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Planning Wildfire Evacuation in the Wildland–Urban Interfaces of Central Portugal

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Abstract: In recent decades, wildfires have become common disasters that threaten people's lives and assets, particularly in wildland–urban interfaces (WUIs). Developing an effective evacuation strategy for a WUI presents challenges to emergency planners because of the spatial variations in biophysical hazards and social vulnerability. The aim of this study was to map priority WUIs in terms of evacuation. The factors considered were the seriousness of the risk of wildfire exposure, and the population centres whose greatest constraints on the evacuation process stemmed from the nature of the exposed population and the time required to travel to the nearest shelter/refuge. An integrated framework linking wildfire hazard, social vulnerability, and the time taken to travel by foot or by car to the nearest refuge/shelter was applied. The study area includes two municipalities (Lousã and Sertã) in the mountainous areas of central Portugal that are in high-wildfire-risk areas and have very vulnerable and scattered pockets of exposed population. The combination of wildfire risk and travelling time to the nearest shelters made it possible to identify 20% of the WUIs that were priority areas for evacuation in the case of Sertã. In the case of Lousã, 3.4% were identified, because they were highly exposed to wildfire risk and had a travelling time to the nearest shelter of more than 15 min on foot. These results can assist in designing effective pre-fire planning, based on fuel management strategies and/or managing an effective and safe evacuation.

Keywords: wildfire risk; evacuation; hazard; vulnerability; Central Portugal

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1. Introduction

In recent decades, researchers have observed an increasing trend in the destructiveness of wildfires around the world [1–3]. Humanity and fire have always coexisted, but the ability to manage fire has not been achieved and could become increasingly complex due to climate change [1,4]. Furthermore, it is expected that wildfire risk will become much more common in areas that are not currently classified as prone [5].

Moreover, when wildfire enters wildland–urban interfaces (WUI) areas, where human development meets or intermingles with undeveloped wildland or vegetative fuels [6] that are both fire-dependent and fire-prone, the effects on communities can be catastrophic, causing environmental and socioeconomic devastation. In the recent past, major forest fires all over the world have resulted in the loss of human life and have forced people to evacuate. In 2009 in Australia, for example, there were 173 deaths, and, in 2014 in Sweden (the Vastmanland Fire), around 1000 people were forced to evacuate, with one death recorded. In Portugal, in 2003, 2005, and 2017 (June and October), there were 21, 16, and 116 fatalities, respectively, while in 2017/18 in California, 44 deaths were recorded. In Greece (Mati) in 2018, dozens of people were surprised by fire inside their homes and cars, resulting in around 100 deaths and 187 injured [7–11].

Multiple investigations into deaths and injuries caused by fires around the world show that more than two thirds of those injured and more than half of those killed could have been evacuated [12–14]. Despite the intrinsic characteristics of combustion, which make it difficult to evacuate due to smoke, incandescent particles, and flames [15], several professionals linked to the subject argue that the safest action residents can take when faced with the threat of a forest fire is to evacuate [16,17]. Thus, when faced with the threat of a wildfire, evacuation is mandatory in the USA and Canada [18]. In Greece, after the Mati fire in 2018, early evacuation was favoured, as was evident during the recent 2021 fire season [19].

However, an evacuation exercise may not be the most appropriate response, especially in places with poor accessibility or in biophysical settings that trigger the rapid movement of flames [20,21]. There are also some complexities associated with evacuation: notification, timing, evacuating pets and evacuating individuals who refuse to leave or who delay leaving [22]. In addition, since evacuation is a contingency exercise, there are always associated risks. The work in [23], which analysed fatalities in Australia in the period 1900–2008, showed, for example, that 32% of fatalities occurred during late evacuations, while only 8% occurred when people remained sheltered in a property that could be protected. Looking at the economic aspect, too, post-fire studies have shown, for example, that a significant percentage of homes are destroyed by falling incandescent particles/embers before or after the fire front passes close to or through the structure, something that could be avoided by people remaining in their homes [24,25].

In this context, there are other alternatives to evacuation, such as the stay and defend strategy used in North America and Australia, for instance [26]. Another alternative is to shelter in place in a specific location, which can be a dwelling or a common area, defined in advance [27]. Evacuation is always complex [28,29], prompting numerous studies on the subject through evacuation simulations [30,31], fire progression and evacuation simulations [32], and models that make it possible to identify a threshold around communities. Once this threshold is breached by the fire, communities should be triggered for evacuation [33,34]. To this end, various software programs have been developed to work with evacuation at different scales and with different possibilities [35]. However, these models typically lack detailed features that account for the interaction between wildfire behaviour and the evacuation behaviour of WUI residents. In fact, factors such as age, sex, culture, race, impairments, occupation type (whether residents or tourists), and income influence each evacuee's decision-making process and should be considered. Moreover, proximity to wildfire hazards significantly impacts evacuees' decision and behaviour [35].

In Portugal, evacuation plans are at an early stage. Rodrigues et al. [36], in an investigation into the Pedrogão fire in 2017, wherein 66 people died, found that 65% of deaths were linked with leaving the site (fleeing/evacuating) without orders or information from the authorities. The author adds that the safety of communities, particularly in the WUIs, depends on risk assessment, planning, and qualified emergency management [36]. This is in line with Thompson et al. [37] and North et al. [38], who state that improving the safety and effectiveness of response to fire requires a multi-faceted approach, i.e., an effective response requires effective pre-fire planning. The work by Oliveira et al. [39], carried out in a Portuguese mountain parish with a very significant history of fires and an elderly population, concluded that knowing the level of risk of each village and the time needed to reach a safe spot by different routes can help define priorities for emergency intervention. It also states that this information is essential to establish safety and evacuation protocols adapted to each village.

Thus, identifying the areas with the most vulnerable inhabitants, especially from the point of view of evacuation, and cross-referencing them with the territory's biophysical favourability to the progression of fires, seems to be a necessary exercise that can produce effective results in terms of risk assessment and evacuation planning. Taking the above perspectives into consideration, the main objective of this study was to identify priority WUIs in terms of evacuation in two municipalities in Portugal (Lousã and Sertã), located in the central mountain range, notable for repeated forest fires. To achieve this objective, the following steps were undertaken: (i) the hazard level of and social vulnerability to forest fires, by combining biophysical and sociodemographic variables to support the evacuation decision, were assessed; (ii) evacuation times in two scenarios, namely walking to nearby shelters/refuges and driving to large shelters, were modelled; and (iii) high and very high fire risk classes at WUI scale and highest evacuation times were correlated. The final goal was to produce maps that identify the WUIs with high and very high wildfire vulnerability, i.e., where communities and assets are more liable to damage in a wildfire scenario. This information can both influence the decision to evacuate or not by the organisations responsible for managing the national emergency system, and also result in a safer and well-timed community response. Moreover, it allows fire risk mitigation measures to be designed that can reduce the danger to people and their exposure to the need to evacuate in the context of a forest fire.

2. Study Area

Located in the central region of Portugal, the municipalities of Lousã and Sertã are characterised by being extremely suitable for forest growth, their hilly terrain, high ageing indices (around a third of the total population), strong population variation, high recurrence of forest fires, and past episodes where deaths, injuries, and evacuations were recorded. Sertã and Lousã have very different areas, 446.7 km^2 and 138.4 km^2, respectively, with the respective WUI boundaries being 942.64 km and 341.77 km (Figure 1). Around half of the municipality of Lousã has a slope of more than 20° and only 27% has a slope of less than 10°. In the case of Sertã, there is a very similar proportion between the classes (<5; 5–10; 10–15; 15–20; and >20°) of around 20% in each.

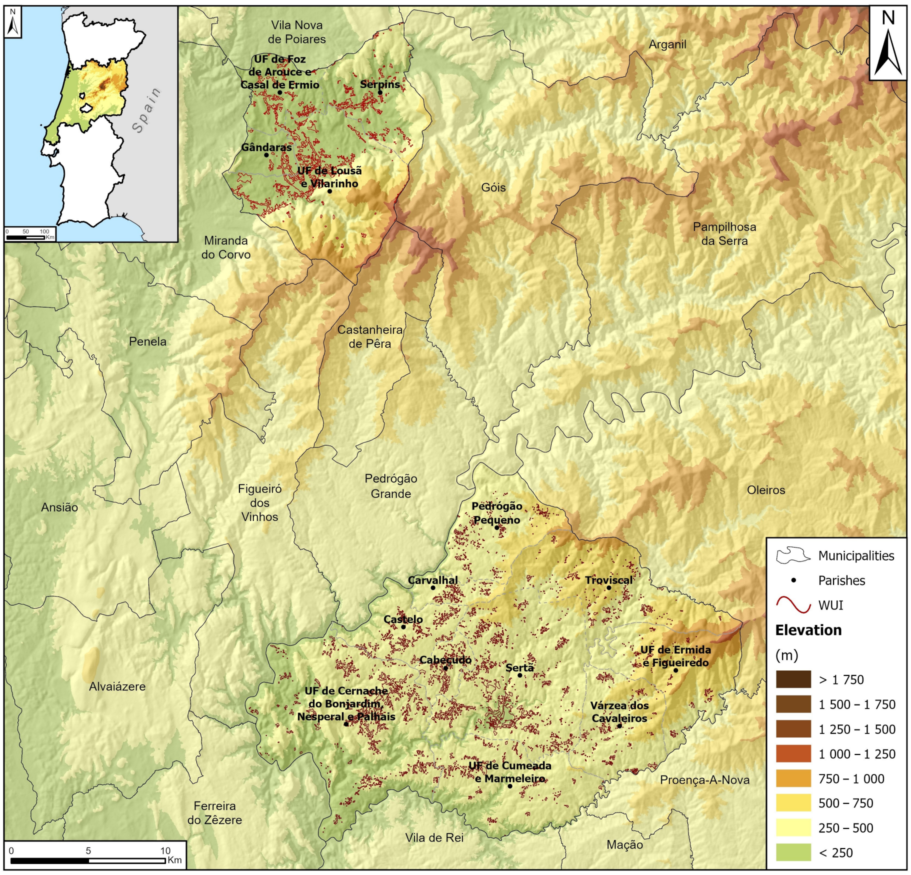

Figure 1. Location, elevation, and wildland–urban interfaces (WUIs) of the municipalities of Lousã and Sertã.

According to the 2021 census [40], 17,006 and 14,769 people lived in the Lousã and Sertã municipalities, respectively, with a population density of 123 inhabitants/km^2 in Lousã and 33 inhabitants/km^2 in Sertã. Between 1950 and 2021, the two municipalities showed very different population variations; Lousã increased its population by 10% and Sertã showed a decrease of around 48%. In both municipalities, more than 70% of their territory is occupied by forests, with coniferous forests predominating, although eucalyptus and invasive species also feature significantly (Table 1).

Table 1. Land use and occupation in the municipalities of Sertã and Lousã in 1995 and 2018.

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

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

Both municipalities have a history of recurrent fires (Figure 2). Thus, between 1980 and 2020, Sertã recorded more than 100,000 hectares burnt and Lousã recorded 63,200 hectares burnt [41]. In Lousã, several areas have been ravaged by fire four or five times, while, in Sertã, around 44% of its territory has been ravaged by fire two or three times. In both cases, the worst affected areas are associated with higher altitudes, steeper slopes, and unbroken forest cover.

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

Also, after the disastrous year of 2017, in terms of forest fires, the Portuguese government prioritised boosting the safety of the residents, creating the 'Safe Village' and 'Safe People' programmes. The first programme aims to establish 'structural measures to protect people, property, and buildings at the urban–forest interface, whilst the second aims to promote 'awareness-raising actions for the prevention of risky behaviour, self-protection measures and evacuation plan drills, in conjunction with local authorities' [42].

The programme's online site (https://aldeiasseguras.pt/, accessed on 10 May 2022) shows that there are 17 'Safe Villages' in the two municipalities as a whole. Sixteen are in the municipality of Lousã and just one is in the municipality of Sertã (Figure 3). Even though the 16 villages in the municipality of Lousã have signed up to the programme, none of them has an evacuation plan, no drills have been carried out, and no places of shelter or refuge have been identified. There is only a reference to the existence of a Local Safety Officer. In the case of the municipality of Sertã, specifically the village of Trízio, the following actions are stipulated: collective shelter, collective refuge, safety officer, and evacuation plan.

However, both municipalities have identified in their respective Municipal Civil Protection Emergency Plans (PMEPC) places that can accommodate people in the event of an evacuation. In the case of Sertã, the document dates from 2012 [43] and identifies 66 sites, classified into two types: temporary shelters and local concentration zones. Temporary shelters are only referenced for primary evacuations, i.e., the removal of the inhabitants from risk areas to a place of safety, followed by the second phase of evacuation, i.e., travelling to shelter facilities, where all basic needs can be met. In the case of Lousã, the

PMEPC [44] identifies 12 sites. Although no typology is specified, all the sites are large and capable of sheltering a significant number of people. The final selection of these sites basically involves schools, day centres, parish councils, pavilions, and sports centres, i.e., fixed structures that are well known to the population.

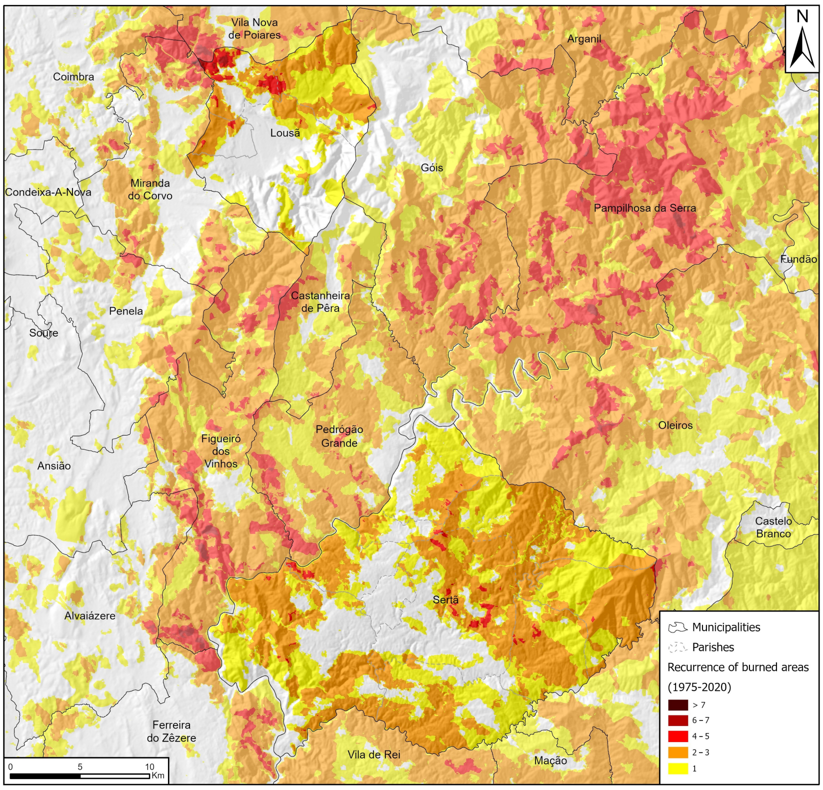

Figure 2. Recurrence of forest fires (1975 and 2020). (Data source: Portuguese National Authority for Nature Conservation, 2021).

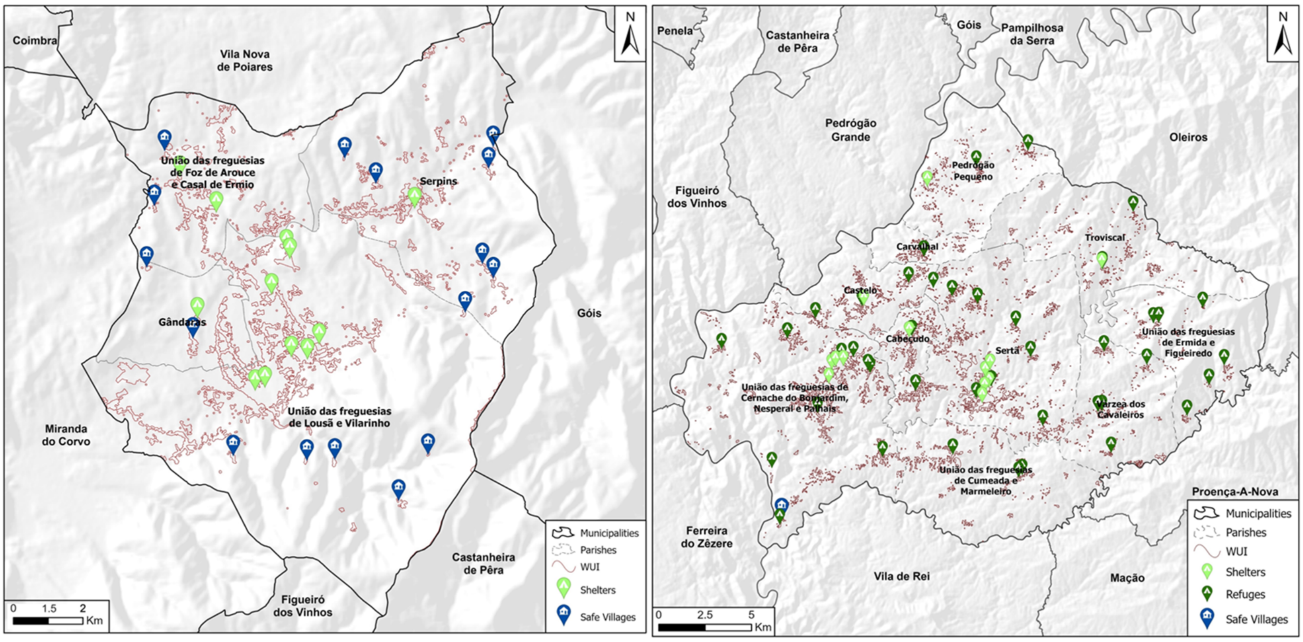

Figure 3. Location of 'safe villages', refuges, and shelters.

3. Methodology

With the aim of mapping priority WUIs to be evacuated in a wildfire scenario, an integrated framework was applied based on the following components: wildfire hazard, social vulnerability, and wildfire risk assessment, in support of evacuation and modelling the travel time—either on foot or by car—to the nearest refuge or shelter. Figure 4 shows the integration of these components.

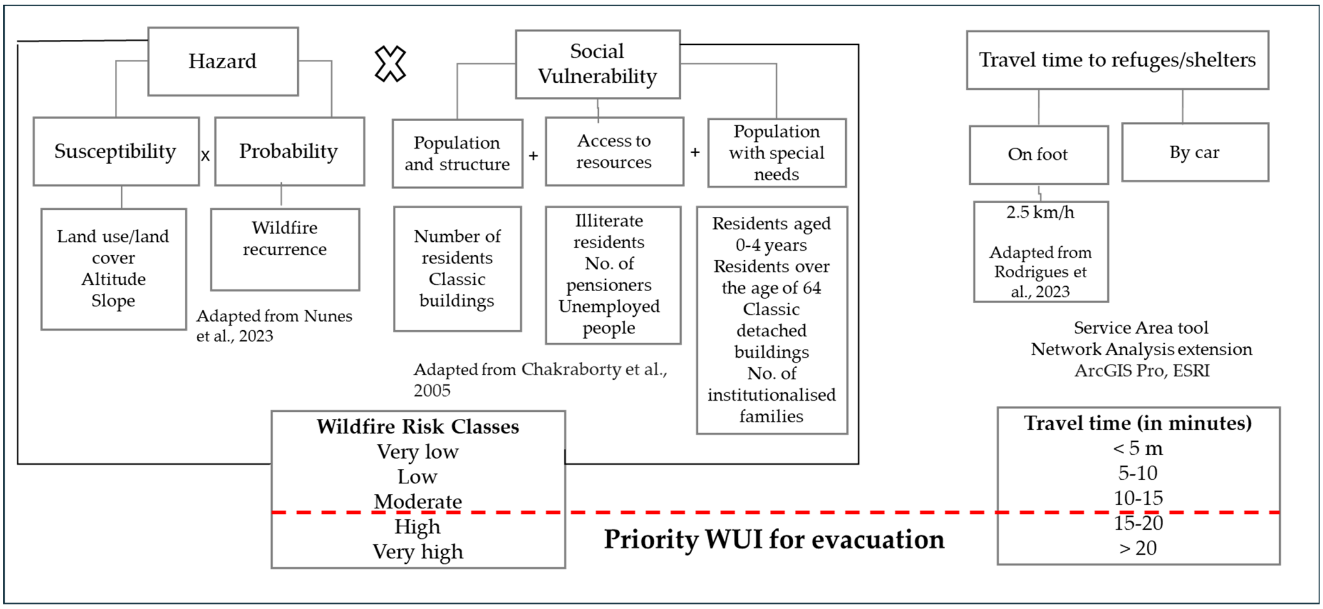

Figure 4. Implementation flow chart components to map priority WUIs for evacuation [45–48].

3.1. Wildfire Risk Assessment in Support of Evacuation

The methodological proposal was adapted from the work of Chakraborty et al. [46], applied to evacuation in the context of hurricanes in the Florida region. This methodology is applied to the risk of forest fire in support of evacuation because these two risks have some similarities, identified by Folk et al. [49] and Intini et al. [38], including, (i) the problem of predicting the direction of travel, (ii) the ability to displace a large number of people, and (iii) a change in direction without warning. In addition to these issues, in an evacuation situation for either of these risks, an early warning allows people to leave by driving vehicles [50]. The original methodology of the work by Chakraborty et al. [46] is based on the following steps: (i) assessing the hazard, (ii) assessing the social vulnerability for evacuation support (SVES), and (iii) assessing the degree of support needed for evacuation resulting from the hazard x social vulnerability for evacuation support.

3.1.1. Wildfire Hazard

The hazard assessment was based on the methodology used in the work by Nunes et al. [45] and involved the following steps: (i) assessing susceptibility, using the slope, altitude, and land use and occupation variables, (ii) calculating probability based on the areas burnt between 1975 and 2020, and (iii) calculating hazard by multiplying susceptibility by probability. The validation process was supported by the ArcSDM toolbox, ArcGIS 10, which helped calculate the AUC (area under the curve). This assessment summarises the ROC (receiver operating characteristics) curve into a value that basically measures the quality of the model's forecasts, i.e., if the model's forecasts were 100% correct, the AUC value would be 1. The results indicate that the model performed well, with an AUC of over 0.80.

3.1.2. Social Vulnerability for Evacuation Support (SVES)

The data used in the SVES assessment were taken from the Geographic Base for Referencing Information (BGRI), relating to the year 2011. The limited list of data for the year 2021 meant that more recent census information could not be used. A total of nine variables were selected. They are subdivided into three important characteristics of the population from an evacuation standpoint, identified in the work by Chakraborty et al. [46] as the following: (i) population and structure, (ii) differential access to resources, and (iii) population with special needs for evacuation (Table 2).

Table 2. Variables included in the calculation of social vulnerability for evacuation support.

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

The procedure used by Chakraborty et al. [46] to calculate SVES consisted of adapting the procedure used by Cutter et al. [51]. In the present study, the Chakraborty et al. [46] approach was retained, and the assessment consists of the following three stages:

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

$$\frac{Ri}{Rmax}$$

where $Rmax$ = maximum value of the ratio calculated previously.

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

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

The Natural Breaks (Jenks) classifying method was used to prioritise wildfire risk (Hazard $\times$ SVES) into five categories, since the variance within each class is minimised while the variance between classes is maximised [48].

3.2. Modelling Travel Time to Refuges and Shelters

Two exercises were carried out for both municipalities under study, namely determining the time it takes to walk to identified shelters and refuges, and determining the time it takes to drive to larger shelters. As both municipalities have high rates of an ageing population (22.9% in Lousã and 31.1% in Sertã), we adopted the figures obtained by Rodrigues et al. [47] in real evacuation tests on foot in Cabanões, a village in the municipality of Lousã. Rodrigues et al. [47] identified the following average speeds: for individuals over 65 without mobility difficulties, 3.13 km/h uphill and 3.65 km/h downhill; for individuals over 65 with mobility difficulties, 2.24 km/h uphill and 2.47 km/h downhill; and for group evacuation, 2.5 km/h. The average speed in a group falls thanks to the support and mutual help given to people with difficulties. We therefore opted for the group average speed, i.e., 2.5 km/h. The travelling time was assessed using the Network Analysis extension, with the Service Area tool in the ArcGis Pro 3.0 software [48].

The exercise of travelling by car has a dynamic speed depending on the speed limits of the localities. The service area shows the road networks that can be reached within different times, in minutes from the assembly points, and have been applied in evacuation route planning in disaster-susceptible areas (disasters such as floods and tsunamis) [52,53]. These outputs were then cross-referenced with the urban–forest interfaces of the two municipalities to find the travel times between these contact areas and the refuges and shelters.

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

4. Results

4.1. Spatial Variability in Wildfire Hazards

The results show the significant expression of the highest hazard classes in the municipalities under study. Sertã has almost 80% of its territory in the highest hazard classes (40.7% very high and 38.2% high), while, in Lousã, this figure is around 70%. In both municipalities, the lowest hazard classes coincide with the central area, where the larger settlements and lower slopes are located (Figure 5).

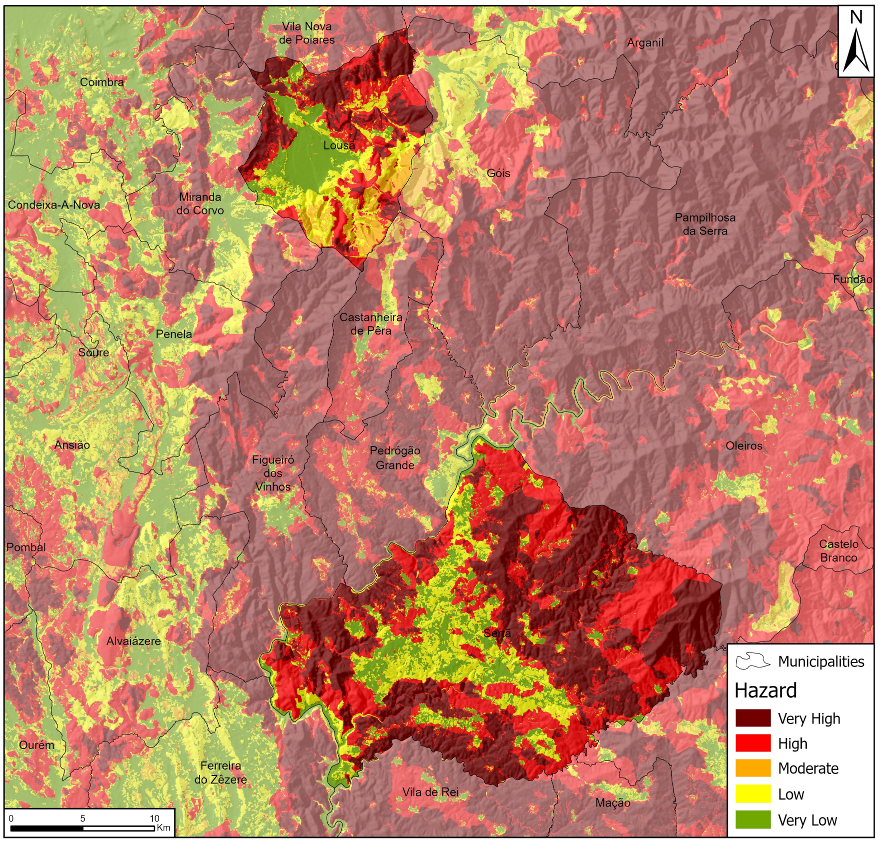

Figure 5. Hazard results for forest fires in the municipalities of Lousã and Sertã.

4.2. Spatial Distribution of Social Vulnerability

The results of assessing the social vulnerability components are shown in Figure 6. In the case of Lousã, the results obtained through the APP1, APP2, and APP3 approaches show a concentration of the most vulnerable areas in the main population centre and settlements located in the north-east and north-west of the municipality. These coincide, respectively with the União de Freguesias [Union of Parishes] (UP) da Lousã e Vilarinho, and the parish of Gândaras.

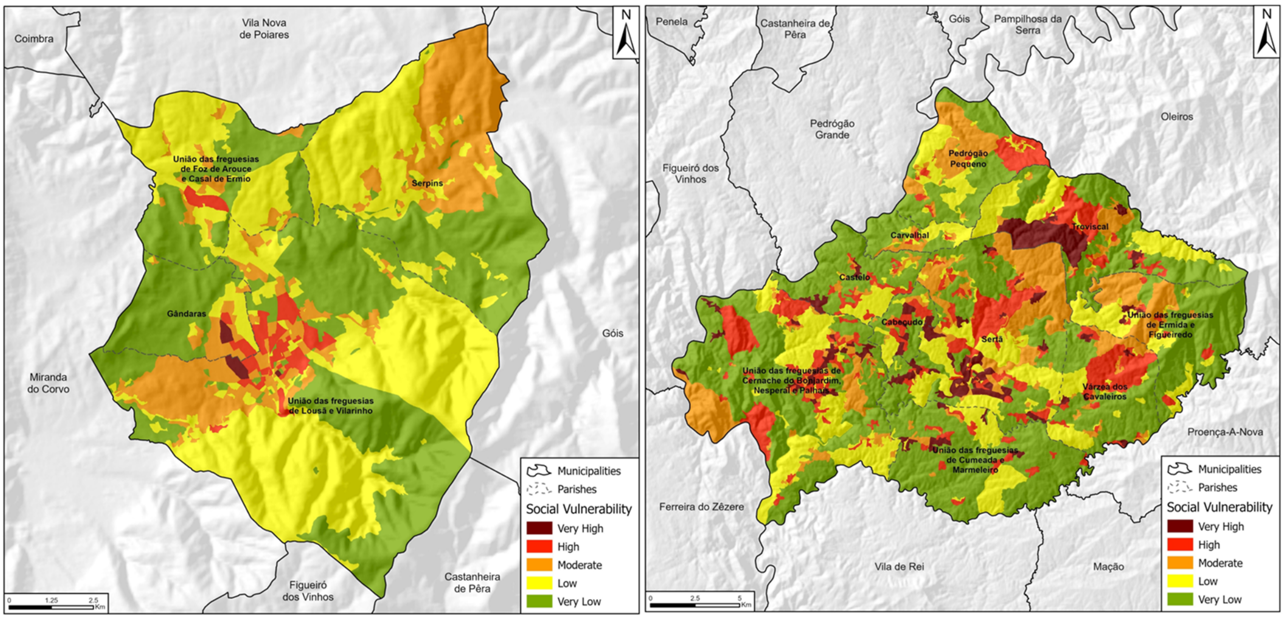

Figure 6. Social vulnerability to evacuation support (SVES) in the in the municipalities of Lousã and Sertã.

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

4.3. Wildfire Risk in Support of Evacuation

The fire risk maps show quite different results from the previous ones. In the case of the municipality of Lousã, its population centre, previously classified as very vulnerable, is now classified as "Very Low", "Low", and "Moderate" in terms of fire risk for evacuation support (Figure 7).

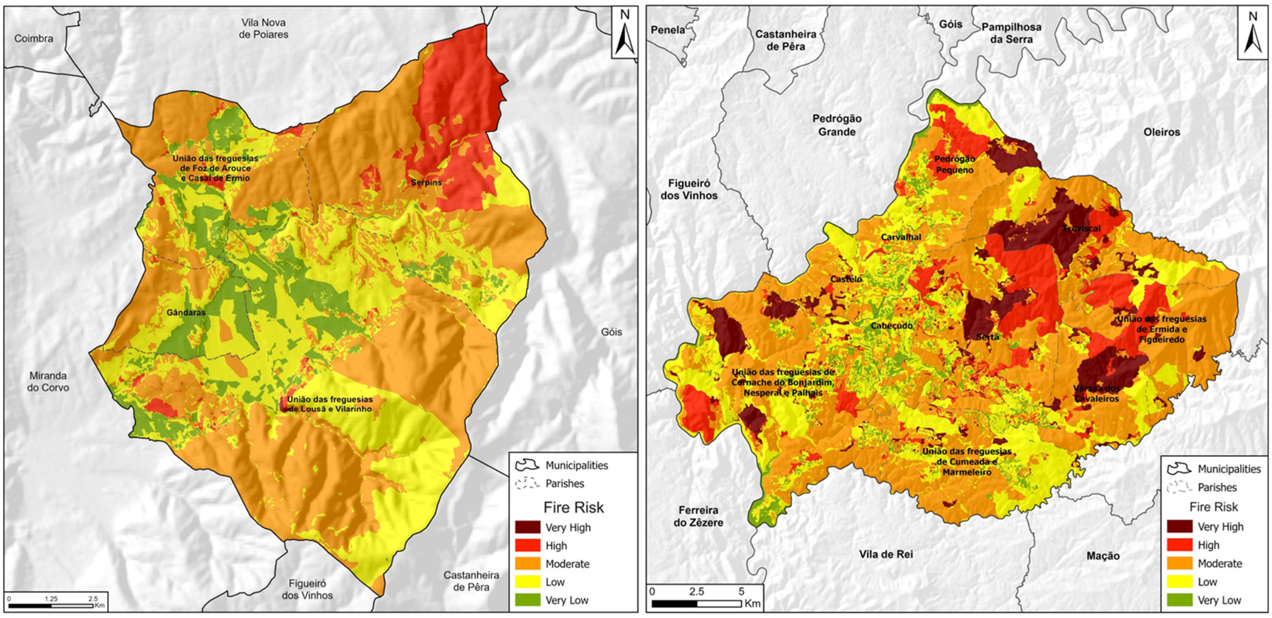

Figure 7. Fire risk in support of evacuation in the municipalities of Lousã and Sertã.

In the case of the municipality of Sertã, the localities in the eastern strip are very problematic, especially when all the approaches are combined (Figure 7). Compared to Lousã, the municipality of Sertã has a predominance of small settlements that are spread throughout the municipality, with a very high risk of fire.

4.4. Travelling Time to the Nearest Refuge/Shelter

In the municipality of Lousã, around 70% of the WUIs are more than 20 minutes' walk from the nearest refuge or shelter, while, in Sertã, the figure is slightly lower, at around 66.6% (Figure 8). If we analyse the results at a parish level, the situation is quite critical in all the parishes in the municipality of Lousã, because between 66 and 72% of their WUIs are more than 20 min away on foot. In the case of Sertã, the most problematic parishes are Pedrogão Pequeno, Cabeçudo, Troviscal, and the UF of Cumeada and Marmeleiro, with figures of over 70%.

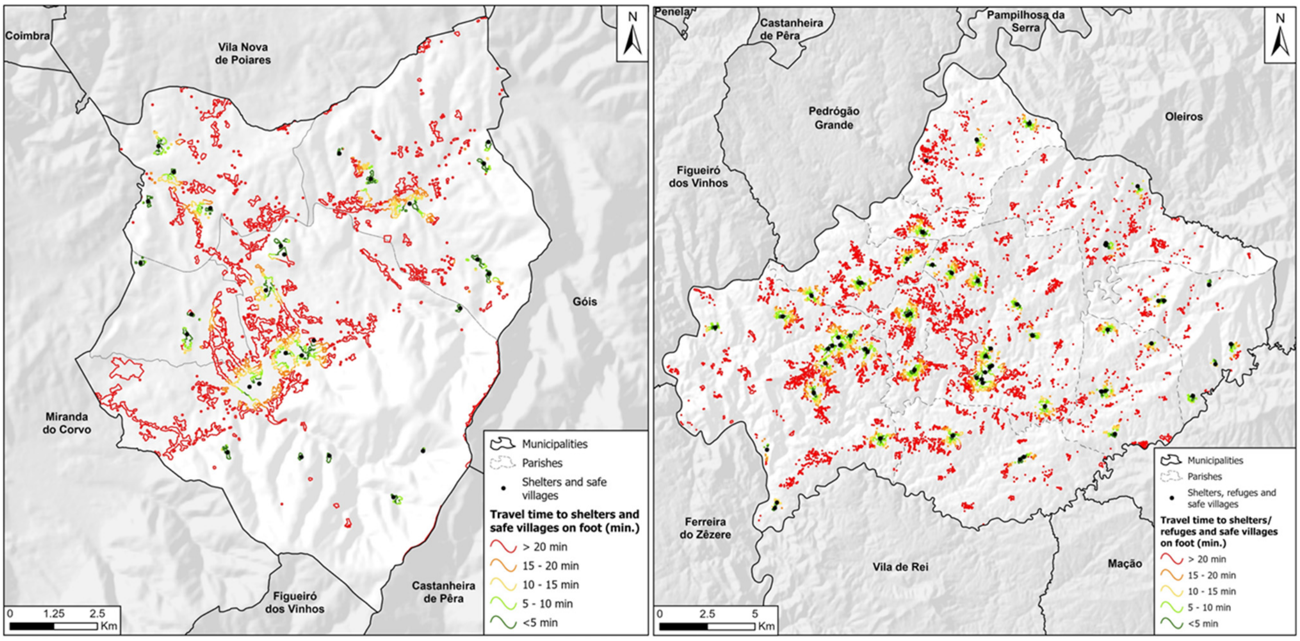

Figure 8. Travel time on foot to the nearest refuge or shelter.

When it comes to travel time by car (Figure 9), the municipality of Lousã is generally more straightforward when it comes to travelling to shelters and refuges than Sertã. Almost 80% of Lousã's WUIs are within a five-minute drive of a shelter. In Sertã, only 42% of the WUIs are in similar conditions, i.e., five minutes or less away from a shelter. Additionally, in Sertã, 36% of the WUIs are between 5 and 10 min from a shelter, 16% are between 10 and 15 min away, and 7% are more than 15 min away. In Lousã, 16% of the WUIs are between 5 and 10 min from a shelter and 3% of them are more than 25 min by car from a shelter.

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

4.5. Correlating the Wildfire Risk with Evacuation Time

The correlation between forest fire risk classes and evacuation times, especially the highest fire risk classes with the highest evacuation times on foot or by car (Figures 10 and 11), makes it possible to identify the priority interfaces in terms of evacuation. The results for the two municipalities are quite different, since, in the case of Lousã, there are practically no WUIs more than 15 min' walk from the shelter points (refuge or shelter) with a high or very high fire risk. In the case of Sertã, the situation is particularly critical in more than 20% of the municipality's WUIs, which are characterised by a high or very high risk of fire and are located more than 15 min from the shelter points. These WUIs are predominantly located in the outlying areas of the municipality (Figure 10). When using a car to travel to the nearest shelter points, in the case of Lousã, all the WUIs with a high or very high risk are less than 15 min away, while in Sertã this figure is 3.4% (Figure 11).

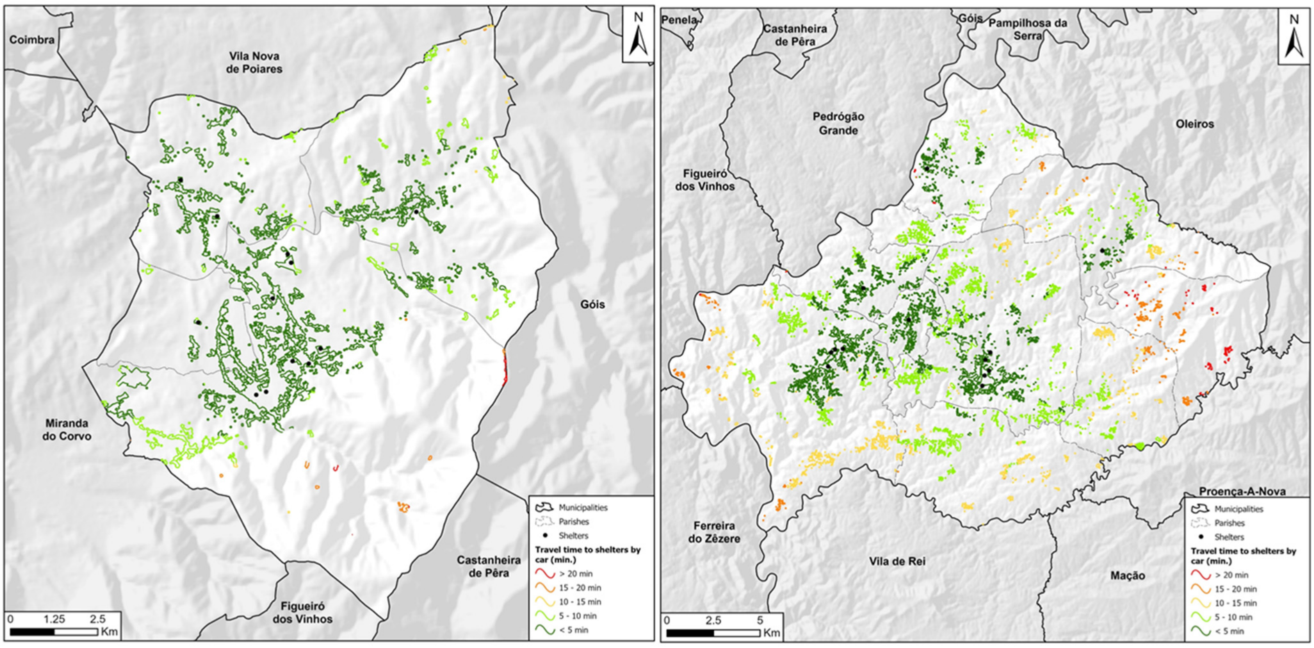

Figure 9. Travel time by the nearest refuge or shelter.

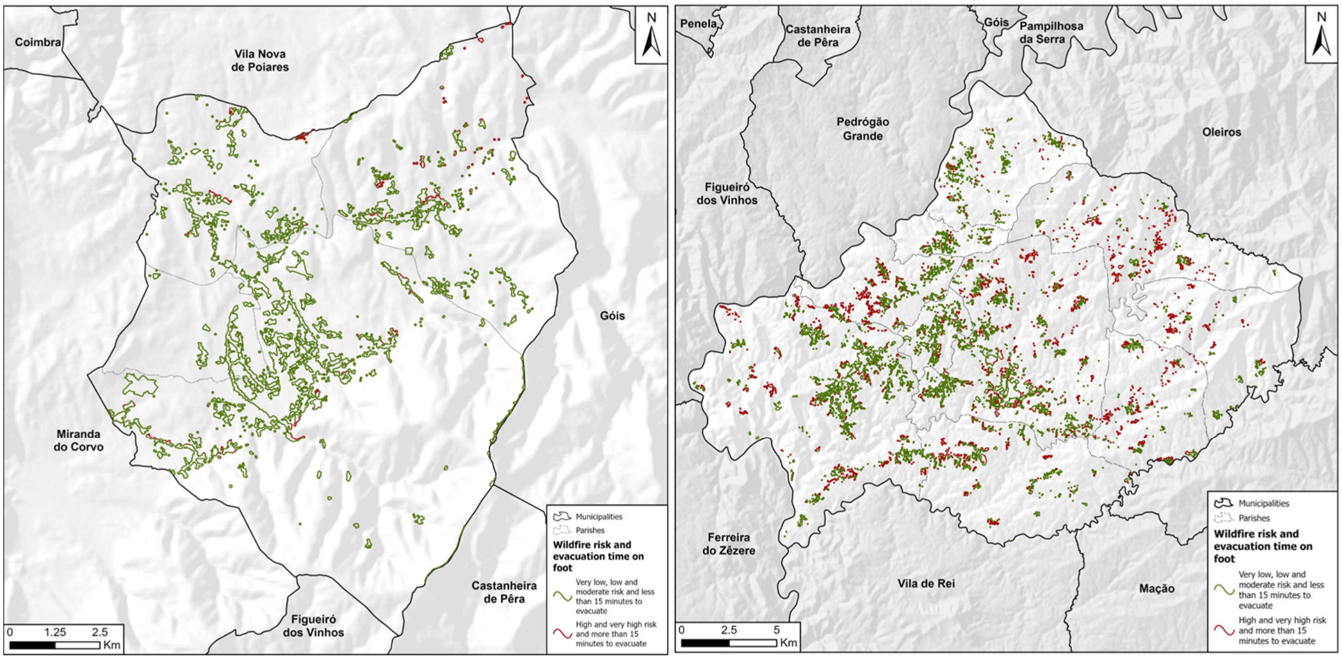

Figure 10. Correlation between the highest forest fire risk classes and evacuation times on foot longer than 15 min.

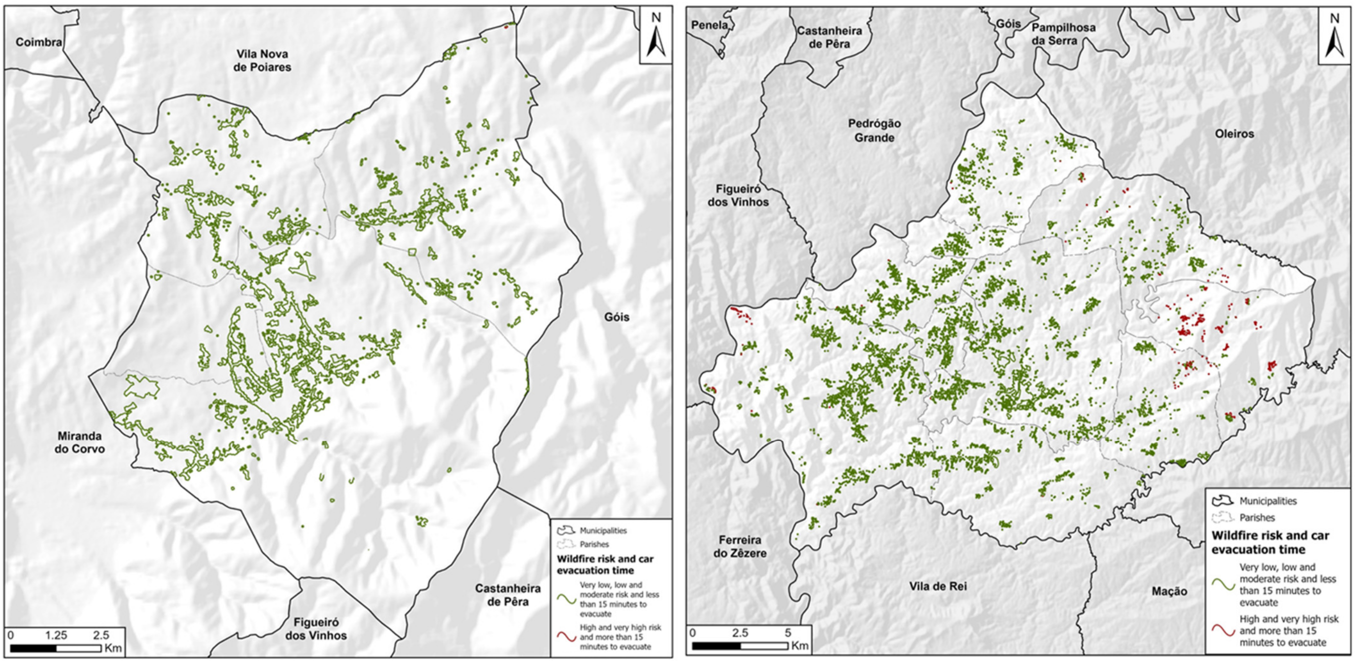

Figure 11. Correlation between the highest forest fire risk classes and evacuation times by car longer than 15 min.

5. Discussion

Over the past few decades, wildfires have impacted extensive regions of Portugal, frequently damaging and threatening urban areas ranging from small rural villages to the outskirts of large towns and cities in central Portugal [54]. The most catastrophic, measured by the number of victims and material damage caused, occurred in 2017 (June and October). After these events, early evacuations began to take place more often in Portugal to prevent human causalities. The two municipalities studied are located in the extensive territory that Lourenço et al. [55] define as favourable to the cyclical progression of large forest fires, thanks to natural features such as orography and vegetation cover, but also due to human influence. In the central region, these areas include the more mountainous and inland areas [48,56]. Because of the topographical conditions, the type of occupation, which is predominantly forest/woodland, and sociodemographic characteristics, the cases studied belong to the group of municipalities with the highest hazard [48] as well as vulnerability to wildfires [56].

When the preponderance of coniferous and eucalyptus forests with high combustibility and flammability [57] is combined with steep slopes, the rapid progression of flames is assured. A number of authors confirm that areas occupied by coniferous forests and scrubland are the most prone to fire [45,58,59] compared to other uses of the land, notably agricultural. In fact, the very low and low wildfire hazard classes are dominant where agriculture is the most widespread land use. The less fire-proneness of agricultural areas has been recognised in several works in different geographical areas [45,58–61] where farmland around isolated houses and villages can act as a buffer zone against wildfires. This only fails in the case of extreme wildfire events when fire selectivity in specific land cover types is drastically reduced [62,63]. Various studies have shown that wildfire hazard can be changed by interventions based on fuel management at the landscape scale to reduce the probability that a wildfire would reach a given settlement [64,65].

Analysing this variable in isolation in the context of evacuation planning makes it possible to prioritise intervention areas with specific biophysical conditions, although the population to be evacuated is a determining component to be considered in conjunction with hazard [46]. Thus, when the hazard is cross-referenced with the SVES, resulting in the forest fire risk, it is possible to identify the most critical zones in terms of evacuation. The combination of high hazard classes and high social vulnerability, plus the greater dispersion of population centres in its territory, means that Sertã has a greater preponderance of high and very high fire risk classes than Lousã. In the case of Lousã, the combination of these two single dimensions has tended to attenuate the level of risk, with one component counterbalancing the other. The results are in line with those reported in Oliveira et al. [39]. These state that settlements with more exposure to hazard do not necessarily have the highest social vulnerability, in a parish located near the Lousã municipality. For most villages, they found that the aggregation of these two components tend to decrease the level of fire risk.

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

Many studies have shown that older people are particularly vulnerable during the evacuation process, noting the importance of considering the elderly when planning for evacuation [66,67], the physical difficulties that they may have with evacuation, especially without social support [68–70], and the community-level support. Also, several studies indicate that significant numbers of people delay evacuation during a wildfire event, which often increases evacuation danger [15]. Tedim [71] also points out that people often resist or choose to stay in their homes in an attempt to defend their property. This behaviour is associated with low levels of preparedness both for defending the home and for evacuation, which can heighten the risk to life and loss of property [72]. Many individuals will prefer to wait and assess the development of the fire while carrying out measures to protect their homes and property rather than evacuating immediately [73]. In this context, Melton et al. [74] note that the ways people in general and the more elderly in particular respond to or are impacted by wildfires are still relatively new and need further development and exploration to better learn from and support this population in the face of worsening wildfire disasters.

Portugal does not have a compulsory evacuation system and so the efficiency of this strategy depends on the willingness of the residents and the capacity of the authorities. Furthermore, in the municipality of Sertã only one "Aldeia Segura" was identified and in the "Aldeias Seguras" of Lousã there were no evacuation plans. In addition, there is no explicit reference to places of shelter or refuge, even though they are identified in the PMEPCs. These findings are in line with the results obtained by Vaqueiro [75], who stated that of the total of 2057 settlements that had signed up to the "Safe Village" programme at the time, only 172 had a set of planned actions, stating that only these could be considered "safe villages". The results of Tedim et al. [76] further reinforce these difficulties; in a questionnaire applied to 139 municipalities that had joined the programme, 91% reported constraints in its implementation.

In this context, taking into account the level of risk of each WUI, it is urgent to set priorities for emergency intervention, as well as to establish safety and evacuation protocols suited to each village. Moreover, considering that more and more catastrophic wildfires will occur with climate change, institutional and suppression capacities will probably be overridden [77–79]. For these reasons, fire management approaches must include strategies to mitigate the wildfire hazard and improve community preparedness and people's coping capacity, tailored to their needs and abilities, and so enable a suitable adaptation to fire-prone environments.

6. Conclusions

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

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

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

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