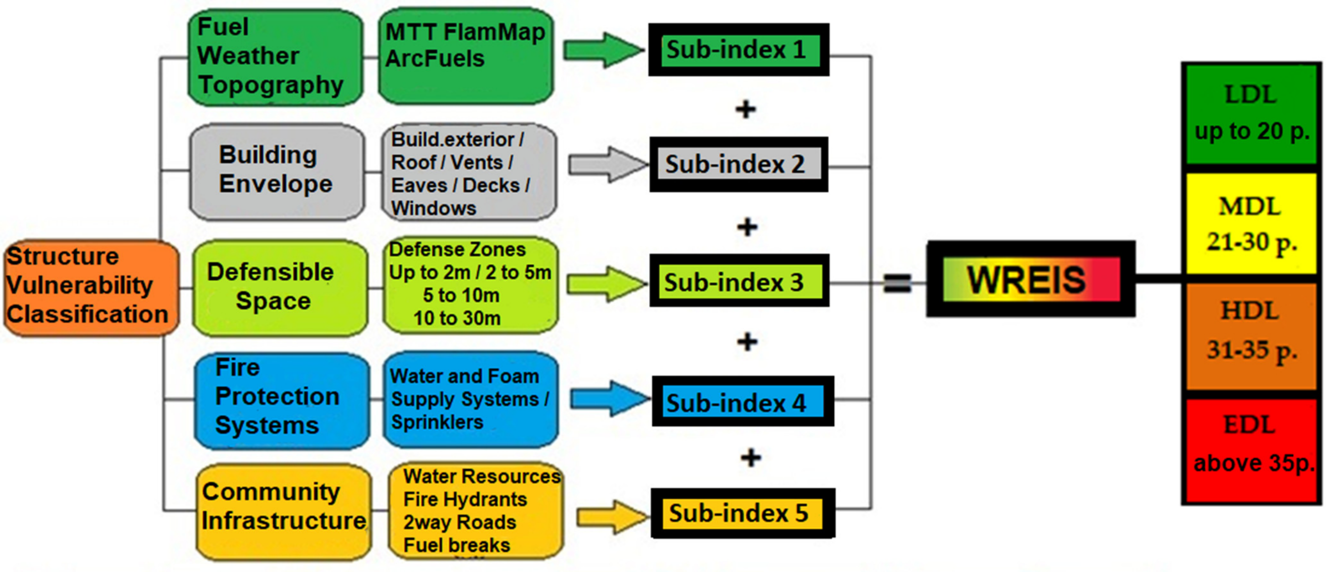

Figure 3. Flowchart of the approach used to estimate the WREIS.

2.3.1. Sub-Index 1—Fuel, Topography, and Weather

Wildfire simulation modeling was conducted using the minimum travel time (MTT) fire spread algorithm of FlamMap 6.1 [48]. MTT computes fire growth between the cell corners at an arbitrary resolution, and fire growth is computed under the same assumptions as the basic fire behavior, holding all environmental conditions constant in time [49–51]. MTT generates fire behavior metrics such as fire rate of spread, burn probability, and conditional flame length.

The CORINE Land Cover (CLC 2018) inventory was the base layer for vegetation mapping (Figure 4A). We intersected the CLC2018 forest classes with a detailed vegetation layer with species information produced by the First National Forest Inventory of Greece (NFIG) that captures the species distribution for the reference year of 1992, in conjunction with field inventories to obtain the necessary up-to-date information of the spatial limits of specific forest vegetation species in the study area. The classification of the land cover in the study area showed that forests with *Pinus brutia* occupy 34% of the total study area, followed by discontinuous urban fabric that includes public buildings, industrial areas, hospitals, schools, and small industries at 26% of the total study area. Urban areas occupy 20%, sclerophyllous vegetation 11%, and finally, agricultural lands and natural vegetation make up 9% of the total study area.

Table 1. Scott and Burgan fuel models [52], ranked by area occupied in the study area, including the 10 km buffer zone.

Fuel Model Code	Description	Area (ha)	Proportion (%)	Fuel Model Code	Description	Area (ha)	Proportion (%)
NB1	Urban/Developed	54.80	40.90	GR2	Low Load, Dry Climate Grass (Dynamic)	6.39	4.78
TU5	Very High Load, Dry Climate Timber-Shrub	40.52	30.24	SH7	Very High Load, Dry Climate Shrub	5.48	4.09
SH5	High Load, Dry Climate Shrub	12.23	9.13	SH2	Moderate Load Dry Climate Shrub	4.45	3.32
GR1	Short, Sparse Dry Climate Grass (Dynamic)	9.46	7.06	GS1	Low Load, Dry Climate Grass-Shrub (Dynamic)	0.64	0.48

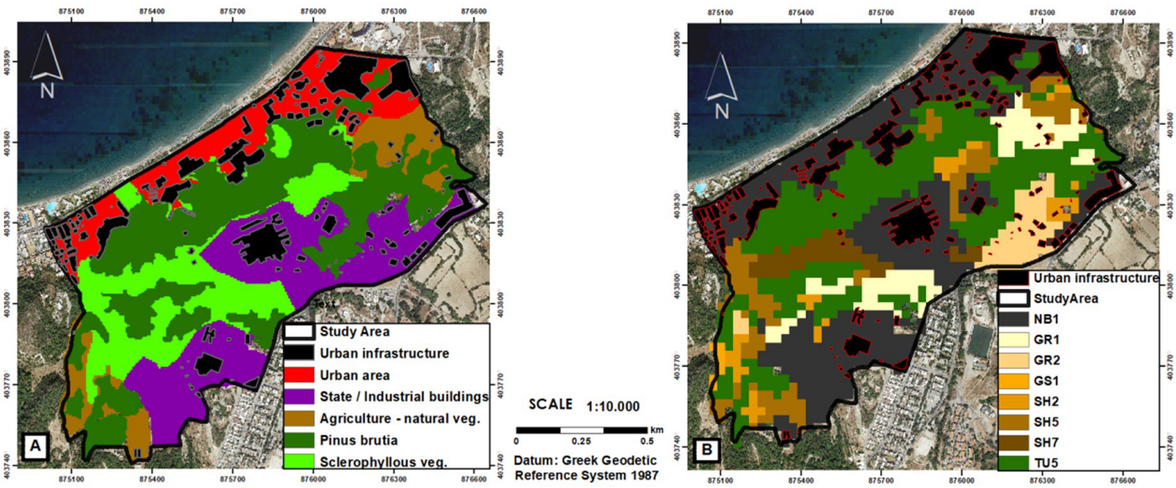

Figure 4. (**A**) General vegetation types within the study area, and (**B**) Scott and Burgan fuel models [52]; NB: Non-Burnable; GR: Grass; GS: Grass-Shrub; SH: Shrub; TU: Timber-Understory. See Table 1.

Based on knowledge gained through extensive field inventories across different Greek eco-regions and our expert knowledge regarding the potential fire behavior of each vegetation class, we assigned one or more fuel models at each land-use/land-cover class depending on topographic and other conditions, which can be detected visually in the field [44]. All raster datasets, both the inputs and the final layers, were resampled at 30 m spatial resolution. From this process, the Fuel Model map of the area was produced (Figure 4B), with eight fuel types as described in detail in Table 1.

MTT outputs, combined with ArcFuels [53,54] post-processing software of ArcGIS version 10.8.1, were used for further processing the simulation results within the study area, incorporating all its features such as road networks, buildings, etc. In order to run FlamMap for the study area of Ixia, we used weather inputs for July 2021 from three weather stations, which was the highest fire hazard month of the last 10 years for the island of Rhodes, due to high temperatures and very low relative humidity. The study area of Ixia is located on the windward side of the island, affected by strong and frequent winds throughout the year. Stochastic fire simulations considered all possible weather scenarios, setting 100,000 random ignition locations using an ignition probability grid for the whole island of Rhodes. Key elements for the increased exposure of a structure to convective and radiant heating were the slope of the ground, the height and distance of the trees from the specific structures, and the distribution of the fuel model of the specific area.

Experts in the analysis of wildfire characteristics have the capability, through the sub-index 1 of WREIS, to draw secure conclusions for specific points within a study area that may have higher burn probability (BP) and be more destructive due to higher fire intensity (conditional flame length—CFL). Specifically, the values presented by BP, which represent a pixel that could be burned on the MTT stochastic simulations in the study area, are categorized into four levels, ranging from low to high. Similarly, the values presented by CFL are subject to a corresponding categorization. Sub-index 1 is a combination of these two previous indices and is divided into four classes: Low, Medium, High, and Extreme with values of 5, 10, 15, and 20, respectively. These results are spatially represented on a Geographic Information System (GIS) map, and reliable conclusions can be drawn for any building within the study area based on its location. In this work, BP values ranged from 0 to 419, representing the number of times a pixel could be burned in the study area (BP 0–0.0419 per 10,000 simulations), and CFL values ranged from 0 to 19.8 m, depending on the density and type of forest fuel (conifers, shrubs, grassland, and agricultural lands). Therefore, in large-scale areas, researchers have the option to focus on the buildings within the study area that sub-index 1 of WREIS has indicated as having "High" and "Extreme" levels of risk, and proceed to assess the subsequent indices of WREIS through on-site inspections in the area. In this way, WREIS sub-index 1 first categorizes the entire study area to distinguish areas where buildings are more at risk, and then it provides the initial scoring for the final hazard score calculation (Table 2).

Table 2. Sub-index 1. Fuel, Topography, and Weather ranking category.

Ranking Category		Score
1.	LOW	5
2.	MEDIUM	10
3.	HIGH	15
4.	EXTREME	20
Sub-index score		...

2.3.2. Sub-Index 2—Building Envelope

Building Envelope describes the construction materials of the building, as well as the characteristics of their external envelope including the roof, openings, and balcony construction materials. Assessments around the world, such as FireWise USA [18], FireSmart CA [19,20], FireReady AU [21], and FireSmart NZ [22] guide on how the construction of new structures in fire-prone areas should be made while supporting the safety upgrade of the existing buildings. Commonly, structures across the Mediterranean Europe, such as those found in Greece, are constructed with non-combustible materials such as stone, bricks, clay stone, mortar, and/or iron. According to Vacca et al. [55], these structures can still be destroyed if the fire gets inside the buildings due to elements, materials, or configurations that have to do with the structure design, as well as the relative position, size, and type of the potential heat source. After consulting and synthesizing the findings reported in the relevant literature, we informed our risk assessment by considering seven factors of high influence on the heat transmission and fire spread outside and inside the building, as seen in Table 3.

Table 3. Building envelope sub-index.

	Hazard Factor	Characteristics and Point Ratings				Score
1.	Structure Material [14,17–23,26,30,33]	Concrete, bricks, cement blocks	Wood		Chip-board, plastic	
		0	5		10	...
2.	Roof Material [14,17–23,26,30,33]	Concrete, asphalt shingles, cement blocks	Clay Tiles Sheets		Wood, Chip-board, plastic	+
		0	5		10	...
3.	Shutters [14,17–23,30,33]	Aluminum, metallic	Wooden, new	Plastic or older wooden	There are no covers on the openings	+
		0	5	5	10	...
4.	Gutter type and cleanliness [14,17–23,30,33]	Metal gutter—no leaf debris	Plastic gutter—no leaf debris	Metal gutter with leaf debris	Plastic gutter with leaf debris	+
		0	5	5	10	...
5.	Unprotected openings (chimneys, ventilation, etc.) [14,17–23,30,33]	Openings are protected by dense metal mesh	Some openings, unprotected		Many unprotected openings	+
		0	5		10	...
6.	Window glass [14,17–23,30,33]	Strengthened (tempered)	Double glazed		Single paned	+
		0	5		10	...

Table 3. *Cont.*

Hazard Factor		Characteristics and Point Ratings			Score
7.	Position on Slope [14,17–23,30,33]	Structure is located on the bottom or lower portion of hill	The structure abuts the hill and has more than 2 floors	Structure is located on the mid to upper portion or crest of hill	+
		0	5	10	…
Total					…

2.3.3. Sub-Index 3—Defensible Space

Defensible Space is defined as "an area where combustible material, including vegetation (e.g., forests, shrubs, grasses), was treated, cleared or modified to reduce the rate and intensity of an advancing wildfire and create a safer area for fire suppression operations" [29]. Figure 5A,B models the fire behavior potential of experimental thinning/slash fuel treatments along the WUI. Under simulated severe fuel moisture and weather conditions, treatments reduced spread rates by more than half and brought flame lengths closer to the limits of direct suppression methods from levels of serious control problems—thus, mitigating fire losses and resistance to control [56].

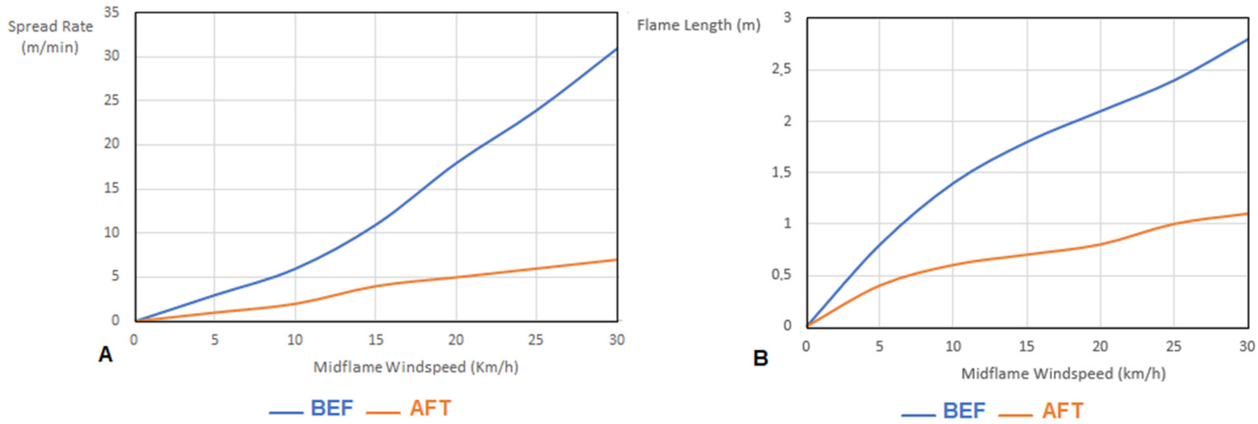

Figure 5. (**A**,**B**). Fire hazard reduction (BEFore treatment versus AFTer treatment fire behavior) through vegetation management (i.e., tree thinning with slash fuel disposal) in the WUI, adapted from [56].

The defensible space is evaluated using four defense zones (seen in Table 4), defined by the distance (radius) from the main building: Zone 1–4 with radii of 2 m, 5 m, 10 m, and 30 m, respectively. Zone 4 is considered if the 30 m distance exists on the plot boundaries of the property. These four zones were chosen by studying the practices applied by the assessments of FireWise USA [18], FireSmart CA [19,20], FireReady AU [21], and FireSmart NZ [22], and adjusted based on findings from field studies of the destroyed buildings from the 2021 Athens wildfire and an early field assessment of the major wildfire on the island of Rhodes in 2023, including their post-fire effects.

Table 4. Defensible space sub-index.

	Hazard Factor	Characteristics and Point Ratings				Score
		Defense Zone 1 (0–2 m)				
1.	2 m from the ground level exterior footprint of the structure including any attachments or extensions [29–32]	Surface with non-combustible debris or materials, fences, or plants present 0		Surface with combustible debris or materials, fences, or plants present 10		…
		Defense Zone 2 (2–5 m)				
2.	Forest vegetation [18–20,31,32]	Deciduous trees 0	Mixed tree types (deciduous and coniferous) 5	Coniferous >3 m distance between trees 5	Coniferous <3 m distance between trees 10	+ …
3.	Surface vegetation and combustible materials [18–20,31,32]	Grass <10 cm height or non-combustible surface, non-combustible materials stored 0		Grass >10 cm height or highly flammable plants, combustible materials stored. (Firewood, branches) 10		+ …
		Defense Zone 3 (5–10 m)				
4.	Forest vegetation [18–20,31,32]	Deciduous trees 0	Mixed tree types (deciduous and coniferous) 5	Coniferous >3 m distance between trees 5	Coniferous <3 m distance between trees 10	+ …
5.	Flammable shrubs [18–20,30,31]	None 0	Scattered 5	Abundant 10		+ …
6.	Surface vegetation and combustible materials [18–20,31,32]	Grass <10 cm height or non-combustible surface, non-combustible materials stored 0		Grass >10 cm height or highly flammable plants, combustible materials stored. (Firewood, branches) 10		+ …
7.	Low-lying coniferous branches (< 3 m above the ground) [18–20,31,32]	None 0		Present 10		+ …
		Defense Zone 4 (10–30 m)				
8.	Forest vegetation [18–20,31,32]	Deciduous trees 0	Mix of tree types (deciduous and coniferous) 5	Coniferous >3 m distance between trees 5	Coniferous <3 m distance between trees 10	+ …
9.	Flammable shrubs [18–20,31,32]	None 0	Scattered 5	Abundant 10		+ …
10.	Surface vegetation and combustible materials [18–20,31,32]	Grass <10 cm height or non-combustible surface, non-combustible materials stored 0		Grass >10 cm height or high flammability plants, combustible materials stored (Firewood, branches) 10		+ …
11.	Low-lying coniferous branches (<3 m above the ground) [18–20,31,32]	None 0		Present 10		+ …
		Total				…

2.3.4. Sub-Index 4—Fire Suppression System

This index estimates the presence and effectiveness of installed fire protection systems, aiming at reducing the vulnerability of a structure to wildfires. These systems can include:

1. The installation of one or more water intake points in the premises of the house that have flexible rubber pipes up to 20 m long and at least 15 mm in diameter with a nozzle to cover every point of the premises.
2. The installation of a self-contained water suppression system with water pumps or a fire suppression foam-generating system that is compatible with three materials during its operation: water, foam, and atmospheric air [57]. Thus, the fire suppression foam production system has superior extinguishing capabilities and receives a more favorable rating in sub-index 4 of the WREIS, wherever it can be used.
3. The installation of an automatic water sprinkler system with an independent control valve, preferably made of galvanized steel with inverted, open-type sprinklers (activated by a suitably designed fire detection device) or automatic sprinklers. It should

cover the ridge of the roof or its perimeter if it is flat and be able to wet the exterior walls emphasizing critical elements such as frames and roof timbers, with a minimum pressure of each sprinkler at 0.5 bar.

After studying the relevant literature, regulations, standards, and guides that examine, certify, and control the firefighting systems [56–61], in addition to the factors of active fire protection (i.e., suppression) for the boundaries of the structure, we derived three factors to estimate the final risk score (Table 5).

Table 5. Fire suppression system sub-index.

	Safety Factor	Characteristics and Point Ratings			Score
1.	Water supply [57–62]	None 10	Permanent water supply system connected to the settlement's network 5	Independent water tank with its own pump and backup power source 0	…
2.	Self-contained water suppression system [57–62]	None 10	Water pumps 5	Fire suppression foam compatible with the self-contained water suppression system 0	+ …
3.	Self-contained wildfire sprinkler systems [57–62]	None 10	Indoor fire sprinklers 5	Exterior fire sprinklers 0	+ …
		Total			…

2.3.5. Sub-Index 5—Community Infrastructure

The Community Infrastructure index accounts for the presence of critical fire prevention and pre-suppression factors inside a community, such as a water supply network and fire hydrants alongside community roads, the existence of sufficient road width for fire trucks, and areas at the edges of the community where fuel breaks can be established [30,38].

By ensuring the access of firefighting trucks inside a WUI area, the chances of the timely intervention of firefighting forces are increased along with a larger availability of human and mechanical resources in the field. According to the Greek State "Regulation for Fire Protection of Properties within or in proximity of forest areas" [36], passage for a vehicle is secured only if a minimum road width of at least 3 m and a minimum vertical clearance of at least 3 m below any structure or feature over the road is established, provided that such an opportunity exists. In addition, the maximum width of a heavy firefighting vehicle is 2.5 to 2.6 m. Therefore, a clearance space with a vertical and horizontal width of 3 m has been chosen, since it satisfies the vehicle access requirements. Additional measures include the prohibition of parking on streets where the final free width will be less than 3.5 m and the prohibition of parking at bends and intersections.

By installing fire hydrants at a distance of less than 100 m between them and with semi-connectors compatible with those of fire trucks, a community firefighting network can be created. This network should be supplied with water from an autonomous municipal water supply network, or from a water tank, ensuring that an automatic switching is in place so that in case of electricity supply interruption, a backup power source will provide electricity to it. Finally, the installation of fire-extinguishing water cannons and/or preventive wetting enhances the community fire defense mechanism, as long as international standards for such systems are met [63–66]. Four factors are assessed for this Index (as in Table 6).

Table 6. Community infrastructure sub-index.

	Safety Factor	Characteristics and Point Ratings				Score
1.	Access to the community [18–20]	Road width where, after parking of vehicles, will leave a free width of <3 m 5		Road width where, after parking of vehicles, will leave a free width of >3 m 0		…
2.	Fuel breaks around the Community [37–41]	No fuel breaks 10		<100 m width 5	>100 m width 0	+ …
3.	Community firefighting network [63–66]	No fire hydrants in the specific area (radius of 200 m) 10		Fire hydrants connected to the city network 5	Fire hydrants connected to an independent water tank with its own pump and spare pump 0	+ …
4.	Fire extinguishing water cannons and/or systems for humidity increase [63–66]	None 10	Water cannons 5	Sprinklers for humidity increase 5	Water cannons and sprinklers 0	+ …
				Total		…

2.4. Adaptation to the Study Area

The study area was divided into four smaller regions to enable a more comprehensive evaluation of their characteristics, safer adjustment of the findings, and the application of customized solutions. Subsequently, 10 buildings were selected in total from all the regions with a high possibility of fire spreading in their surrounding environment, which could significantly affect their integrity. The selection was based on the following factors:

(a) Results of the WREIS sub-index 1, which combines the burn probability at specific locations with the conditional flame length that can develop there, (Figure 6).

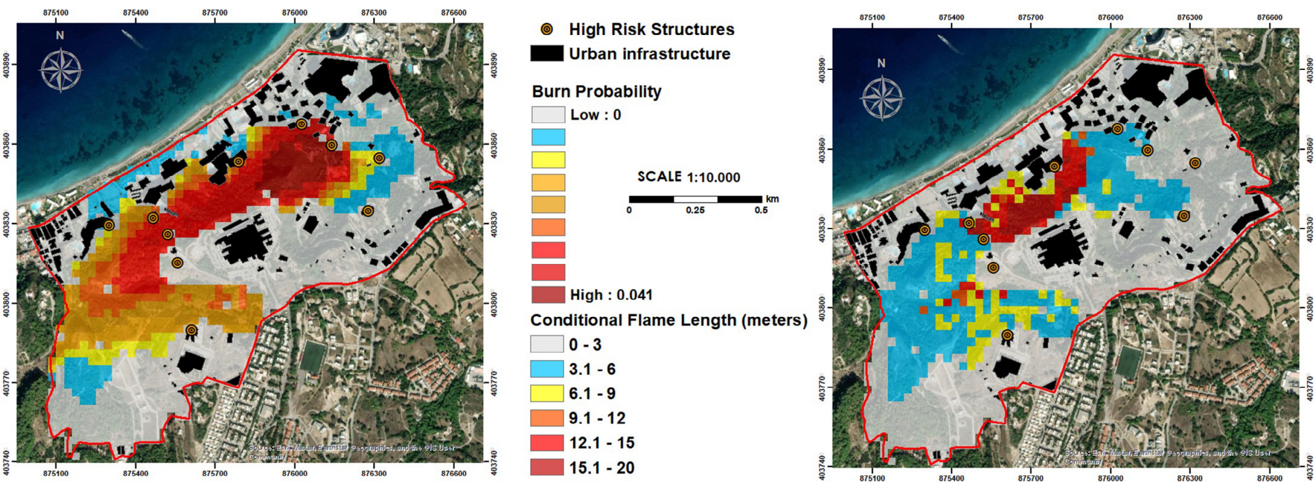

Figure 6. High-risk structures of the study area based on Burn Probability and Conditional Flame Length estimates of the study area of Ixia, Rhodes Island.

(b) Historical information on fire initiation and spread in the specific WUI area. The points of fire ignitions were studied, as well as those that developed destructively during the period 1978–2023.

(c) Empirical knowledge from the results of our study and the outcomes of real wildfires in buildings with similar characteristics during the 2021 wildfires in Attica.

The next step involved in situ inspections of the aforementioned 10 buildings and the evaluation of the remaining four sub-indices of the WREIS (Building Envelope, Defensible Space, Fire Suppression System, and Community Infrastructure) to ascertain the final level of risk associated with them, and to propose measures for their protection. The last step was to categorize the danger level in all the remaining buildings of the study area using WREIS to be able to propose a set of measures to mitigate their vulnerability.

3. Results and Discussion

According to the WREIS score, 44 buildings (28.57% of all 154 buildings in the study area) were categorized with extreme damage likelihood -EDL (23 buildings presented a score above 45 and 21 buildings a score of 45), 42 buildings (27.27%) with high damage likelihood -HDL (a score of 35), 68 buildings (44.16%) with moderate damage likelihood—MDL (22 buildings a score of 30 and 46 buildings a score of 25) and finally none of the 154 buildings in the study area registered a score with lowest damage likelihood—LDL (below 25) (Table 7).

Table 7. WREIS index structures classification.

WREIS	(No. of Structures)	Proportion (%)	Hazard Classification
Up to 20	0	0	lowest damage likelihood (LDL)
21–30	68	44.16	moderate damage likelihood (MDL)
31–35	42	27.27	high damage likelihood (HDL)
Above 35	44	28.57	extreme damage likelihood (EDL)
Total	154	100	

From the analysis we conducted and the on-site inspections in the study area, we found that the factor that exacerbates the vulnerability of buildings is the presence of excessive combustible material within the building courtyards and in contact with them. Vegetation negatively affects WREIS sub-indices 1 and 3, which in turn contribute significantly to the level of risk to the sustainability of the building itself.

Another noteworthy factor is the absence of fire protection measures in residential buildings due to a lack of relevant legislation mandating such measures. This fact negatively affects the WREIS sub-index 4. However, in commercial constructions such as hotels, industrial complexes, etc., fire protection systems were present to address fires within the buildings. These systems can also be used in the external areas of these buildings to suppress fire incidents coming from nearby forested areas.

Similarly, the state or community intervention is also limited due to the significant absence of infrastructure throughout the study area. This includes roads for the movement of heavy firefighting vehicles, or community-level firefighting resources to address wildfire incidents. There is a serious lack of water reservoirs with firefighting equipment exclusively for extinguishing fires in the external areas of buildings. These circumstances have greatly increased WREIS sub-index 5 (Figure 7).

Another useful element of our study is the toolbox of protective measures for buildings before each fire season, based on the hazard category associated with each WREIS sub-index. This toolbox would include short-term and long-term interventions that can be implemented, considering the cost and time required for their implementation (Table A1). Finally, we have developed a structure risk assessment card due to wildfire (Table S1—Supplementary Materials), which is based on the WREIS index and can be used jointly by wildfire analysts and the owners of these specific structures to categorize the vulnerability of their construction. Then, by using the aforementioned intervention toolbox step by step, they can intervene to reduce the risk to acceptable limits.

Figure 7. (**A**) Excessive Forest fuel consisting of pines (*Pinus brutia*) and shrubs, which are in contact with a building greatly increase the WREIS sub-indices 1 and 3. (**B**) Increasing of WREIS sub-indices 1 and 3 due to the presence of trees and dry branches that abut building balconies. (**C**) The building balcony door is not protected by a shutter and its glazing is single, greatly increasing WREIS sub-index 2. Sub-index 2 is significantly reduced due to the absence of flammable materials on the building exterior and its roof. (**D**) WREIS sub-index 3 is reduced due to the large distance (15 m) of the building's external perimeter from the neighboring forested area. (**E**,**F**) Independent water tank with its own pump and backup power source connected to water cannons can reduce the WREIS sub-index 4. However, the presence of dense forest vegetation consisting of pines, shrubs, and dry vegetation over 20 cm in height, significantly increases the values of WREIS sub-index 3. (**G**) The construction of a road to provide access for firefighting vehicles around this tourist facility, as well as the establishment of a permanent fire suppression system consisting of an autonomous water tank with a capacity of 100,000 L, reduces WREIS sub-index 3 due to the interruption of forest fuel continuity, as well as the WREIS sub-index 4 (Fire Protection Systems) and sub-index 5 (Community Infrastructure). (**H**) WREIS sub-index 2 is significantly reduced due to the absence of flammable materials on the building exterior and the roof of the building. However, the presence of dense grass and shrub vegetation significantly increases the values of the WREIS sub-index 3.

4. Concluding Remarks

The July 2023 large wildfire of Rhodes coincided chronologically with our study on the island. Although the specific study area we selected, located in the northwestern part of the island, was not affected by the fire that occurred in the central and southern parts, it remains of particular significance in our research endeavors. Initially, a notable observation was the fact that the entire management of wildfire suppression automatically changed when the wildfire approached a WUI area, with particular emphasis placed on ensuring the safety of citizens first and then safeguarding their properties. This necessitated the involvement of all firefighting forces (both aerial- and ground-based), resulting in the main front of the wildfire often being guided by the wind, without significant efforts to contain it as long as inhabited areas nearby were at risk. Therefore, it is absolutely essential to implement immediate interventions in all WUI areas of Rhodes, applying the WREIS index to make them more resilient to future fires, whenever and wherever necessary.

Additionally, it became evident from the results of the fire that in structures where there were significant open spaces nearby, such as car parks, hotel pools, and lawns, the fire did not manage to approach the main buildings of the properties with the same intensity or cause damage to them. Furthermore, in many cases, damage to the structures occurred long before the main front of the fire reached the area, due to the countless embers that preceded the fire front and found open windows in houses, wooden pergolas, wooden roofs, and open fabric covers. As a result, dozens of fire points ignited within the settlement even before the main front had a chance to test the buildings in terms of pyro-thermal loads.

Another critically adverse factor that occurred in the specific fire and is directly related to our research, specifically to safety factor 3 (Community firefighting network) of sub-index 5 (Community infrastructure) of WREIS, was a significant malfunction in the uninterrupted water supply to firefighting vehicles. This happened for two main reasons; firstly, a large number of Public Power Corporation (DEI) power poles were destroyed by the fire over a considerable area, resulting in power outages in the residential areas near the approaching fire, and secondly, there were no backup energy sources at the pumping stations of the Water Supply and Sewerage Company of Rhodes (DEYAR), which could have provided the necessary water supply to the firefighting trucks. As a result, there were significant delays in many cases, as heavy vehicles had to travel long distances to transport the required water to the location where firefighting efforts were underway. Therefore, it was confirmed that sub-index 5 (Community infrastructure) of WREIS is extremely critical for the successful suppression of fires within the WUI and the protection of both the settlement and the lives of its residents, and also demonstrated that sub-index 4 (Fire Suppression System) of WREIS is of paramount importance. Specifically, the presence and use of an independent water tank with its own pump and backup power source in each structure have proven to be crucial. This setup makes fire suppression capabilities independent of the availability of electricity or water supply from communal networks.

In May 2023, the Greek Government issued a Ministerial Decision by three Ministries (Environment and Energy, Interior, Climate Crisis, and Civil Protection) titled "Regulation for fire protection of properties within or in proximity of forested areas", which is an initial effort to organize all relevant stakeholders in cooperation with the residents of WUI areas to reduce the damages caused by wildfires to peri-urban properties. It is necessary that this effort be combined with relevant legislation for the fire protection of these buildings. The legislation should enforce the installation of mandatory fire protection measures by property owners, as well as technical interventions by the government in vulnerable peri-urban areas. This can include road construction and the transformation of specific public or communal lands surrounding these settlements into fire prevention areas (fuel discontinuity zones and secure parking/operational areas for ground firefighting forces to suppress forest fires before they enter the settlements).

Our study uses wildfire simulations to estimate the exposure of buildings to the wildfire phenomenon and proposes the WREIS index to calculate the vulnerability of each building in case the fire spreads to its property boundaries. In Greece, measures have been taken to promote the fire resilience of buildings in areas at risk from wildfires, such as forested zones and WUI areas.

An innovation in this research is the simultaneous integration of modern wildfire simulation programs with on-site inspections in the WUI. This approach serves two main purposes: first, to enhance the precision of their application in the actual dimensions of the study area, and second, to enable verification and validation of the generated results at every stage of the research. This index introduces the innovation of including in its rating, apart from the other aspects evaluated internationally in other studies (such as building characteristics and environmental surroundings), the fire extinguishing measures of the building itself. At the same time, it takes into account firefighting and intervention measures for the community infrastructure, including the width of community roads and the presence or absence of fuel break zones near the settlement to which the building belongs. Furthermore, the proposal in Table A1 (Appendix A) transfers knowledge directly to the building owners in reducing the vulnerability of their construction to wildfires with straightforward instructions. This is achieved through a toolbox that suggests interventions, with those of lower cost and ease of implementation taking precedence over those that are more difficult and costly to accomplish in a short period of time. The entire research design of this paper targets WUI areas with Mediterranean vegetation and was applied and tested in two regions of Greece (Attica and Rhodes Island) that traditionally experience large-scale wildfire incidents with significant effects. These areas have extensive urban development and have suffered from large-scale, devastating fire outbreaks. In this manner, we examined both fire behavior in these specific forested ecosystems and the resilience of structures that are traditionally constructed within them.

However, there are still some gaps in the legal framework that could improve the protection of buildings from wildfires in WUI areas. We have a set of proposals for action targeting all stakeholders involved in fire management, such as the Fire Service, Forest Service, Civil Protection, property owners, and citizens. These are:

1. It is deemed necessary to establish a legal framework for controlling the fire resistance of buildings located in mixed or interface zones with wildlands so that a categorization of their risk can be made prior to a wildfire event that can reach their boundaries. This framework can replicate how the strict requirements of different seismic codes of Greece (1959, 1985, 2000) impose pre-event measures to structure owners and categorize each new building based on the overall seismic risk of each region.
2. Adapting regulatory provisions for the construction and maintenance of buildings in WUI areas considering the risk of wildfires and strengthening the requirements for achieving fire resilience and fire resistance.
3. Introducing legislation that will enforce the creation and maintenance of fire protection zones around buildings in WUI areas, as well as supervising compliance with these regulatory provisions.
4. Strengthening fire prevention measures in WUI areas, such as removing forest fuel at a distance of at least 10 m from the boundaries of each house, pruning and thinning vegetation at a distance of 30 m from the boundaries of each house, and selecting ornamental plants with high fire resistance.
5. Educate and change the attitudes of people and authorities regarding the role of fire protection.

Without a doubt the implementation of WREIS, as is the case with other assessment tools, also has limitations that are worth listing. Its application in other countries, even those in the broader Mediterranean region (such as Italy, Serbia, Croatia, etc.), could only be reliably achieved if an adaptation to the characteristics of the buildings in this area is carried out from the outset. During our inspections of the post-fire characteristics of buildings that suffered damage from the mega-fires in Attica and Rhodes, it was observed that buildings in Greece exhibit increased fire resistance due to their cement-brick construction, compared to buildings that undergo comparable international assessments. Similarly, the implementation of WREIS in areas with different forest vegetation than the Mediterranean will require adaptation not only of sub-index 2, as mentioned earlier, but also of sub-index 3. Another limitation of WREIS is the fact that, in order to apply the overall assessment, stakeholders must have a solid knowledge of stochastic wildfire simulation programs as well as GIS data processing systems for sub-index 1. Lastly, it is worth noting that for the application of sub-indices 2 to 5 of WREIS, prior training of the individuals involved is essential, and this training should be at least two days long (one day theoretical and one day practical). This fact simultaneously increases the cost of implementation due to the on-site demonstrations.

The analysis of the wildfires of 2021 in the Attica region and an early assessment of the major wildfire on the island of Rhodes in 2023, including their post-fire effects, revealed that buildings usually composed of reinforced concrete in Greece showed great resistance to external fire with much less damage compared to other studies elsewhere. However, the same was not the case with the fuel management near and within WUI areas, where the lack of development plans and the existence of strict forest laws and regulations prohibit vegetation cleaning that, in turn, greatly enhances the intensity of wildfires. In addition, the general public stance and the existing institutional framework do not reward the existence and/or installation of fire extinguishing systems (autonomous domestic tanks, sprinkler systems, etc.), at a structure or at a community level.

Procedures discussed in this paper should aid in the development of pre-suppression planning that will ensure public safety, maintain natural resources both physically and aesthetically intact, and yet allow people to live in the natural environment. Once homeowners accept the fact that fire risks are substantial when they are built in wildland situations, it is prudent for the homeowners to take all necessary steps to reduce the potential impact of wildfires on their lives and homesites.

All in all, it would be extremely useful if the composite WREIS could be applied at a preventive level, initially in every settlement that contains wildland urban intermix, and by extension in every wildland-urban interface. In order to carry out this specific adaptation, a necessary prerequisite is the mapping of these areas, the assessment of their exposure to fires, their selection by priority, the assessment of the WREIS for each community building, and finally the proposal of measures according to the final index value. Thus, the proposed Index could be tested in more communities and WUI areas of Greece, especially those with variable and unique characteristics of building construction or forest fuel management practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire6100403/s1, Table S1. Structure Risk Assessment Card due to Wildfire based on the WREIS—Wildfire Risk Evaluation Index for Structures.

Author Contributions: Conceptualization, D.M. and P.P.; methodology, D.M., P.P. and K.K.; software, D.M.; validation, P.P. and K.K.; formal analysis, P.P.; investigation, D.M.; resources, D.M.; data curation, D.M.; writing—original draft preparation, D.M.; writing—review and editing, D.M., P.P. and K.K.; visualization, D.M.; supervision, K.K.; project administration, K.K. and P.P.; funding acquisition, K.K. and P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received support from the Project "Coastal Environment Observatory and Risk Management in Island Regions AEGIS+" (MIS 5047038), implemented within the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014–2020), co-financed by the Hellenic Government (Ministry of Development and Investments) and the European Union (European Regional Development Fund).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Hellenic Fire Service and the Hellenic Forest Service for their valuable contribution throughout this effort.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Toolbox of interventions in structures in WUI areas.

	Intervention	Implementing Agency	Affected Sub-Indices
1	At a distance of 2–5 m from the structure remove all combustible debris or materials, fences or plants	Structure owner	Sub-index 1 Sub-index 3
2	At a distance of 2–5 m from the structure remove trees so that there is a mandatory distance of 3 m between them or the structure itself	Structure owner	Sub-index 1 Sub-index 3
3	At a distance of 2–5 m from the structure prune the trees so that they start from a distance of 3 m from the ground	Structure owner	Sub-index 3
4	At a distance of 2–5 m from the structure remove all shrubs	Structure owner	Sub-index 3
5	At a distance of 2–5 m from the structure the grass should be kept below 10 cm in height and watered daily to maintain sufficient moisture content	Structure owner	Sub-index 3
6	If there are no shutters, metal ones should be constructed to be installed in case of fire and cover all the openings of the structure	Structure owner	Sub-index 2
7	Construction of a dense metal mesh that will cover the gutters to prevent leaf debris from accumulating inside	Structure owner	Sub-index 2
8	Protect all openings (chimneys, ventilation) with dense metal mesh	Structure owner	Sub-index 2
9	At a distance of 5–10 m from the structure remove trees so that have a mandatory distance of 3 m between them	Structure owner	Sub-index 1 Sub-index 3
10	At a distance of 5–10 m from the structure prune the trees so that they start from a distance of 3 m from the ground	Structure owner	Sub-index 3
11	At a distance of 5–10 m from the structure remove all shrubs	Structure owner	Sub-index 3
12	At a distance of 5–10 m from the structure the grass should be kept below 10 cm in height and watered daily to maintain sufficient moisture content	Structure owner	Sub-index 3
13	Replacement of plastic gutters with metal ones	Structure owner	Sub-index 2
14	Replacement of window glasses with reinforced tempered glasses	Structure owner	Sub-index 2
15	At a distance of 10–30 m from the structure remove trees so that there is a mandatory distance of 3 m between them	Structure owner Municipality or Region	Sub-index 1 Sub-index 3
16	At a distance of 10–30 m from the structure prune the trees so that they start from a distance of 3 m from the ground	Structure owner Municipality or Region	Sub-index 3

Table A1. *Cont.*

	Intervention	Implementing Agency	Affected Sub-Indices
17	At a distance of 10–30 m from the structure remove all shrubs located near or under the trees	Structure owner Municipality or Region	Sub-index 3
18	At a distance of 10–30 m from the structure the grass should be kept below 10 cm	Structure owner Municipality or Region	Sub-index 3
19	Changing the construction material of the structure roof from chip-board, plastic to clay tile sheets or asphalt shingles	Structure owner	Sub-index 2
20	Permanent water supply system in each structure connected to the community network or from independent water tank with its own pump and spare pump	Structure owner	Sub-index 4
21	Self-contained water pumps with suppression foam	Structure owner	Sub-index 4
22	Self-contained sprinklers systems indoor and exterior to structure	Structure owner	Sub-index 4
23	Widening the road construction with a minimum width of 3 m towards each construction in the area	Municipality or Region	Sub-index 5
24	Clearing of unused public or communal lands surrounding the settlement prior to each fire season, in order to serve as a barrier against the spread of forest fires towards the settlement due to fuel discontinuity and their selection as strategic firefighting points by aerial and ground firefighting forces	Municipality or Region	Sub-index 1 Sub-index 5
25	Community firefighting network with fire hydrants in radius of 200 m connected to an independent water tank with its own pump and spare pump	Municipality or Region	Sub-index 5
26	Fire extinguishing water cannons on the side of the buildings that borders the wildland-urban interface (WUI) vegetation	Municipality or Region	Sub-index 5
27	Replacement of the external construction material of the building from chip-board or plastic to concrete, bricks, or cement blocks	Structure owner	Sub-index 2

References

1. Palaiologou, P.; Ager, A.A.; Nielsen-Pincus, M.; Evers, C.R.; Kalabokidis, K. Using transboundary wildfire exposure assessments to improve fire management programs: A case study in Greece. *Int. J. Wildland Fire* **2018**, *27*, 501–513. [CrossRef]
2. *EUR 24121 EN. 75*; The Fatal Fire Entrapment of Artemida (Greece) 2007. Recent Forest Fire Related Accidents in Europe. European Commission, Joint Research Centre, Institute for Environment and Sustainability: Brussels, Belgium, 2009. Available online: https://data.europa.eu/doi/10.2788/50781 (accessed on 5 July 2022).
3. Xanthopoulos, G.; Athanasiou, M. Attice Region Greece, July 2018. *Wildfire* **2019**, *28*, 18–21. Available online: https://www.iawfonline.org/article/fire-globe-attica-region-greece-july-2018/ (accessed on 5 July 2022).
4. Koutsias, N.; Arianoutsou, M.; Kallimanis, A.S.; Mallinis, G.; Halley, M.J.; Dimopoulos, P. Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather. *Agric. For. Meteorol.* **2012**, *156*, 41–53. [CrossRef]
5. Cohen, J. Wildland-urban fire—A different approach. In Proceedings of the Firefighter Safety Summit, Missoula, MT, USA, 6–8 November 2001; International Association of Wildland Fire: Fairfax, VA, USA, 2001.
6. Cohen, J.D. *Examination of the Home Destruction in Los Alamos*; United States Department of Agriculture (USDA) Forest Service: Missoula, MT, USA, 2000; Available online: https://www.srs.fs.usda.gov/pubs/4686 (accessed on 10 July 2021).
7. Cohen, J.D.; Stratton, R.D. *Home Destruction Examination Grass Valley Fire*; Technical Paper, R5-TP-026b; Vallejo, C.A., Ed.; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 2008; 26p, Available online: https://www.fs.usda.gov/rmrs/publications/home-destruction-examination-grass-valley-fire-lake-arrowhead-california (accessed on 10 July 2022).
8. Quarles, S.L.; Valachovic, Y.; Nakamura, G.; Nader, G.; De LaSaux, M. Home Survival in Wildfire-Prone Areas: Building Materials and Design Considerations. *Agric. Nat. Resour.* **2010**, *8393*, 22. Available online: https://escholarship.org/uc/item/4vt8w5qk (accessed on 5 July 2022).
9. Manzello, S.L.; Shields, J.R.; Yang, J.C.; Hayashi, Y.; Nii, D. On the Use of a Firebrand Generator to Investigate the Ignition of Structures in Wildland-Urban Interface (WUI) Fires. In Proceedings of the Eleventh International Fire Science and Engineering Conference (INTERFLAM), London, UK, 3–5 September 2007. Available online: https://www.nwfirescience.org/sites/default/files/publications/f07081.pdf (accessed on 7 July 2022).
10. Manzello, S.L.; Foote, E.I.D. Characterizing Firebrand Exposure from Wildland–Urban Interface (WUI) Fires: Results from the 2007 Angora Fire. *Fire Technol.* **2014**, *50*, 105–124. [CrossRef]
11. Syphard, A.D.; Brennan, T.J.; Keeley, J.E. The Role of Defensible Space for Residential Structure Protection during Wildfires. *Int. J. Wildland Fire* **2014**, *23*, 1165–1175. Available online: https://www.publish.csiro.au/wf/wf13158 (accessed on 5 June 2022). [CrossRef]
12. Alcasena, F.J.; Salis, M.; Ager, A.A.; Castell, R.; Vega-Garcia, C. Assessing wildland fire risk transmission to communities in northern Spain. *Forests* **2017**, *8*, 30. [CrossRef]
13. Alexandre, P.M.; Stewart, S.I.; Keuler, N.S.; Clayton, M.K.; Mockrin, M.H.; Bar-Massada, A.; Syphard, A.D.; Radeloff, V.C. Factors related to building loss due to wildfires in the conterminous United States. *Ecol. Appl.* **2016**, *26*, 2323–2338. [CrossRef]
14. Syphard, A.D.; Brennan, T.J.; Keeley, J.E. The importance of building construction materials relative to other factors affecting structure survival during wildfire. *Int. J. Disaster Risk Reduct.* **2017**, *21*, 140–147. [CrossRef]
15. Syphard, A.D.; Keeley, J.E. Factors Associated with Structure Loss in the 2013–2018 California Wildfires. *Fire* **2019**, *2*, 49. [CrossRef]
16. California Wildland Hazard Building Code. (CBC). Available online: https://osfm.fire.ca.gov/divisions/community-wildfire-preparedness-and-mitigation/wildland-hazards-building-codes/ (accessed on 2 July 2022).
17. International Wildland–Urban Interface Code. (ICC). Available online: https://codes.iccsafe.org/codes/i-codes/2021-icodes (accessed on 25 June 2022).
18. FireWise Communities USA. (National Fire Protection Association). Available online: https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Wildfire/Firewise-USA (accessed on 2 July 2022).
19. FireSmart Canada. (BC FireSmart Committee). Available online: https://firesmartbc.ca/ (accessed on 18 July 2022).
20. FireSmart TM Home Ignition Home Assessment Card. Available online: https://firesmartbc.ca/wp-content/uploads/2021/04/FSC-CRI-Home-Ignition-Zone-Assessment-Score-Card-Fillable.pdf (accessed on 18 July 2022).
21. FireReady Australia. (Cooperative Community Led Emergency Ready Project). Available online: https://fireready.org.au/index.php (accessed on 22 July 2022).
22. FireSmart New Zealand. Partners in Protection—Protecting our Communities from Interface Fires (National Rural Fire Authority). Available online: https://gfmc.online/wp-content/uploads/Fire-Smart-New-Zealand.pdf (accessed on 28 September 2023).
23. Australian Standard. Construction of Buildings in Bushfire—Prone Areas. (The Council of Standards Australia). Available online: https://naturaldisaster.royalcommission.gov.au/system/files/exhibit/PTS.030.006.1352.pdf (accessed on 22 July 2022).
24. *AS 3959: 2020*; Construction of Buildings in Bushfire-Prone Areas. Council Standards of Australia: Sydney, Australia, 2020. Available online: https://hia.com.au/resources-and-advice/building-it-right/australian-standards/articles/construction-of-buildings-in-bushfire-prone-areas (accessed on 2 July 2022).
25. Diário da República, 1a Série(DRE) Portaria no. 135/2020, in Portuguese. Available online: https://dre.pt/dre/detalhe/portaria/135-2020-134991810 (accessed on 18 July 2022).
26. Cohen, J.D. Preventing Disaster-Home Ignitability in the Wildland-Urban Interface. *J. For.* **2000**, *98*, 15–21.
27. Mell, W.; Manzello, S.L.; Maranghides, A.; Butry, D.; Rehm, R.G. The wildland-urban interface fire problem—Current approaches and research needs. *Int. J. Wildland Fire* **2010**, *19*, 238–251. [CrossRef]

28. Federal Emergency Management Agency (FEMA). Home Builder's Guide to Construction in Wildfire Zones. Available online: https://www.fema.gov/media-library/assets/documents/15962 (accessed on 1 July 2021).
29. Ramsay, G.C.; McArthur, N.A.; Dowling, V.P. Building in a fire-prone environment: Research on building survival in two major bushfires. *Proc. Linn. Soc. NSW* **1996**, *116*, 133–140. Available online: http://hdl.handle.net/102.100.100/228186?index=1 (accessed on 25 July 2022).
30. *NFPA 1144*; Standard for Reducing Structure Ignition Hazards from Wildland Fire, 2018 Edition. NFPA National Fire Codes Online: Quincy, MA, USA, 2018.
31. Alexandre, P.M.; Stewart, S.; Mockrin, M.; Keuler, S.N.; Syphard, A.; Massada, A.B.; Clayton, M.K.; Radeloff, V. The relative impacts of vegetation, topography and spatial arrangement on buildings to wildfires in case studies of California and Colorado. *Landsc. Ecol.* **2016**, *31*, 415–430. [CrossRef]
32. Ganteaume, A.; Jappiot, M. Assessing the fire risk in the wildland-urban interfaces of SE France: Focus on the environment of the housing. In *Advances in Forest Fire Research*; Viegas, D.X., Ed.; UC Digitalis: Coimbra, Portugal, 2014; pp. 648–656.
33. Bikas, D.; Baniotopoulos, C. General Overview of the Problems, Needs and Solutions in the Greek Urban Building Envelopes. In *Improving the Quality of Existing Urban Building Envelopes*; Melgaard, E., Hadjimichael, G., Almeida, M., Verhoef, L.G.W., Eds.; IOS Press under the Imprint Delft University Press: Delft, The Netherlands, 2007; Volume 3, pp. 49–57. Available online: https://www.scribd.com/document/143812610/Improving-the-Quality-of-Existing-Urban-Building-Envelopes# (accessed on 1 June 2021).
34. Xanthopoulos, G. An Integral Planning and Management Challenge. In Proceedings of the 2nd International Workshop on Forest Fires in the Wildland-Urban Interface and Rural Areas in Europe, Athens, Greece, 15–16 May 2003.
35. Vieira, F.N.; Almeida, M.; Rodrigues, J.P.C.; Lopes, R.F.R. Study of Building Vulnerabilities to Forest Fires in Portugal. In Proceedings of the World Building Congress 2022, Melbourne, Australia, 27–30 June 2022; Available online: https://iopscience.iop.org/article/10.1088/1755-1315/1101/2/022022/meta (accessed on 5 January 2023).
36. *Ministerial Decision 3475/2023*; Regulation for Fire Protection of Properties within or in Proximity to Forest Areas. Greek Government Gazette: Athens, Greece, 2023; (In Greek). Available online: https://www.et.gr/api/DownloadFeksApi/?fek_pdf=20230203475 (accessed on 5 July 2023).
37. Green, L. *Fuelbreaks and Other Fuel Modification for Wildland Fire Control*; US Department of Agriculture, Forest Service, Agricultural Handbook: Washington, DC, USA, 1977; Available online: https://www.fs.usda.gov/psw/publications/documents/usda_series/usda_ah499.pdf (accessed on 5 June 2022).
38. Oliveira, T.M.; Barros, A.M.G.; Ager, A.A.; Fernandes, P.M. Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. *Int. J. Wildland Fire* **2016**, *25*, 619–632. [CrossRef]
39. Pereira, J.M.C.; LePage, Y. *Optimizing the Design of Portugal's Primary Fuelbreak Network*; Lisbon, Portugal, 2019.
40. Aubard, V.; Pereira-Pires, J.E.; Campagnolo, M.L.; Pereira, J.M.C.; Mora, A.; Silva, J.M.N. Fully automated countrywide monitoring of fuel break maintenance operations. *Remote Sens.* **2020**, *12*, 2879. [CrossRef]
41. Aparício, B.A.; Alcasena, F.; Ager, A.; Chung, W.; Pereira, J.M.C.; Sa, A.C.L. Evaluating priority locations and potential benefits for building a nation-wide fuel break network in Portugal. *J. Environ. Manag.* **2022**, *320*, 115920. [CrossRef] [PubMed]
42. *2023-EMSR686*; Fire in the Regional Unit of Evros—Cartographic Products and Data from Copernicus Emergency Management Service (EMS). Ministry for Climate Crisis and Civil Protection: Marousi, Greece, 2023. Available online: https://civilprotection.gov.gr/copernicus/2023-emsr686-pyrkagia-stin-perifereiaki-enotita-ebroy-hartografika-proionta-kai-dedomena (accessed on 31 August 2023).
43. *2023-EMSR675*; Fire in Rhodes—Cartographic Products and Data from Copernicus Emergency Management Service (EMS). Ministry for Climate Crisis and Civil Protection: Marousi, Greece, 2023. Available online: https://civilprotection.gov.gr/copernicus/2023-emsr675-pyrkagia-sti-rodo-hartografika-proionta-kai-dedomena-kata-tin-exelixi-tis (accessed on 10 August 2023).
44. Kalabokidis, K.; Vaitis, M.; Palaiologou, P.; Tataris, G.; Retsilidou, O.; Chatzopoulos, I. Geographical Data Base of Rhodes Island for Achieving Risk Management. In Proceedings of the Safe Rhodes 2014—1st International Conference on Civil Protection & New Technologies, Rhodes, Greece, 24–26 October 2014. (In Greek).
45. Georgakopoulou-Vogiatzi, C. *Ornamental Outdoor Plants*; Gartaganis Printing & Publishing Company: Thessaloniki, Greece, 2008. (In Greek)
46. Hellenic Statistical Authority (ELSTAT). Available online: https://www.statistics.gr/en/2021-census-pop-hous (accessed on 2 January 2023).
47. Papathoma-Köhle, M.; Schlögl, M.; Garlichs, C.; Diakakis, M.; Mavroulis, S.; Fuchs, S. A wildfire vulnerability index for buildings. *Sci. Rep.* **2022**, *12*, 6378. Available online: https://www.nature.com/articles/s41598-022-10479-3 (accessed on 5 December 2022). [CrossRef]
48. Finney, M.A. An Overview of FlamMap Fire Modeling Capabilities. In *Fuels Management—How to Measure Success: Conference Proceedings, Proceedings of the RMRS-P-41, Portland, OR, USA, 28–30 March 2006*; Andrews Patricia, L., Butler Bret, W., Eds.; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2006; pp. 213–220. Available online: https://www.fs.usda.gov/research/treesearch/25948 (accessed on 5 June 2022).
49. Finney, M.A. Fire Growth Using Minimum Travel Time Methods. *Can. J. For. Res.* **2002**, *32*, 1420–1424. [CrossRef]

50. Palaiologou, P.; Kalabokidis, K.; Ager, A.A.; Day, M.A. Development of comprehensive fuel management strategies for reducing wildfire risk in Greece. *Forests* **2020**, *11*, 789. [CrossRef]
51. Kalabokidis, K.; Palaiologou, P.; Finney, M.A. Fire Behavior Simulation in Mediterranean Forests Using the minimum Travel Time Algorithm. In Proceedings of the 4th Fire Behavior and Fuels Conference—At the Crossroads: Looking Toward the Future in a Changing Environment, St Petersburg, Russia, 1–4 July 2013. Available online: https://www.fs.usda.gov/research/treesearch/47012 (accessed on 15 June 2022).
52. Scott, J.H.; Burgan, R.E. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model*; Rocky Mountain Research Station: Fort Collins, CO, USA, 2005; p. 72. Available online: https://www.fs.usda.gov/rm/pubs/rmrs_p041/rmrs_p041_169_184.pdf (accessed on 17 June 2022).
53. Vaillant, N.M.; Ager, A.A. *ArcFuels10 Tutorial Supplemental Information*; Western Wildland Threat Assessment Center Internal Report; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2012; 186p, Available online: https://www.fs.usda.gov/wwetac/tools/arcfuels/downloads/ArcFuels10_SupplementalInfomation.pdf (accessed on 5 June 2022).
54. Ager, A.A.; Bahro, B.; Barber, K. Automating the Fireshed Assessment Process with ArcGIS. In *Fuels Management—How to Measure Success: Conference Proceedings, Proceedings of the RMRS-P-41, Portland, OR, USA, 28–30 March 2006*; Andrews, P.L., Butler, B.W., Eds.; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Portland, OR, USA, 2006; pp. 163–168. Available online: https://www.fs.usda.gov/rm/pubs/rmrs_p041/rmrs_p041_163_168.pdf (accessed on 5 July 2022).
55. Vacca, P.; Caballero, D.; Pastor, E.; Planas, E. WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level. *J. Saf. Sci. Resil.* **2020**, *1*, 97–105. [CrossRef]
56. Kalabokidis, K.D.; Omi, P.N. Reduction of fire hazard through thinning/ residue disposal in the urban interface. *Int. J. Wildland Fire* **1998**, *8*, 29–35. [CrossRef]
57. Puchovsky, M.; Simeoni, A.; Han, E.; Parrow, D.; Rozen, A. *The Feasibility of Protecting Residential Structures from Wildfires Using a Fixed Exterior Fire Fighting System*; Worcester Polytechnic Institute (WPI): Worcester, MA, USA, 2020.
58. *EN 16925*; Fixed Firefighting Systems. Automatic Residential Sprinkler Systems. Design, Installation and Maintenance. BSI Standards Publications: London, UK, 2018. Available online: https://www.thenbs.com/PublicationIndex/documents/details?Pub=BSI&DocID=326782 (accessed on 15 December 2022).
59. *EN 12845:2015/AC 2016*; Fixed Firefighting Systems—Automatic Sprinkler Systems—Design, Installation and Maintenance. European Committee for Standardization: Vienna, Austria, 2016. Available online: https://isrsm.gov.mk/en/project/show/isrsm:proj:54773 (accessed on 15 December 2022).
60. *NFPA 13*; Standard for the Installation of Sprinkler Systems. NFPA National Fire Codes Online: Quincy, MA, USA, 2022. Available online: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13 (accessed on 15 December 2022).
61. *NFPA 13D*; Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes. NFPA National Fire Codes Online: Quincy, MA, USA, 2022. Available online: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13D (accessed on 15 December 2022).
62. *Technical Guide 2451/1986*; Installations in Buildings, Permanent Water Fire Extinguishing Systems. Technical Chamber of Greece: Athens, Greece, 2000; (In Greek). Available online: https://web.tee.gr/wp-content/uploads/totee_2451_86.pdf (accessed on 20 December 2022).
63. *EN 14384:2005*; Pillar Fire Hydrants. European Committee for Standardization: Vienna, Austria, 2005. Available online: https://shop.standards.ie/en-ie/standards/EN-14384-2005-347184_SAIG_CEN_CEN_793681/ (accessed on 20 December 2022).
64. *EN 15182*; Portable Equipment for Projecting Extinguishing Agents Supplied by Firefighting Pumps-Hand-Held Branchpipes for Fire Service Use. European Committee for Standardization: Vienna, Austria, 2019. Available online: https://infostore.saiglobal.com/preview/538915342905.pdf?sku=883391_SAIG_NSAI_NSAI_2775656 (accessed on 20 December 2022).
65. *NFPA 1964*; Standard for Spray Nozzles and Appliances. NFPA National Fire Codes Online: Quincy, MA, USA, 2018.
66. *NFPA 1965*; Standard for Fire Hose Appliances, 2014 Edition. NFPA National Fire Codes Online: Quincy, MA, USA, 2014.