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An Evaluation of Wildfire Vulnerability in the Wildland–Urban Interfaces of Central Portugal Using the Analytic Network Process

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Abstract: Vulnerability assessment is a vital component of wildfire management. This research focuses on the evaluation of wildfire vulnerability in the Central Region of Portugal, an area historically affected by catastrophic fire events. The overall methodology entailed applying an analytical hierarchy process (AHP) to the relevant spatial variables for evaluating vulnerability associated with exposure, sensitivity, and response capacity at landscape and the wildland–urban interface (WUI) scale. Of the selected criteria, the existence of fuel in direct contact with built-up areas, population density, and firefighters' travel time were considered the most important criteria for inclusion in the vulnerability map. At landscape scale, 31% of the Central Region presents high and very high classes of vulnerability, while 22% of WUIs are classified as highly vulnerable to fire. Although the inland areas emerge as the most vulnerable, this approach enables scattered vulnerable hotspots to be identified in almost all of the Central Region. The results could be very helpful in terms of developing and enhancing local policies to mitigate human and material damage.

Keywords: vulnerability; wildfires; urban interface; analytical hierarchy process; central Portugal

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1. Introduction

Wildfires (whether occurring naturally or caused by human action) are one of the most serious hazards for human societies and forest wildlife [1–4]. In various regions of Europe, the incidence and severity of large, destructive wildland fires are increasing [5,6]. Causes include ongoing changes in land use such as the decline in farming activities and on the exploitation of timber and wood resources [7,8], increasing vulnerability in the wildland–urban interface, and climate change [9]. Climate projections suggest significant warming and a rise in the intensity and number of heatwaves, droughts, and dry spells across most of southern Europe, thereby increasing both the length and severity of the fire season [10–12].

When wildfires occur in the vicinity of settlements where a human–nature interface is being created due to the proximity of flammable vegetation, the consequences from a human perspective are far more severe [13,14]. Hence, greater attention is being paid to the wildland–urban interface (WUI) [15–18] following recent disastrous fires that have affected these areas in Greece (2007 and 2018), Russia (2010), and Portugal (2017), which had devastating consequences for human lives and property. In 2017, Portugal suffered the deadliest WUI fires in its history, which caused around 110 deaths and severely damaged thousands of buildings, including industrial facilities [19,20].

In fact, wildfires at WUIs are complex phenomena [15] that present huge management challenges when it comes to fire mitigation and civil protection because of the exposed communities, houses, infrastructure, and ecosystems. These wildfires often exceed firefighters' capacities, since they have to respond simultaneously to fire control, protection of structures, and community evacuation. This means that assessing vulnerability is of paramount importance to wildfire management as this can identify areas of high concern in terms of the potential impact of wildfire, which helps to support decisions and policies designed to reduce human and economic loss.

Vulnerability is, however, a multifaceted concept which can be described in many ways [21,22]. It involves the likely impacts of a stochastic event, i.e., hazard [23], comprising damage and consequences for people, infrastructure, and ecosystems [24,25]. Variables such as age, level of education, income, gender, health, and the robustness of social organisations that enhance coping capacity have all been shown to determine the vulnerability of individuals to different hazards [26–28].

It is also widely accepted that vulnerability to a given hazard is geographically distributed according to the circumstances that collectively affect the likelihood of exposure [29]. For example, people living in rural and woodland settings are more exposed to wildfires than those living in urban neighbourhoods, since rural housing is close to the source of danger, e.g., flammable forests and shrubland. Even when the levels of exposure remain constant, not all people are affected by a wildfire disaster in the same way: some are more vulnerable than others. This vulnerability component (i.e., social vulnerability) is related to economic, social, and cultural factors which provide or constrain access to information and material factors, thus exacerbating simple exposure to hazard; these factors have been receiving increasing attention from academics in recent decades [18,30–33]. Even though social vulnerability to natural hazards is important in decreasing the risk of wildfires and improving policies to reduce the impact on humans [34–36], spatial variation in risk is not only related to socioeconomic variables but is also associated with a community's capacities to plan for, comply with, respond to and resist harmful events [37].

Several authors have carried out studies aimed at operationalizing vulnerability in order to determine the populations most susceptible to hazards, identify the components that contribute to hazardous conditions, or develop potential adaptation policies that reduce the possibility of future impacts [38,39]. Most of the literature identifies three main components of vulnerability, which interact to create potential impact patterns: (i) exposure, associated with the presence of assets (people, property, ecosystems) in areas where wildfires may occur [23,40–42]; (ii) sensitivity, related to the extent to which assets may be impacted by a wildfire, which is associated with their susceptibility to certain types and magnitudes of losses [23,40–42]; (iii) coping capacity, associated with measures applied to anticipate the potential effects or the capacity of populations to adapt in ways that diminish their exposure or sensitivity and thus reduce future effects [23,32,43–45], based on institutional practices within the various different countries. Vulnerability is also a changing process that varies over space, time, and scale [46–48].

As an example, Oliveira et al. [23] evaluated and mapped vulnerability for different Mediterranean areas (Minho region, Portugal, SW Sardinia, and NE Corsica), incorporating factors of exposure, sensitivity, and coping capacity. Following a stepwise approach, the results showed the influence of fuel sensitivity levels, population distribution and the presence of areas with protection status for the overall vulnerability classes. For the Central Region of Portugal, Bergonse et al. [17] analysed the wildfire risk at parish level, based on three factors: hazard, exposure, and vulnerability. The number of inhabitants and residential buildings in each parish were used to determine the exposure whilst social vulnerability was based on two components: criticality, related to personal characteristics, which are associated to vulnerability and to the potential for recovery (e.g., age, employment, housing conditions, and mobility). The importance of each component in the level of risk, assessed by a cluster analysis, showed the highest values of wildfire risk are concentrated in the centre–south sector of the study area, with high-risk parishes also dispersed in the northeast.

Farinha et al. [49] also investigated the social component of vulnerability for the parishes of the sub-region Pinhal Interior Sul (also located in Central Portugal), associating demographic, cultural, socio-economic, and infrastructural conditions to establish a comparative analysis between the more urban and rural parishes. Based on a principal component analysis (PCA), the results demonstrated that the population living in more markedly rural and peripheral parishes is more vulnerable to forest fires than those living in the more urban conditions.

Within a civil parish in Central Portugal, Oliveira et al. [50] assessed wildfire risk specifically for human settlements (villages) combining burn probability scenarios with exposure and vulnerability levels. The latter was based on the social characteristics of the resident population whilst coping capacity factors integrated the time required to reach a potential fire shelter and the distance of each village to the nearest fire station. The results obtained for each risk component were ranked with a hierarchical cluster analysis.

As is shown, multiple components/variables and methodologies can be used to evaluate wildfire vulnerability of a specific area since different phenomena occur at different scales: from the macroscale or landscape scale, the mesoscale or the settlement scale, and the microscale or home-owner scale [14,51].

The main objective of this study was to evaluate wildfire vulnerability in the Central Region of Portugal at the landscape and WUI scales. To achieve this aim, the overall methodology involved establishing a database, which includes the relevant spatial variables for evaluating vulnerability (exposure, sensitivity, and response capacity), at subsection and WUI, and implementing an analytical hierarchy process (AHP), using expert choice techniques to calculate the weighting for the relative importance of the criteria before applying the weighted-sum method (WSM). In this work, we employ a new detailed scaled approach, the WUI scale, and explore a new methodology based on the viewpoints of the multi-stakeholders to characterise wildfire vulnerability in the central region of Portugal. Expert opinion-based multi-criteria analysis and modelling (MCM) has been widely employed to determine vulnerability indices [52–56] and aims at "objectivising" the experience and knowledge of experts, involving academics, firefighters and land and forest managers, in order to rank the vulnerability criteria by assigning a quantitative weight to each one [57]. The final goal was to produce maps that identify the WUIs with high and very high wildfire vulnerability, i.e., where populations and assets are more liable to damage.

2. Material and Methods

2.1. Study Area

The Central Region of Portugal includes 100 municipalities and covers an area of 28,199 km^2 (Figure 1). The population density varies and there are significant morphological contrasts and heterogeneous climate features. It is also highly susceptible to wildfires [8,58]. In the period 1980–2020, a total of 2,481,712 hectares were burnt in the Central Region, i.e., an annual average of 62,000 hectares, amounting to more than half of the 120,000 hectares registered for the national average.

The map in Figure 1, which shows overlapping burnt areas from 1975 to 2020, confirms that the Central Region has been severely affected by wildfires, in more mountainous areas, as well as in the northern and northeastern countryside municipalities. Indeed, fire has impacted a significant part of the territory at least once (20.7%), although there are extensive areas that have been ravaged by fire 2 or 3 times in recent years (18.8%) and it is also possible to identify areas that have been burnt 6 or more times in the last 40 years. It should also be noted that the fires in 2003 (425,000 ha), 2005 (338,000 ha), and 2017 (540,000 ha) mostly affected the Central Region and several areas of wildland urban interface, with catastrophic effects on some areas. In June 2017, 66 civilian fatalities were recorded in the Pedrógão Grande fire in Central Portugal and a further 253 people were injured. This catastrophe saw more than 450 houses destroyed and over 49 companies were directly affected by the fire. In total, 53,000 hectares of land burnt, including 20,000 hectares of forest [19]. In October of the same year, also in the centre of Portugal, 41 people died after over 500 fires broke out, caused by extremely dry conditions and strong winds from Hurricane Ophelia, and more than 800 houses and 500 companies were affected [20].

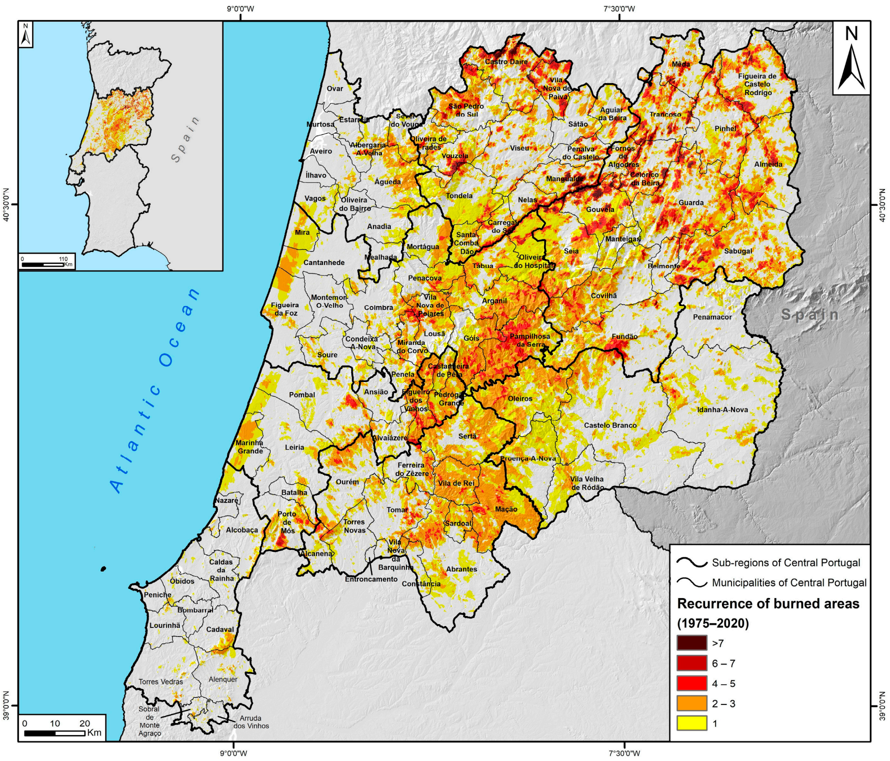

Figure 1. Recurrence of burnt areas between 1975 and 2020.

The WUI map presented in Figure 2 is an adaptation of the built environment map (2018) and the urban–rural interface map (2018) (Carta de áreas edificadas 2018 and Carta da interface urbano-rural de 2018), produced by the Direção Geral do Território [58]. In accordance with these maps, the WUI is defined as an area where structures and wildland vegetation are in direct contact or in close proximity, separated by a clearly defined boundary [4]. It represents the perimeter (segment) of the built area, classified according to its proximity to fuel (wildland vegetation). Two main types of contact are identified: (i) direct interface segments that are in direct contact with the fuel cover, meaning that built-up areas are in direct contact with fuel; and (ii) indirect interface segments or built-up areas that are from 1 to 500 m away from the fuel cover. (i) dense forests of eucalyptus, maritime pine and other coniferous trees, as well as areas of high to medium density of cork oak and holm oak; (ii) open forests, with areas of low to medium density of cork oak and holm oak, stone pine, with herbaceous cover; (iii) scrubland; and (iv) spontaneous herbaceous vegetation.

Thus, the WUI in Central Portugal is 60,373 km long [59], 15,000 km of which are built-up areas in direct contact with fuel. The predominant typology is discontinuous built-up area (80.6%), followed by continuous built-up area (13.1%) and industry (6.3%). In Figure 2, the spatial contrasts that can be observed between the coastal municipalities, which have a greater population density, and those in the inland, which have low-density and aged populations as a consequence of the recent demographic trends characterised by significant rural depopulation and the abandonment of farming and forest. The municipalities most affected by these trends, which have the lowest interface ratio (km/km^2), are in the central, northern inland, and mountain areas and include 14 municipalities with less than 1 km of interface/km^2. Conversely, the highest values for interface density can be found in the coastal areas, where 15 municipalities register more than 4 km of WUI/km^2.

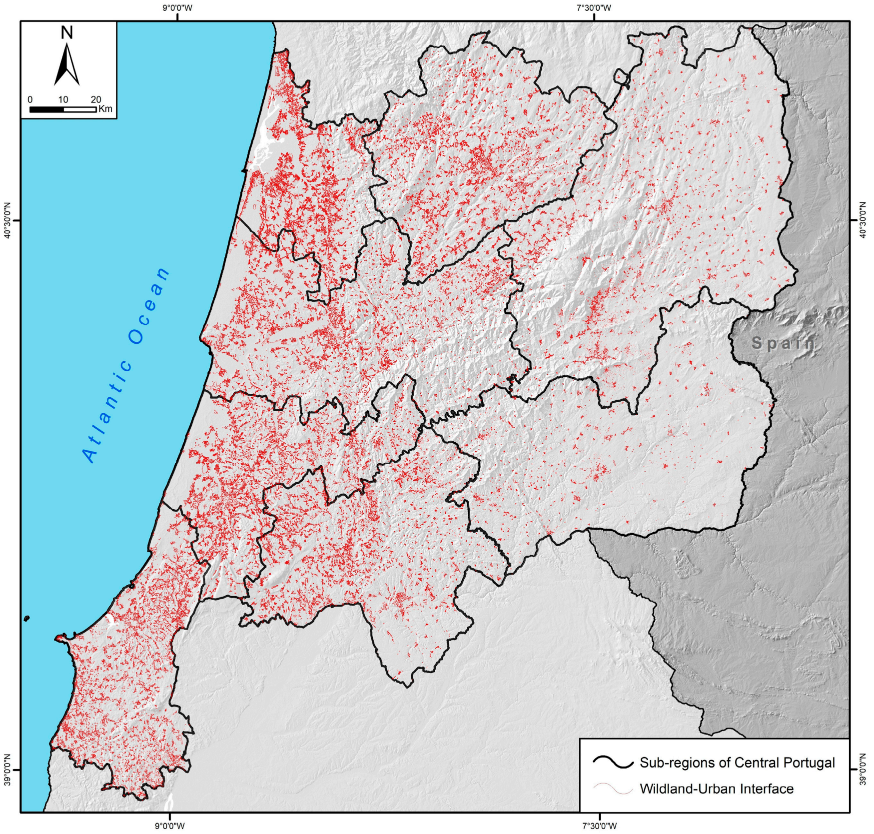

Figure 2. WUIs in Central Portugal [Adapted from: 58].

2.2. Variables and Data Collection

In accordance with the above premises, estimating WUI vulnerability to wildfires requires information on three main components: (i) exposure, associated with the presence of people, property, and ecosystems; (ii) sensitivity, associated with the likelihood that the population and assets will suffer certain types and values of losses; (iii) response capacity, associated with the measures applied to respond in the event of a fire. The selection of the variables to include in the vulnerability assessment was based on previous studies that either show empirically or argue theoretically that certain factors influence wildfire vulnerability (Table 1). Socioeconomic data associated with exposure and sensitivity were obtained from the Census, provided by the Instituto Nacional de Estatística (Statistics Portugal) [60], at the statistical subsection level. The statistical subsection is the territorial unit that identifies the smallest homogenous built-up or undeveloped area within a given statistical section. It corresponds to a block in urban areas, a settlement or part of a settlement in rural areas, or areas which may or may not contain (isolated) statistical units. For the selected variables, Pearson correlation coefficients were then used to determine collinearity between the variables and discard those that are highly correlated. A correlation coefficient threshold of $|r| > 0.7$ ($p < 0.05$) between predictor variables was used as reference, considering that is assumed as the point at which collinearity starts to severely bias the model estimation and subsequent forecast [61].

Regarding sensitivity, another variable directly related to WUIs was included, namely the total number of kilometres of combustible vegetation in direct contact with built-up areas. The total number of kilometres of WUI in direct contact with combustible vegetation was obtained from the Urban-Rural Interface Charter (2018) produced by the Direção Geral do Território (DGT), cross-referenced with the 2018 Land Use and Land Cover Map, also produced by the same institution. After identifying the areas in direct contact with combustible vegetation, only forests and woodland areas were considered since several studies carried out in Mediterranean regions have found that shrubland and coniferous forests are more prone to fire than cropland and broadleaf forests [62,63]. In order to "crop" the direct contact areas, a 10-metre buffer zone was created for both classes of combustible vegetation, followed by a clip of the direct contact zones.

Table 1. Variables selected.

Components	ID	Variables	Source/Year	Unit/Scale	Previous References
Exposure	1	Population density (no. of people/ km^2)	BGRI, 2011 (Statistics Portugal)	Subsection	[23,49,50,64–66]
	2	Building density (no. buildings/km^2)	BGRI, 2011 (Statistics Portugal)	Subsection	[17,23,50,64–67]
	3 *	Percentage of buildings with 1 or 2 floors	BGRI, 2011 (Statistics Portugal)	Subsection	[17]
Sensitivity	4	Youth index (% Population < 14 years)	BGRI, 2011 (Statistics Portugal)	Subsection	[23,49,50,65]
	5	Ageing Index (% of Population > 64 years)	BGRI, 2011 (Statistics Portugal)	Subsection	[17,23,49,50,57,64,65,67,68]
	6	Unemployment Rate (%)	BGRI, 2011 (Statistics Portugal)	Subsection	[49,57,65,68]
	7	Fuel in direct contact with built-up areas (km/subsection)	Statistics Portugal, 2018; DGT, 2018	Subsection	[15]
Response capacity	8	Accessibility/ Firefighters' travel time (minutes)	ESRI, with adaptations based on OSM	10 × 10 m	[23,57,64,65]
	9	Ratio of firefighters to fuel in direct contact with built-up areas (no. Firefighters/ km)	Statistics Portugal, 2018; DGT, 2018	Municipality	[7,17,18]

* Refers to the percentage of buildings with 1 or 2 floors, usually isolated that mainly house one-family, in opposition to taller buildings.

Two variables were also incorporated for response capacity: the first refers to the total number of firefighters in relation to the WUI area (no. firefighters/km of WUI), while the second is related to the travel time of the intervention units, taking the geographical locations of the fire stations as reference points.

For the "Firefighters' travel time" variable, it was necessary to gather information on the Central Region road network and the location of the fire stations. The former was taken from open street maps and the latter requested from the various District Centres for Relief Operations (CDOS) in the Central Region and later checked using Open Street Maps. The "Service Area" function of the Network Analyst tool was used to calculate the travel time. This function considers the locations of the fire stations as "facilities" and, using the road network, draws isochrones which map the relationships between three criteria: distance, accessibility, and time. For this purpose, 60 one-minute intervals were defined between each isochrone. These variables were produced in a GIS (ArcGIS, 10.8) environment. The variables selected for the study are presented in Table 1.

Since each of the variables was measured for a distinct unit, it was necessary to normalise each one as an index value. The following Equation (1) was applied, with values varying between 0 and 1:

$$\mathrm{Norm}(\mathrm{var}\ 0\text{–}1) = \mathrm{var}(\mathrm{value}) - \min(\mathrm{var})/\max(\mathrm{var}) - \min(\mathrm{var})$$

in which Norm (var 0–1) is the resulting normalised value on a scale 0–1; var(value) is the initial value of the variable defined for the study unit (subsection or municipality); min(var) and max(var) are respectively the lowest and highest values for the variable registered in Portugal at Central Region level.

2.3. Weighting Different Thematic Layers Using AHP

Assigning weights to different variables for a composite index has long been a contentious topic due to the pros and cons associated with various approaches. In the literature, several methodologies have been employed to weight indicators, including econometric modelling, revealed weights [67], factor analysis, principal component analysis, multiple regression models, distance to target, the analytic hierarchy process, expert judgment, the multicriteria decision approach and endogenous weighting [69]. Of the methodologies mentioned, PCA was the predominant method used to weight critical factors [70], although the analytical hierarchy process (AHP) has proved to be well suited to solving complex decisions with multiple criteria. For example, the analytical hierarchy process has been used for suitability mapping for flooding [71,72], soil erosion [73,74] landslide mapping [75], and wildfire risk analysis [76–79]. In this context, for the Central Region of Portugal, the evaluation of vulnerability to fire was based on the application of an analytic hierarchy process. This multi-criteria decision analysis (MCDA) approach uses the expert choice technique, and the decision was based on the lack of dependent variables usually explored with PCA approaches, in particular the burnt area; that was discarded because of the lower frequency of wildfires in WUI areas, very likely leading to an underestimation of vulnerability to fire. Higher values of these around large urban areas could promote a spatially biased analysis. In this study, four academic experts, two civil protection experts, and one forestry engineer expert weighted each of the variables included in the prediction of vulnerability to wildfires.

The AHP introduced by Saaty [80,81] is a mathematical procedure to analyse complex decision-making issues using multiple criteria. It should help decision makers identify the most relevant thematic layers and the weight of each variable for prediction. It is a decision-added method that generates relative ratio scales for paired comparison [82]. In this study, AHP-based pairwise comparison matrices were constructed between distinct thematic layers at each level of the hierarchy. A standard Saaty 1–9 scale (Table 2) was applied to define the intensity of importance for all variables and their respective features, in which '1' represents "equal importance" between the two themes, and '9' represents the "extreme importance" of one variable when compared to the other [81].

Table 2. Scale for a pairwise comparison matrix.

Scale	Intensity of Importance
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

In AHP, complex decisions are broken down into a hierarchical structure by applying a series of pairwise comparisons with the aim of comparing the relative importance between two layers. The weights of each layer were determined using the principal eigenvector of the square matrix to scale each criterion (Table A1). The normalised relative weight was then calculated by dividing each element of the pairwise matrix (scaling) by the sum of its column (Table A2). The higher the weights the greater the influence of the criteria on vulnerability to wildfire.

AHP includes a helpful method for examining the reliability of the decision maker's evaluations, which helps to reduce bias in the decision-making procedure. Thus, a consistency ratio (CR) (Equation (3)) was calculated as the ratio of the consistency index (CI)

(Equation (2) to a random index (RI) (Table 3). That is the average CI of sets of judgments (from a 1 to 9 scale) for randomly generated reciprocal matrices.

Table 3. Average random consistency index (RI).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0	0	0.53	0.90	1.12	1.24	1.32	1.41	1.45

The equations used for calculating the degree of consistency are shown below:

$$\text{Consistency Index (CI)} = \lambda\text{max} - \text{n}/\text{n} - 1 \tag{1}$$

where CI = consistency index, λmax is the maximum eigenvalue, n = number of criteria.

$$\text{Consistency ratio (CR)} = \text{CI}/\text{RI} \tag{2}$$

where RI = random inconsistency, according to the values of the Table 3.

According to Saaty, when the value of the consistency ratio (CR) is less than or equal to 0.10, the inconsistency is acceptable [80–82]. All procedures were carried out through MCDA using AHP, developed by Goepel [83] and available at https://bpmsg.com/ahp/ (accessed on 2 January 2022).

Each criterion (selected variable) was then assigned a specific value based on fire sensitivity, ranging from 0 (very low fire vulnerability) to 1 (very high fire vulnerability). Maps were created for the most important criteria using a raster calculator function in ArcGIS software, based on the weighted values of each criterion for each pixel.

2.4. Assignment of the Weighted Sum Method for the Wildfire Vulnerability Map

After ranking each criterion, wildfire vulnerability at landscape level was estimated by the weighted sum method. This method combines all the different thematic layers and the results of all the attributes and obtains the total scores by using Equation (4) [84]:

$$A^{\text{weighted sum}} = a_1 A_1 + b_2 B_2 + \ldots a_y A_Y \tag{3}$$

In Equation (4), $A^{\text{weighted sum}}$ is the general objective function, while a_y is the weighting factor for the individual criteria function A_y. This method scales multiple objectives into an aggregated scalar objective function by first attributing a weighting factor to each objective function and then adding up all the contributions to obtain the overall objective function. The values obtained (scale 0–1) for the final vulnerability map (landscape scale) were classified into 5 classes: 0–0.2 (very low); 0.2–0.4 (low); 0.4–0.6 (moderate); 0.6–0.8 (high); 0.8–1 (very high).

Finally, in order to identify the contact perimeters between WUI and vulnerability classes at landscape scale, the WUIs were cross-referenced with the final vulnerability raster map, thus enabling the interfaces segments that are most problematic in terms of wildfire vulnerability to be located.

3. Results

3.1. Weighting Wildfire Vulnerability by Criteria

Table 4 presents the weighting for each of the wildfire vulnerability criteria based on the AHP approach. The WUI zones in direct contact with fuel continuity (in km), population density, and firefighters' travel time were considered the most important criteria, with weightings of 17.8%, 16.8%, and 16.3%, respectively. The ageing index (14.4%) and the ratio of firefighters to WUI directly exposed to fuels (12.3%) were also highlighted by the experts, while the youth index (4.5%) and unemployment rate (2.5%) were undervalued as criteria for evaluating vulnerability to wildfires. The CR for all pairwise comparison criteria was 0.02, thus providing acceptable consistency.

Table 4. Weighting for wildfire vulnerability criteria.

Criteria	AHP Weight (%)	Final Weighting (0–1)	Weighting Sign
Population density (PD)	16.8	0.191	+
Building density (BD)	10.1	0.116	+
Percentage of buildings with 1 or 2 floors (PB12F)	5.3	ni	
Youth index (YI)	4.4	ni	
Ageing index (AI)	14.4	0.164	+
Unemployment rate (UnR)	2.5	ni	
Fuel in direct contact with built-up areas (in km) (FDCBA)	17.8	0.202	+
Ratio of firefighters to fuel in direct contact (RFFDC)	16.3	0.185	+
in direct contact with fuel (RFFWUI)	12.3	0.142	−

ni = not included.

Hence, the wildfire vulnerability map for Central Portugal was produced by performing an additive weighting of the six most important criteria (AHP > 10%) using the Equation (5):

$$\text{Vulnerability} = [(0.191 \times \text{PD}) + (0.116 \text{ x } \text{BD}) + (0.164 \times \text{AI}) + (0.202 \times \text{FDCBA}) + (0.185 \times \text{FFTT})] - (\text{RFFDC} \times 0.142) \quad (4)$$

3.2. Spatial Variability of Selected Criteria

About one-third of the Central Region has no resident population (Figure 3). In general, the highest population and building densities (Pearson's correlation = 0.55), considering the subsection level, are concentrated in the coastal areas whilst in the mountainous and inland areas of the Central Portugal, population and building densities are low and present a scattered pattern in the territory (Figures 3 and 4). In these areas, the predominant typology is discontinuous built-up area, which corresponds, according to the specifications of the Land Cover Map (2018), to isolated residential buildings. The inland and mountainous areas of Central Portugal also have the highest percentages of elderly residents (Figure 5).

Despite the high spatial dispersion of fuel in direct contact with built-up areas (in km), it can be seen that the largest extensions occur in the most mountainous areas of the centre and north of the Central Region, although it is worth noting some patches with high contact extension in coastal sections (Figure 6).

The larger number of fire brigades associated with the availability of human resources to cope with fire events represented by the ratio of firefighters in relation to fuel in direct contact with built-up areas-located in coastal municipalities together with a greater density of road networks and a flat or slightly uneven topography, allows for a maximum response time of 20 min in a forest fire scenario (Figures 7 and 8). Conversely, in mountainous and inland municipalities with fewer fire brigades (less than 1 firefighter per km of WUI in direct contact with fuel) and a more rugged topography, such as Castelo Branco, Idanha-a-Nova, Covilhã and Almeida, the timing usually ranges between 20 and 40 min.

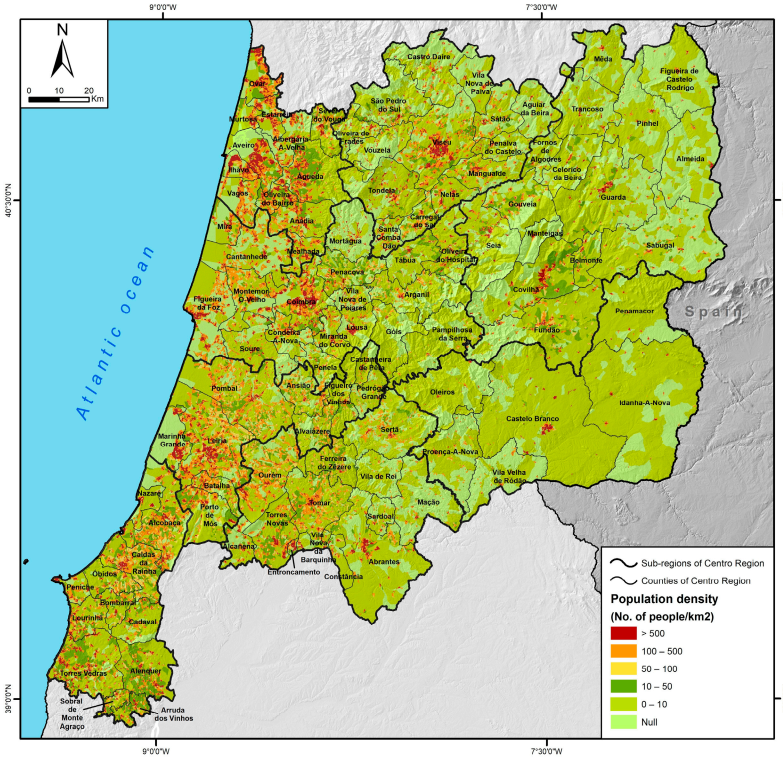

Figure 3. Population density at subsection level.

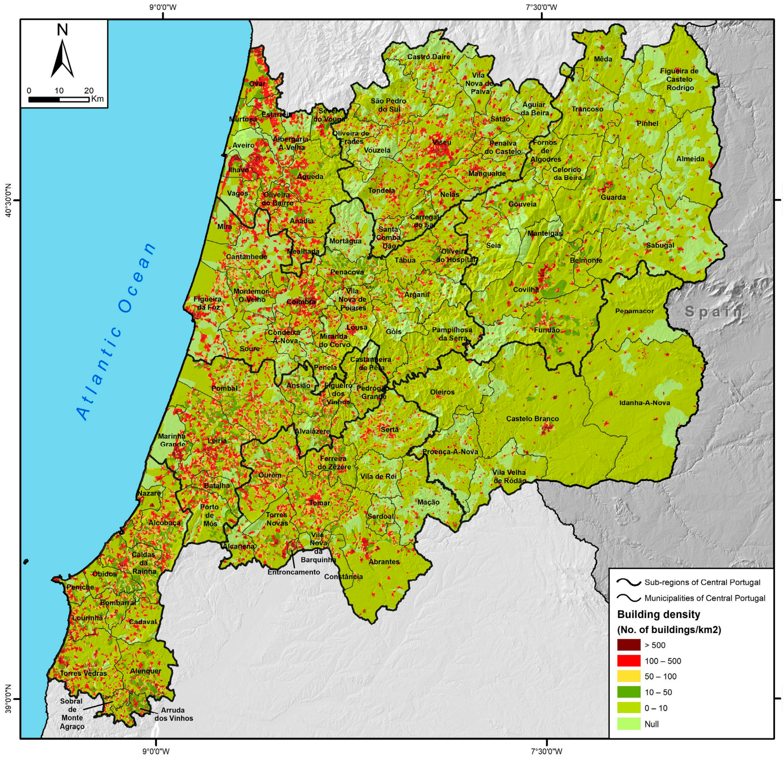

Figure 4. Spatial variability in building density at subsection level.

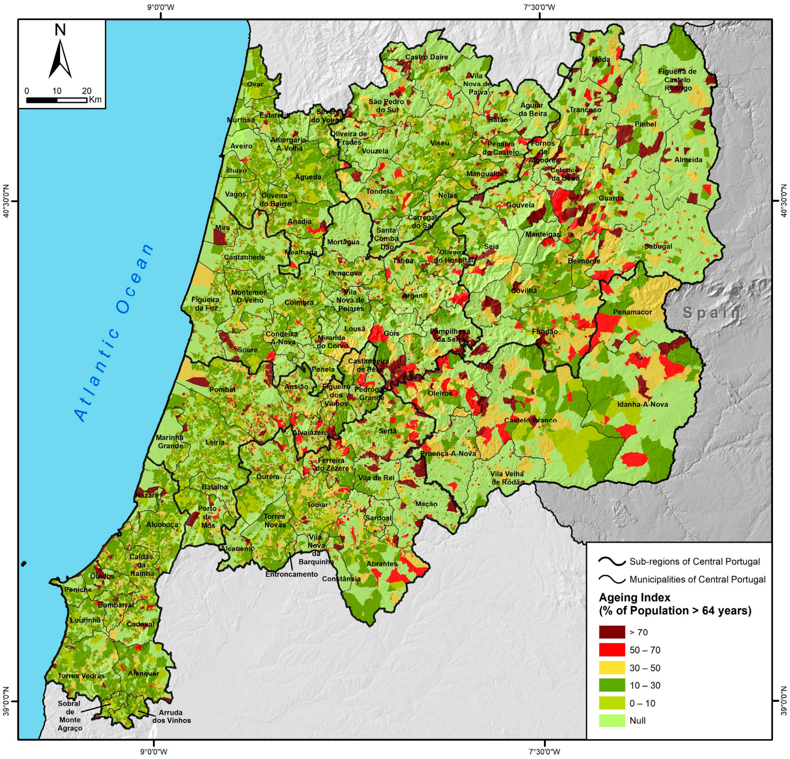

Figure 5. Spatial variability in the ageing index at subsection level.

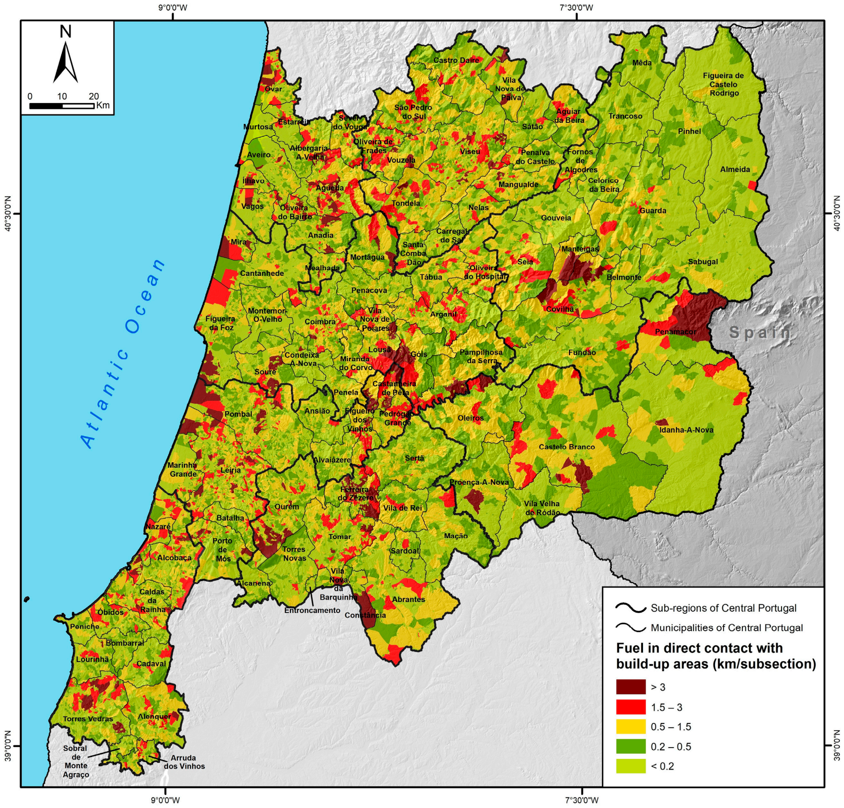

Figure 6. Fuel in direct contact with built-up areas.

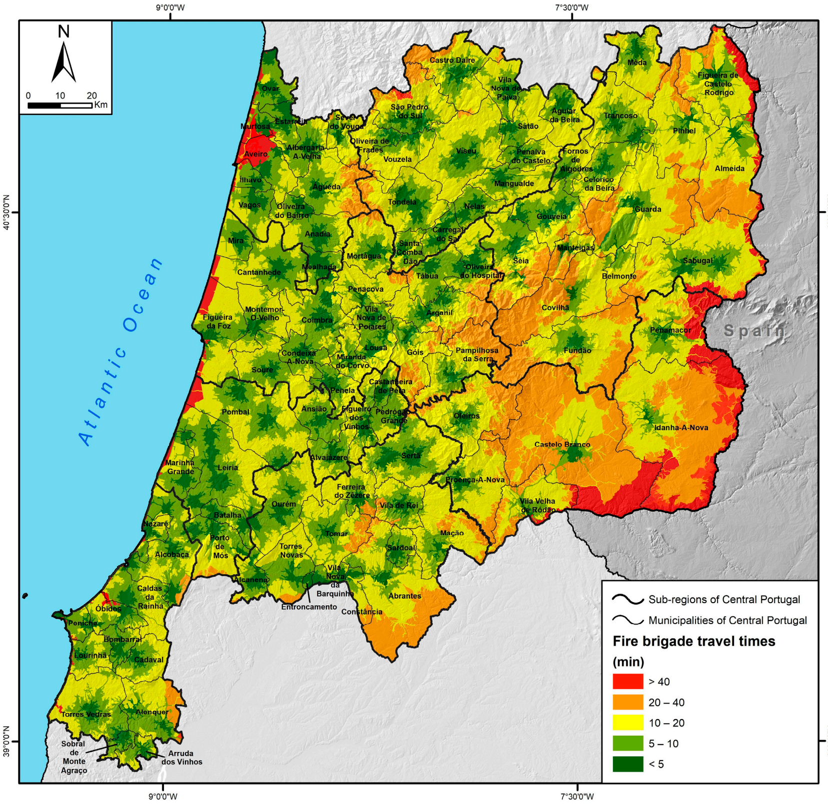

Figure 7. Fire brigade travel times.

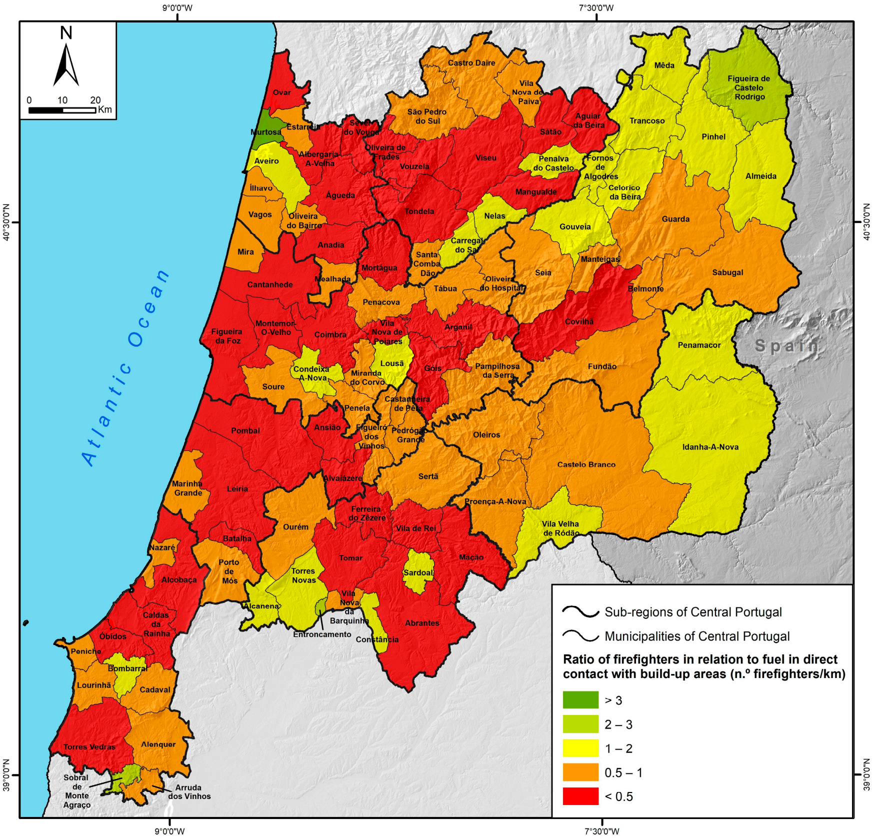

Figure 8. Ratio of firefighters in relation to fuel in direct contact with built-up areas.

3.3. Wildfire Vulnerability at Landscape and at WUI Scale

In the Central Region of Portugal, the most representative classes of wildfire vulnerability, at landscape scale, are "moderate" (35.9%) and "low" (32.3%) (Figure 9). The classes defined as "high" and "very high" cover 23.1% and 7.9% of the area, respectively. The most problematic classes appear in the Beira Baixa (southeast) and in central mountain areas (e.g., Serra da Estrela mountain). Conversely, the municipalities with lowest classes of wildfire vulnerability are in the coastal areas, although it is possible to identify some highly vulnerable spots in these areas.

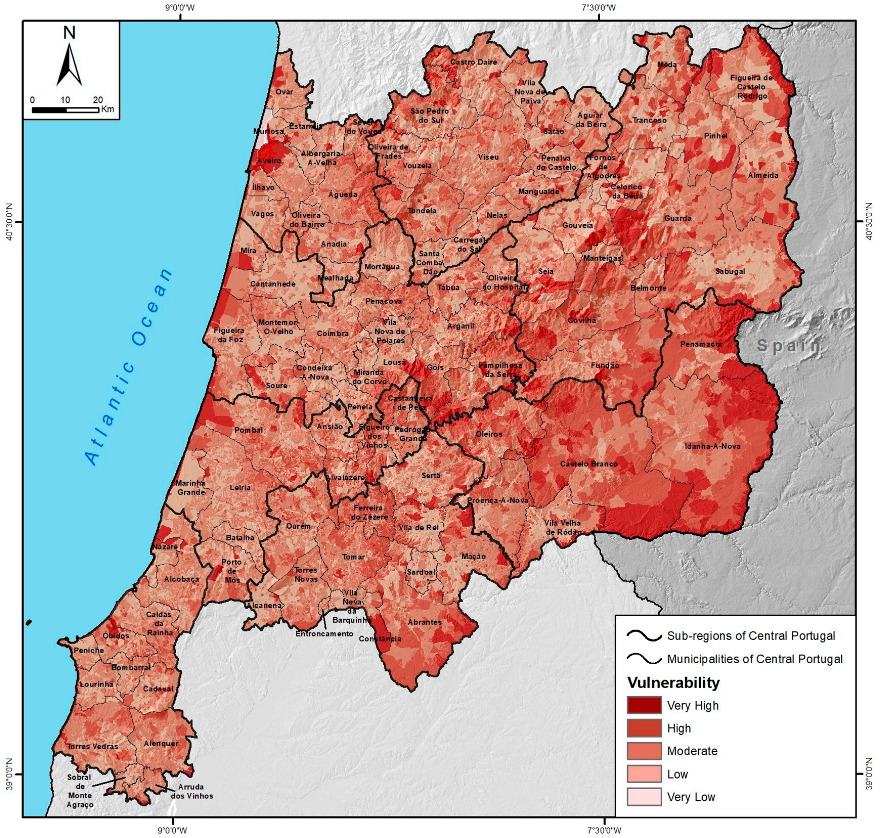

Figure 9. Vulnerability at landscape scale.

At the WUI scale, the finer scale, the "moderate" vulnerability class predominates in almost half (48%) of the built-up perimeter in the Central Region, followed by low (28.9%), high (19.7%), very high (2.4%) and very low (0.9%) classes (Figure 10). Although the highest classes (high and very high) of wildfire vulnerability predominate in around 22% of the WUI, when their spatial incidence is analysed at municipal level it is clear that they are mostly concentrated in the eastern and centre–south sectors of the Central Region, namely in the municipalities of Castelo Branco, Idanha-a-Nova Oleiros, Pampilhosa da Serra, Ferreira do Zêzere and Abrantes. In these municipalities more than half of the WUI are characterised by a high or very high vulnerability to fire (Figure 11).

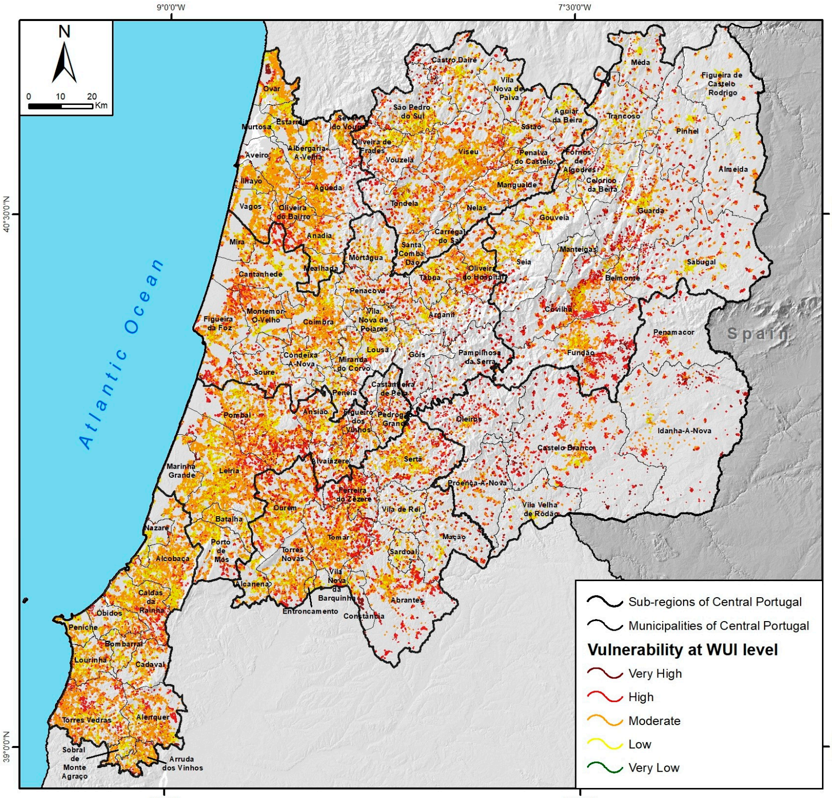

Figure 10. Vulnerability at WUI scale.

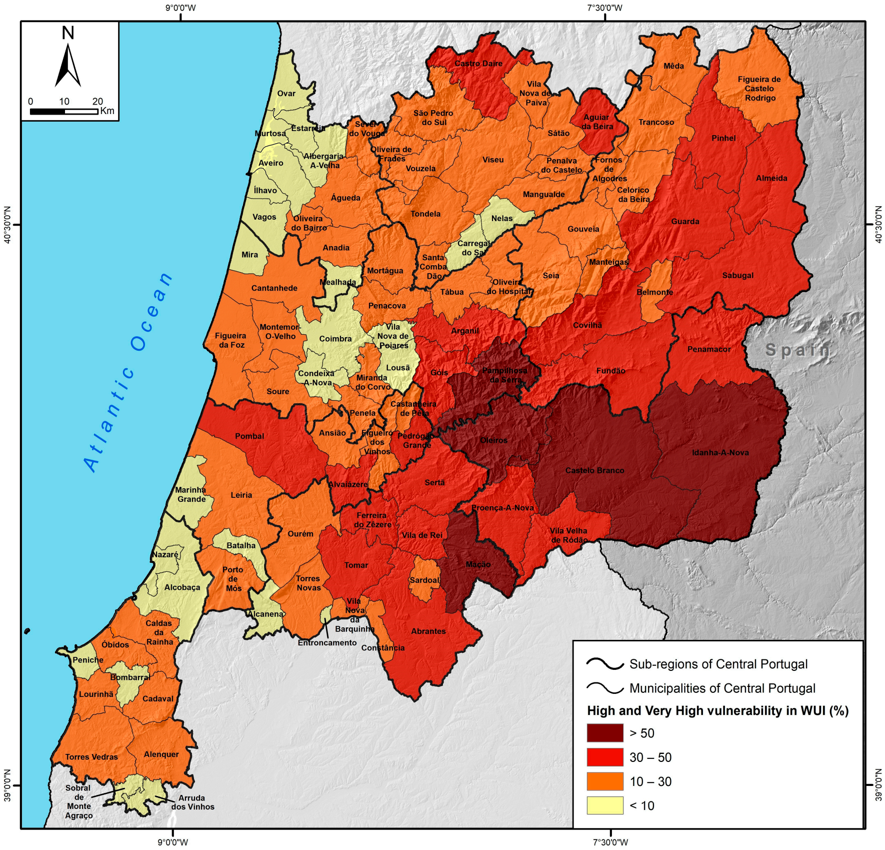

Figure 11. High and very high wildfire WUI vulnerability, at municipal level.

4. Discussion

In the past few decades, wildfires have affected vast areas of the territory and often damage and threatened urban areas, from small rural villages to the edges of large towns and cities of Central Portugal [85]. The most catastrophic, measured by the number of victims and material damages caused, occurred in 2017.

In Portugal, WUIs are expanding [86] as a result of the increasing mix of urban settlements and woodland mainly due to (i) urbanised areas expanding into forest areas and (ii) woodland/scrubland colonizing rural areas as a result of rural abandonment and depopulation [59,87,88]. These changes in the vicinity of WUI areas have contributed to a large amount of fuel build-up as a result of the increase of forest and shrubland areas [88]. In fact, fuel in direct contact with the urban and industrial areas was the most important criterion highlighted by the experts concerned, especially when scrub and woodland dominate. A study carried out by Nunes et al. [59] found that scrubland and pinewood are the most common fuels in direct contact with the build-up in the Central Region of Portugal, meaning that these WUIs are more prone to fire in comparison to areas in which cropland and broadleaf forests predominate [61–63], since they can act as protective buffer against wildfires [50,59].

Several studies suggest that clearing or changing vegetation (fuel) type with the aim to slow down or stop the spread of wildland fires is a key strategy that should be implemented to contain and control wildfires in the vicinity of houses and other structures built within or close to wildland vegetation, thus reducing WUI wildfire vulnerability [88–92].

In Portugal, the catastrophic fires of 2003 and 2005 that affected several WUIs, particularly in the Central Region, led the national government to enact Decree-Law 124/2006, which set out a set of ‘measures and actions to be developed within the National Wildfire Defence System’ with the aim of defending and protecting both forest resources and, first and foremost, people and property. With the 2017 fire episodes, the law was amended by Decree-Law. 10/2018, which repealed the previous decree law, held to be ’ineffective at containing the progression of fires and ensuring the safety of people and property’. According to Decree-Law 10/2018, urban and rural settlements must have a protection buffer area, where fuel management should be implemented and land use must be restricted to low-fuel activities such as agriculture and grazing, and for which native or broadleaf trees were prescribed. Its width varies from 100 m for settlements and up to 50 m for isolated buildings.

However, the relative importance of defendable space compared to other factors is still unclear, although some studies suggest its relative importance varies according to location, housing pattern, structural characteristics, and scale [92–94]. For example, Syphard et al. [92,93] found that housing arrangement and pattern in southern California were more influential than defendable space in explaining structure loss. This study is consistent with other results that have more broadly found that housing pattern and topographic variables are more influential in explaining structure loss than vegetation amount and configuration or other proxies for vegetation [93,95,96]. In this context, further work is needed to assess the effectiveness and efficiency of fuel management measures implemented in the WUI of Portugal’s Central Region, as well as to evaluate how the topography and housing layout determine the likelihood of housing loss to wildfire.

In the region under study, in addition to fuel in direct contact with the built-up areas, local variations in characteristics of population (density of population and ageing index), building density, availability of human resources to cope with fire events, and firefighting response times gave rise to significant differences in the spatial wildfire vulnerability. The results obtained showing that the most vulnerable WUIs to fire are located in centre–south areas and in the most mountainous areas, although it is possible to identify some highly vulnerable spots in the north and coastal areas.

Our results agree in part with the study carried out by Bergonse et al. [17] on the same region, at parish level, which found that the communities in the eastern and centre–south areas are subject to a fairly high social vulnerability, with a few scattered parishes presenting the highest values, while in the coastal and centre–north regions parishes with relatively low social vulnerability predominate. Our findings also agree with the results of Chas-Amil et al. [18] for the Galicia region, namely that communities that are highly vulnerable to wildfires, which also tend to be the most socially vulnerable, are mainly located in rural areas with low population density and a prevalence of older people, sometimes isolated and living alone. In fact, various studies have demonstrated that as people age they become more susceptible to the direct impact of a natural hazard, since they tend to lack the physical ability and economic resources to respond effectively. They are more prone to accidents and less able to recover from the effects of a disaster resulting from a natural hazard [8,32,67,97–100]. Moreover, there are high levels of illiteracy among the elderly population in Portugal (Pearson's correlation = 0.77), which results in a reduced effectiveness at finding information on personal and environmental protection.

The study area is notable for its discontinuous built-up area (80.6%), meaning that single person households are very common. They can involve older people living alone, facing health and economic issues, being classified as vulnerable to wildfires, and needing support [101]. Moreover, these areas are potentially vulnerable to the impact of wildfire smoke, which contains numerous hazardous air pollutants. Several studies have recognised the effects of this exposure on the health of populations [102–104] who, in some cases, need to be evacuated. Evacuation procedures are a critical issue especially when involving high population densities [105,106].

In fact, in combatting forest fires, firefighting response times are critical when assessing fire progress speed and potential fire damage as a function of time [107]. The fire spread risk is directly related to this maximum time and is usually affected by fuel type, topography (slope and exposure), and advance and control speed properties, as well as access to major fire outbreaks in terms of distance and the accessibility of firefighting equipment [108,109].

In large areas of the Central Region, the response time of fire brigades is over 20 min, and the number of full-time firefighters is small. Work carried out by Félix and Lourenço [110] in the mountains of Lousã (central Portugal) demonstrated that as the time of the first intervention increases the average size of burnt areas also increases. They observed that for each occurrence in which the initial attack time was delayed for more than 20 min, the burnt area was, on average, 161.5 ha, almost three times the value observed when response times were shorter.

Statistical data on the number of firefighters over the last 20 years confirm a general decrease of about 30% in the number of personnel, mainly in the inland and most mountainous areas, as a result of rural exodus and ageing population. However, when the ratio of firefighters in relation to fuel in direct contact with built-up areas is analysed, we find that in the majority of central and coastal municipalities there is less than one firefighter per kilometre of WUI in direct contact with fuel. It is in the coastal areas of Portugal that urban sprawl has often been unplanned, and in some cases it is illegal [86,111]. According to Tedim et al. [111] the residents in such settlements tend to understand little about the fire risk associated with where they have settled. Indeed, they expect that public firefighting procedures will protect them in any case and so do not take measures to make their homes safer and defendable. In fact, the backbone in any firefighting system is not the aircraft or the vehicles, but the firefighters. Despite the fire prevention efforts that have been made in such areas, protecting any particular WUI has become a difficult and risky operation for firefighters. Furthermore, in Portugal, under severe fire propagation conditions, firefighters are often forced to withdraw for safety reasons, and all efforts are instead channeled into protecting lives and homes.

5. Conclusions and Limitations

Our results showed that more than 31% of the total territory of the Central Region of Portugal and 22% of the region's WUI have high or very high levels of vulnerability to wildfires. While inland municipalities emerged as the most vulnerable areas, our approach also showed scattered vulnerable pockets, or “hot spots”, in almost all areas of the Central Region.

The use of “the WUI” as a spatial unit of risk analysis is a novel approach in Portugal, which identified interface areas with higher levels of vulnerability to wildfire. Understanding and mapping the spatial variations in wildfire vulnerability at landscape and particularly, at the WUI scale, is therefore critical in reducing wildfire risk, since this can provide enough detail to create specific, implementable strategies for management. For example, local authorities can identify priority measures for use in more exposed areas. These would be based on fuel and fire management options for developing suitable prevention actions, thereby improving the efficacy of fire prevention measures. It can also provide support for local civil protection in preparing resources before a fire starts and for firefighting resource allocation decisions during the fire event.

Although this study presents valuable results, efforts to assess vulnerability to fire on any scale involve making careful decisions about the methodology and variables to be used. The methodology used (AHP) is based on the knowledge and experience of experts, an approach never applied in wildfire risk assessment in Portugal. It involves academics, firefighters, and forest land managers in assigning a quantitative weight to each of the vulnerability criteria. The results seem to provide an adjusted and spatially detailed perspective of wildfire vulnerability, closer to the reality of the study region. This method can also be easily applied to other study areas, using any spatial unit for which spatial and statistical data are available.

However, the use of AHP techniques rather than other methods, notably PCA, a method often used to assess vulnerability to a wildfire, has both advantages and limitations. Whilst the PCA method seeks covariance between a practically unrestricted number of components, it is hardly possible for AHP to perform entirely consistent pairwise comparisons with more than nine criteria [112]. Thus, the AHP weights assignment can be more complicated for a higher number of indicator pairs. The AHP method is, however, advantageous if there is data inconsistency [113] and in ranking alternatives regarding the different criteria selected [114]; nevertheless, it does not have inbuilt techniques to signify an optimal model structure. Therefore, the AHP permits assumptions, whereas, thanks to its rigorous statistical procedure, the PCA eliminates the inconsistent model elements [115]. In this context, future research should focus on a mixed-method experiment that is based on the strengths of both methods and their weaknesses of weighting model indicators, while at the same time, it explores the obtained correlation results.

Vulnerability is multifaceted and subject to geographic variability, in addition to many other factors, which include certain variables that are difficult to assess and quantify. These can include social perceptions of risk, local knowledge and approaches to resilience, and public trust in institutions and forest management organisations. In this context, more accurate analyses will be needed to provide a better characterisation of WUIs, using updated land use/ land cover variables and defining the diversity of WUI typology, residents, and community dynamics as well as the local knowledge and approaches to resilience that already exist. Developing networks to exchange this knowledge among different WUI resident groups is also a key instrument for developing resilience and public trust in public institutions and forest management companies.

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Appendix A

Table A1. Pairwise comparison matrix of the thematic layers.

	PD	**BD**	**PB12F**	**YI**	**AI**	**UnR**	**FDCBA**	**FFTT**	**RFDC**	**Interactions**	**Scaling**
Population density (PD)	1.0	2.0	2.6	4.3	1.5	5.5	0.7	1.1	1.6	2.03	0.94
Building density (BD)	0.5	1.0	2.5	1.8	0.6	4.3	0.5	0.7	1.1	1.30	0.56
Percentage of buildings with 1 or 2 floors (PB12F)	0.4	0.4	1.0	1.0	0.4	2.0	0.5	0.4	0.3	0.63	0.30
Youth index (YI)	0.2	0.5	1.0	1.0	0.2	2.5	0.2	0.3	0.4	0.63	0.25
Ageing index (AI)	0.6	1.8	2.6	5.2	1.0	5.4	0.5	0.9	1.3	1.93	0.81
Unemployment rate (UnR)	0.2	0.2	0.5	0.4	0.2	1.0	0.2	0.2	0.2	0.30	0.14
Fuel in direct contact with build-up areas (FDCBA)	1.5	2.0	2.2	5.0	1.9	6.1	1.0	0.8	1.1	2.15	1.00
Firefighters' travel time (FFTT)	0.9	1.4	2.5	3.8	1.1	5.6	1.3	1.0	1.8	1.94	0.91
Ratio of firefighters to fuel in direct contact (RFDC)	0.6	0.9	3.8	2.3	0.8	6.1	0.9	0.6	1.0	1.70	0.69
Total	6.0	10.2	18.7	24.8	7.7	38.4	5.7	5.9	8.7	0.10	5.60

Table A2. Normalised pairwise matrix.

	PD	**BD**	**PB12F**	**YI**	**AI**	**UnR**	**FDCBA**	**FFTT**	**RFDC**	**Normalised Weight**
Population density (PD)	0.17	0.20	0.14	0.17	0.20	0.14	0.12	0.18	0.19	0.168
Building density (BD)	0.08	0.10	0.13	0.07	0.07	0.11	0.09	0.12	0.13	0.101
Percentage of buildings with 1 or 2 floors (PB12F)	0.07	0.04	0.05	0.04	0.05	0.05	0.08	0.07	0.03	0.052
Youth index (YI)	0.04	0.05	0.05	0.04	0.03	0.06	0.03	0.04	0.05	0.044
Ageing index (AI)	0.11	0.17	0.14	0.21	0.13	0.14	0.09	0.15	0.15	0.144
Unemployment rate (UnR)	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.025
Fuel in direct contact with built-up areas (in km) (FDCBA)	0.25	0.19	0.12	0.20	0.25	0.16	0.17	0.13	0.12	0.178
Firefighters' travel time (FFTT)	0.15	0.13	0.14	0.15	0.14	0.15	0.22	0.17	0.20	0.162
Ratio of firefighters to fuel in direct contact (RFDC)	0.10	0.09	0.20	0.09	0.10	0.16	0.16	0.10	0.11	0.123

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