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Research article

Mapping the wildland-urban interface at municipal level for wildfire exposure analysis in mainland Portugal

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ABSTRACT

The Wildland-Urban Interface (WUI), where vegetation and built-up structures intermingle, encompasses a variety of territorial elements that interact spatially, being variable both in space and time. Mapping the WUI at finer scales is paramount to assess wildfire exposure and define tailored mitigation strategies. Our aim was to develop a semi-automated method to map the WUI at municipal level, leveraging recent advances in data and technology. We tested the procedure in four municipalities of mainland Portugal with different fire history, biophysical conditions, and sociodemographic contexts. We considered WUI as either *intermix* or *interface*. Our approach integrates both building location data and high-resolution vegetation maps, to calculate the density of buildings and forest cover proportion within different circular moving window sizes. Within each radius, we evaluated the total area and spatial distribution of the WUI types, as well as the number of buildings within WUI and within the fire perimeters recorded between the years 2000 and 2022 and analysed the differences between municipalities. We then compared the mapped WUI with previous WUI mappings for mainland Portugal, to identify common spots and potential spatial divergences. We found that the area mapped as WUI within all four municipalities ranged from about 400 km^2 to 1135 km^2 depending on the radius size. A distinct distribution for each type of WUI was observed as the radius size increased: the *intermix* WUI showed a tendency to increase, and the *interface* WUI increased only between the radius of 100 and 200 m, decreasing gradually in subsequent radii. Between 39.4% and 45.5% of the nearly 200,000 buildings in the study areas were within WUI, depending on radius size and a total of 5436 buildings were within the historic fire perimeter. Although the comparison with other maps showed fair agreement, due to differences in data and methodology, common areas mapped as WUI were found, which suggests that these areas should receive greater attention from decision-makers regarding fire management strategies, since their classification as WUI remains consistent across different methodologies.

1. Introduction

Over the past 30 years, an average of 450 thousand hectares of burnt area per year has been recorded in the European Union. Portugal has experienced the most significant impact from wildfires over the past two decades, with an average of approximately 150,000 ha burned per year. Notably, the years 2003, 2005, and 2017 stand out as particularly severe (San-Miguel-Ayanz et al., 2022). Wildfires were responsible for over 800 deaths between 1945 and 2016 in Southern Europe, and in 2017, just in Portugal, more than 100 fatalities occurred (Molina-Terrén et al., 2019; R. Oliveira et al., 2018).

Recent years have witnessed an increase in the exposure of human settlements to wildfires, stemming from two distinct trends: on one hand, urban expansion into vegetated areas prone to burning; on the other hand, rural exodus leading to the abandonment of pastures and cultivated areas, facilitating the accumulation of combustible material and the conversion of agricultural lands into shrublands (Bar-Massada et al., 2023; Bowman et al., 2013; Nunes et al., 2016; Radeloff et al., 2018). These mixed areas, where vegetation and built-up structures intermingle, commonly referred to as the Wildland-Urban Interface (WUI), are characterized by the coexistence of human settlements and wildland vegetation. As such, they bring additional challenges regarding firefighting, along with the potential for wildfires effects to extend beyond its boundaries and impact neighbouring lands (Stewart et al.,

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2007).

The interface areas encompass a variety of territorial elements that interact and spatially associate, being variable both in space and time. Within the WUI, houses and other built-up structures are susceptible to destruction by wildfires due to the intensification of human activities that promote changes in land use and land cover. (Radeloff et al., 2005; Stewart et al., 2007). These elements are determinant for the risk faced by the population and for the behaviour of fires, especially when aggravated by extreme weather conditions (Bergonse et al., 2021; Castellnou et al., 2018; Royé et al., 2020).

Recent decades have seen a surge in studies on WUI areas due to the increase in wildfires from climate change and urban expansion, and the challenges in managing these areas (Bento-Gonçalves and Vieira, 2020; Intini et al., 2020; Taccaliti et al., 2023). These studies span various scales, from global mapping by Schug et al. (2023) to continental analyses for Europe (Bar-Massada et al., 2023; Modugno et al., 2016), and country-specific mappings for the United States (Carlson et al., 2022), Canada (Johnston and Flannigan, 2018), Poland (Kaim et al., 2023), and Israel (Tikotzki et al., 2023). More localized studies include state-level mapping for Alaska (Liang et al., 2022) and regional mapping for Galicia, Spain (Chas-Amil et al., 2013) as well as municipal-level mappings (Pereira et al., 2018; Whitman et al., 2013).

WUI maps provide visual representations that reflect conceptual understandings of these areas (Stewart et al., 2007), often using population or housing data and vegetation data from satellite image classification. Despite using standard definitions, different analytical approaches can yield varying WUI classifications (Stewart et al., 2009). A common WUI classification, from the United States Federal Register (USDA, & USDI, 2001) operationalized by Radeloff et al. (2005), distinguishes WUI between: *intermix*, which involves the blending of housing with wildland vegetation, directly exposing the structures to wildfires; and *interface*, which entails the proximity of settlements to wildland areas, exposing them to wildfires indirectly, such as through flying embers. While the fire itself may not directly reach the structures, embers carried by the wind can ignite buildings, vegetation, or other combustible materials within the settlement. To be considered WUI, areas must have a minimum density of 6.17 houses/km^2. *Intermix* areas contain more than 50% combustible material, whereas *Interface* areas have less but are within a 2.4 km of a vegetation patch larger than 5 km^2.

Using this concept, there are two main methodologies for mapping the WUI (Bar-Massada, 2021): the zonal-based approach (Radeloff et al., 2005, 2018) that considers house density and the percentage of combustible material within a specific area, such as the census block, and the point-based approach (Argañaraz et al., 2017; Bar-Massada et al., 2013; Carlson et al., 2022; Kaim et al., 2023; Li et al., 2022), which typically involves using a circular moving window to estimate 'housing density' and the percentage of vegetation, based on the location of buildings, which can be acquired through visual interpretation (Argañaraz et al., 2017) or provided by governmental institutes (Bar-Massada et al., 2013; Kaim et al., 2023; Lampin-Maillet et al., 2009, 2010; Tikotzki et al., 2023). Schug et al. (2023b) employed a similar approach using a global raster dataset with estimates of built-up surface area per pixel.

Nonetheless, not all governmental institutes possess such data, and the process of visual image interpretation can be time-consuming and costly, depending on the size of the study area. In recent years, Microsoft® has made substantial progresses in employing deep learning, computer vision, and Artificial Intelligence (AI) technologies for mapping purposes, harnessing the capabilities of machine-learning to analyse satellite imagery and delineate the outlines of buildings globally. These data have the advantage of being open access and have already been employed for mapping WUI in recent studies (Bar-Massada, 2021; Carlson et al., 2022; Li et al., 2022).

Other methods can incorporate additional elements. Lampin-Maillet et al. (2010) identified twelve interface classes by considering housing density and vegetation aggregation, this approach was adapted for mapping WUI in northern Portugal (Santos et al., 2023), and in Italy (D'Este et al., 2021). Amato et al. (2018) developed a stochastic map expressing the probability of being part of an interface based on Multilayer Perceptron Artificial Neural Network and Fuzzy Set Theory. Tikotzki et al. (2023) developed an empirical approach creating a WUI index from building, vegetation, and fire history data. Other terms can be used to define WUI (Taccaliti et al., 2023), some approaches also include agricultural areas as combustible material, termed Rural-Urban Interface (RUI), acknowledging the influence of agricultural areas on fires (Bouillon et al., 2014; Sirca et al., 2017; Tonini et al., 2018). In Australia, the term Bush-Urban Interface (BUI) is used (Solangaarachchi et al., 2012). All these terms specify the characteristics of WUI in different regions, functioning as synonyms for the broader WUI concept (Bento-Gonçalves and Vieira, 2020).

As for Portugal, Tonini et al. (2018) examined the historical evolution of the RUI between 1990 and 2012 using the CORINE Land Cover map. They delineated interfaces with a 1000 m buffer around artificial surfaces intersecting forest, semi-natural, and heterogeneous agricultural areas. Their findings indicated an RUI increase mainly along the coast and northwest, driven by agricultural-to-urban transitions. Additionally, the burn area within the RUI grew proportionally more than the RUI area. Amato et al. (2018) projected RUI probabilities for 2030, consistent with Tonini et al. (2018), showing likely increases along the coast and northeast. However, both studies used a coarse-scale Land Use/Land Cover (LULC) map, which might have led to information loss about artificial areas and combustible materials.

The Directorate-General for Territory (DGT) provides two interface maps based on Portugal's official LULC cartography (see section 2.4) These maps delineate built-up areas based on their proximity to combustible materials. While they offer valuable information about urban surroundings, their linear format restricts the ability to measure fire exposure or calculate areal spatial metrics. Moreover, these maps do not account for the specific locations of individual buildings.

For Portugal, there are currently no studies classifying interfaces based on the relationship between built structures and combustible material in the surrounding environment, specifically in *intermix* and *interface* areas. Considering the importance of mapping WUI at finer scales to assess wildfire exposure and taking advantage of recent advances in data and technology. Our aim is to map the interface areas in four municipalities of mainland Portugal, with different territorial conditions. We intend to verify if they have distinct WUI format and extension and how these differences may influence wildfire exposure. To achieve these objectives, the most detailed data currently available and different moving window radius sizes, namely the location of buildings available in the Microsoft® database and the land cover map for the year 2022 with a spatial resolution of 10 m. For Portugal, this level of detail has not yet been used for mapping interfaces; therefore, we want to assess the feasibility of its utilization and the possibility of developing an algorithm that allows for dynamic mapping of interface areas as new data becomes available. We use published WUI maps at European level to compare the areas mapped as WUI with our methodology.

2. Materials and methods

2.1. Study area

Our study area comprises four municipalities in mainland Portugal, namely: Chaves, Loulé, Mangualde, and Sintra, as shown in Fig. 1a. They were selected due to their diverse social and biophysical conditions, such as settlement type, proportion of built-up area, population density, and level of fire hazard (Nunes, 2012; S. Oliveira et al., 2017, 2021). Given the issue of wildfires in Portugal, the DGT identified "Vulnerable Forest Territories" composed of civil parishes (the smallest administrative unit in the country) with higher susceptibility and hazard to wildfires. The criteria for selecting these parishes were established in Decree-Law No. 28-A/2020, of June 26, which states that territories

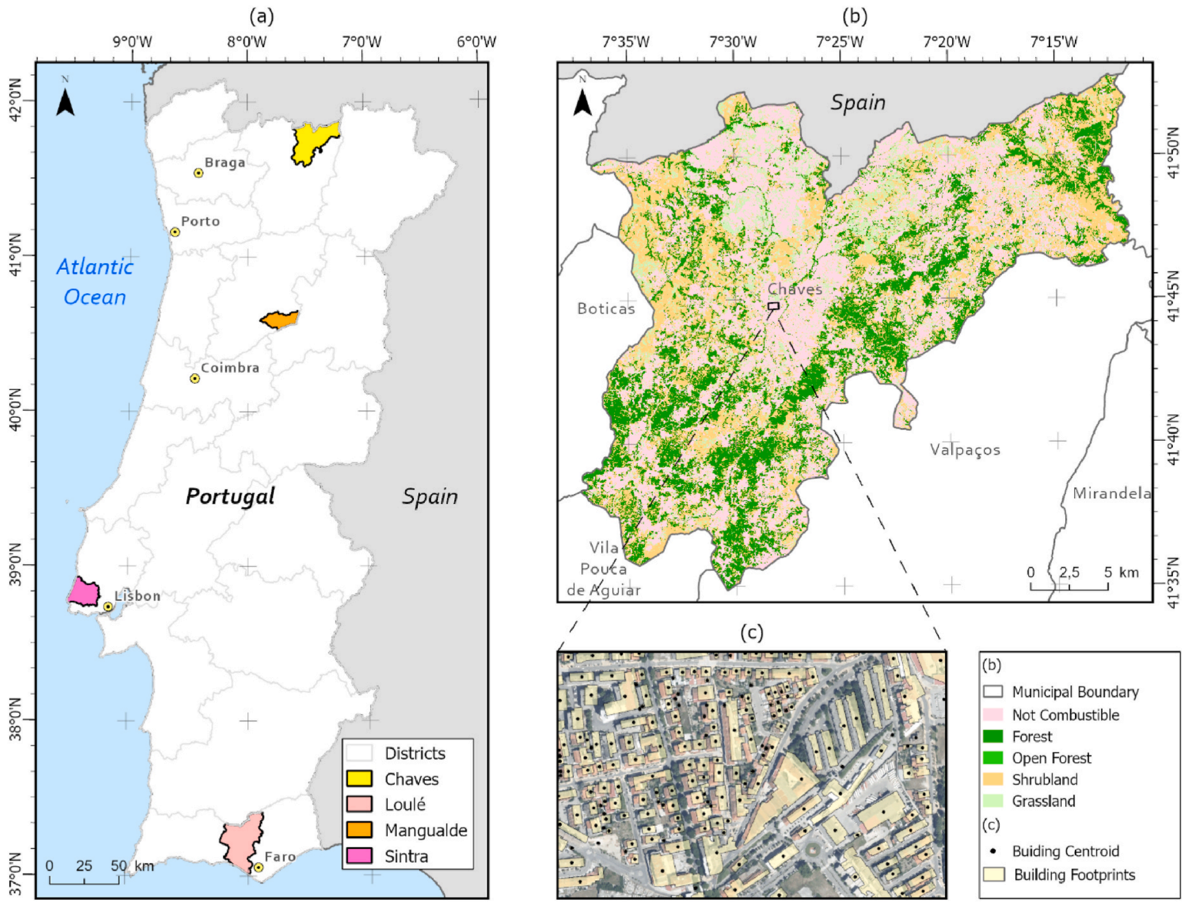

Fig. 1. Study area municipalities (a); example of combustible materials in Chaves obtained from Conjunctural Land Cover Map (DGT, 2022) (b) and detailed building footprints and their centroids obtained from GlobalMLBuildingFootprints (c).

with over 40% of the area under high and very high structural fire hazard (Institute for Nature Conservation and Forests - ICNF, 2022) and those not meeting the hazard criterion but surrounded by parishes that do, are considered vulnerable. In our study area, a total of 50 parishes within the selected municipalities were identified as vulnerable. Sintra is the only municipality with no parishes in this condition. Among the nine parishes in Loulé, one is vulnerable. Mangualde has eleven of its twelve parishes in vulnerability, and Chaves has thirty-eight vulnerable parishes out of thirty-nine.

2.2. Buildings footprint

The distribution of the population in the territory is one of the main components of a WUI, which we represented in this study using the buildings footprints database. The building footprints dataset were obtained from Microsoft® global buildings dataset (Microsoft, 2023). That were obtained by semantic segmentation using Deep Neural Networks in high resolution satellite images and converting the buildings detected into polygons. Microsoft® reports that this dataset, in Europe, had very high accuracy levels, with 94.3% of precision, 85.9% of recall and the false positive ratio was 1.4% in a random sample of 5000 buildings. This dataset accuracy was tested by Bar-Massada (2021) that found similar accuracy ratios using circular buffers (250 m) around 99 random building points on the United States of America.

2.3. Land cover map

The land cover map used for the identification of combustible materials was the Conjunctural Land Cover Map (COSc) of mainland Portugal for the year 2022 (Direção Geral do Território - DGT, 2022b). It comprises 15 thematic classes at its most detailed level and has a pixel resolution of 10 m. Its production is carried out using spatial technologies and AI, which includes machine-learning algorithms and expert knowledge rules for the automatic classification of multispectral and intra-annual series of data obtained from Sentinel-2 satellite images. These are integrated into the methodology developed to produce the first COSc in 2018 (Costa et al., 2022). To execute this process, a spectral database is built, comprising monthly composites, spectral indices, and intra-annual metrics derived from Sentinel-2 imagery for the agricultural year under analysis.

The data related to combustible materials were derived from the vegetation classes of COSc and encompass five thematic classes, with four considered combustible, namely: forest (eucalyptus, other broadleaves, maritime pine and other conifers), open forest (agroforest system - ASF, evergreen oaks and stone pine, associated with shrublands), shrublands, grasslands and not combustible (artificial lands, agriculture lands, bare soil, wetland, water and ASF associated with agriculture). These data are not available to the public, they have been kindly provided to us by the DGT, and are the same as those used for the elaboration of the Conjunctural Built-up Area Intini et al., 2020; Direção Geral do Território - DGT, 2022a) (see section 2.4). We chose to include natural grasslands as combustible material because DGT considered this class in its official mapping.

More than 60% of the study area consists of combustible materials (Table 1), a pattern observed in all municipalities except Sintra. Mangualde has the highest proportion of combustible materials at 68.3%, with significant amounts of shrublands (38.3%) and grasslands (15.9%). Sintra is unique for having most non-combustible materials covering

Table 1
Combustible materials (%) by class in the 4 municipalities that compose the study area.

Municipality	NUTS 3	Not Combustible	Forest	Open Forest	Shrubland	Grassland	Total Area (km^2)
Chaves	Alto Tâmega	34.5%	24.5%	–	27.5%	13.5%	591.2
Loulé	Algarve	35.3%	17.7%	11.1%	30.0%	6.0%	763.7
Mangualde	Viseu Dão-Lafões	31.7%	13.8%	0.2%	38.3%	15.9%	219.3
Sintra	Metropolitan area of Lisbon	50.7%	18.3%	1.2%	16.4%	13.3%	319.2
Total Study Area		37.2%	19.5%	4.7%	27.9%	10.7%	1893.4

over 50% of its territory. Loulé, the largest municipality, predominantly features open forests (11.1%), although shrublands and forests are more prevalent overall. Chaves stands out with 27.5% shrublands and the highest proportion of forest cover (24.5%) among the municipalities analysed. Fig. 1b presents the spatial distribution of combustible materials in the municipality of Chaves.

2.4. Portugal interface official data

DGT provides two cartographies of interfaces aimed at supporting forest fire defence planning. They are called "Built-up Area Interface Maps" and can be either Conjunctural (Direção Geral do Território - DGT, 2022a) or Structural (Direção Geral do Território - DGT, 2020; Pereira et al., 2018). They are polylines that represent the perimeter of built-up areas, categorized according to the distance to combustible material. The main difference between them is the basis used to define the material considered as combustible.

The Structural map (Pereira et al., 2018) have three classes and is based on the Structural LULC Map (COS) of 2018, which is a vector product based in photo interpretation with a minimum cartographic unit of 1 ha, and the combustible material considered includes the COS classes that burned the most during the period between 2010 and 2018.

The Conjunctural map have the same methodology but has four classes and is based on the COSc of the current year, which is a raster product with a spatial resolution of 10 m and a minimum cartographic unit of 0.1 ha. For its classification, the combustible material considered includes forest, open forest, shrubland, and grassland vegetation.

2.5. Mapping the wildland - urban interface

To map the WUI in the selected municipalities, we employed the definition from the United State Federal Register (USDA, & USDI, 2001): *intermix* and *interface*. Our approach, inspired by the point-based methodology (Argañaraz et al., 2017; Bar-Massada et al., 2013; Carlson et al., 2022; Tikotzki et al., 2023), integrates both building location data and high-resolution vegetation maps. We convert the building centroids into a raster layer with a 10 m resolution and subsequently calculate the density of buildings and the proportion of forest cover within five different circular moving window radii sizes: 100, 200, 500, 600, and 1000 m. To be considered a WUI candidate, and achieve the limit of 6.17 buildings/km^2, each circular moving window size needs a minimum number of structures, as presented in Table 2.

For identifying *intermix* WUI, we employ a threshold of combustible material cover exceeding 50% (Radeloff et al., 2005) within each moving window size. WUI candidates with less than 50% combustible material cover but situated within a 600 m adjacent to large combustible material patches (>5 km^2) are classified as *interface* WUI. The 600 m distance from large vegetation patches was also employed by Argañaraz et al. (2017) in the central region of Argentina as the maximum distance that a flying ember can reach in that area and Bar-Massada et al. (2023) used the same distance to map WUI in Europe, considering that this value represents approximately the median value of the maximum travel distances of flying embers. We chose to adopt this distance to align with the study conducted in the European continent and to be less permissive than the 2.4 km distance employed in other studies (Kaim et al., 2023; Radeloff et al., 2005; Schug et al., 2023b). To adjust our WUI maps, we converted our raster layers to polygons and removed those without any buildings (Carlson et al., 2022).

Table 2
– Minimum number of buildings for each circular moving window radius size.

Radius (m)	Area (km^2)	Buildings (No.)
100	0.0314	1
200	0.1256	1
500	0.7860	5
600	1.1304	7
1000	3.1400	20

Finally, after mapping the WUI using different parameters, we evaluated the total area and spatial distribution of both *interface* and *intermix* WUI categories, as well as the number of buildings within each moving window size and their exposure to wildfires, to identify the generated differences. Buildings within WUI areas are vulnerable to fire depending on the fire resistance of their construction systems and the materials used (Lopes et al., 2023). To identify buildings exposed to wildfires, we analysed their presence within the fire perimeters recorded between the years 2000 and 2022, obtained from the Portuguese Forest Services (ICNF). The presence of buildings within areas that were burned does not necessarily imply that they were affected by fire, but these areas are more fire-prone due to their recent history of burns (Argañaraz et al., 2017; Caggiano et al., 2020).

2.6. WUI comparison

To access the level of agreement of the identified WUI, we compared the results with the most updated WUI mappings for mainland Portugal. The first comparison was made with the WUI map created by Bar-Massada et al. (2023), we will henceforth use only the term 'WUI_BM'. This map was provided to us upon request to the authors, who also classified the WUI as *intermix* and *interface* within a 100 m radius from built-up areas.

The second was made with the WUI map to entire world created by Schug et al. (2023b), hereafter referred to as 'WUI_SC'. This dataset is available online (Schug et al., 2023a). This map classifies two types of *intermix* and *interface* WUI based on the vegetation types ('Grassland-dominated' and 'Forest/Shrubland/Wetland-dominated') within a 500 m radius from built-up areas. We merged these classifications to obtain a single class for each WUI type: *intermix* or *interface*. After this merging, we compared it with our mapping within a 500 m radius.

We compared the total area mapped as either *interface* or *intermix* WUI combining the WUI maps produced to generate a single composite map indicating areas that are: (0) Not WUI, (1) WUI in both studies, (2) only our WUI, or (3) only WUI in the other study. Subsequently, we calculated the Jaccard similarity coefficient score and the Accuracy classification score considering each type of WUI in two steps: (i) considering the entire study area and (ii) only where there is intersection between the mappings. To calculate this, we use the functions disponible in the module Scikit-learn for Python (Pedregosa et al., 2011).

The third comparison was made with the Conjunctural Built-up Areas Interface Map (DGT, 2022) of mainland Portugal for the year 2022. We examined the density (km/km^2) of each DGT's interface class within our WUI for the moving windows radius size of 100, 500, and 1000 m.

A summary of the methodology used in these three approaches is presented in Table S1 at supplementary material. Despite the different approaches in each method, the underlying notion is that there are locations that will always be considered as WUI regardless of the method used.

2.7. Spatial analysis and automation

The spatial analyses conducted in this study were performed using the tools available in the Geographic Information System (GIS) ArcGIS Pro, integrated with automated routines enabled by the Python language interface within this software. Initial preprocessing tasks, such as identifying building centroids and converting them to raster format or locating large combustible material fragments, were individually executed in ArcGIS Pro. Statistical processing within each moving window radius size, as well as the identification and classification of different interface types, were optimized and automated using Python. The developed routines enabled the generation of new analyses by simply adjusting the input parameters, such as the radius or the study area.

3. Results

3.1. Wildland - urban interface map

The area mapped as WUI, considering the total study area, ranged from approximately 400 km^2 (21.5%) to 1.135 km^2 (60%) according to the circular moving window radius size. Fig. 2 shows three examples of the resultant spatial patterns of WUI for all municipalities, and distinct distribution for each type of WUI were observed as the radius size increased.

Fig. 3 shows that the area defined as *intermix* showed a tendency to increase, with the largest increase occurring between the radii of 100 and 200 m, accounting for 54% of the total study area. The difference in the area mapped as *intermix* between the 200 and 500 m buffers was smaller, at 31% of the total study area, despite the larger increase in the moving window radius size. On the other hand, the area identified as *interface* increased only between radii of 100 and 200 m, and in subsequent radii, it gradually decreased.

Each municipality exhibited different patterns as the radius size increased. The area mapped as *interface* exceeded *intermix* only in Loulé and Chaves for the 100 m radius; in all other cases, *intermix* presented a larger area. Sintra had the area mapped as WUI increase up to the 500 m radius and then begin to decline. The proportion of WUI in this municipality never exceeded 40% of the territory. Loulé had the largest mapped *interface* area for all radii compared to the other municipalities, however, proportionally it always occupied less than 15% of the territory. Mangualde exhibited a higher proportion of *intermix* for all radii, ranging from approximately 22%–82% of the territory between the 100 m and 1000 m radii. Conversely, the area mapped as *interface* decreased from the 200 m radius onwards. Despite this decline, it was the municipality that showed the highest proportion of WUI regardless of the analysed radius, reaching a maximum of 88.7% at the 1000 m radius. Chaves had the largest total mapped area as WUI, ranging from 130 km^2 to 428 km^2; however, proportionally, the WUI occupied a maximum of about 72% of the territory.

Fig. 4a shows an example of the WUI identified in the municipality of Sintra using a 500 m radius. The *intermix* category predominates, with a few *interface* fragments mainly in the northern part of the municipality. Fig. 4b illustrates the variation in the spatial pattern of WUI with the different tested moving window radii sizes. Despite the overall increase in mapped WUI area some areas ceased to be classified as WUI as the radius size increased: between 100 and 500 m, there was a total loss of 50.6 km^2, and between 500 and 1000 m, the loss was 67.8 km^2. We observed that using larger moving windows resulted in fewer clusters of individual buildings and more interface areas in surrounding combustible materials.

Table 3 shows the relationship between areas mapped as *intermix* and *interface*. Sintra exhibited the greatest disparity in WUI mappings across all radius sizes, with *intermix* areas being ten to sixteen times larger than *interface* areas. Except for Mangualde at the 1000 m radius, this proportion was not greater than seven times in other municipalities and

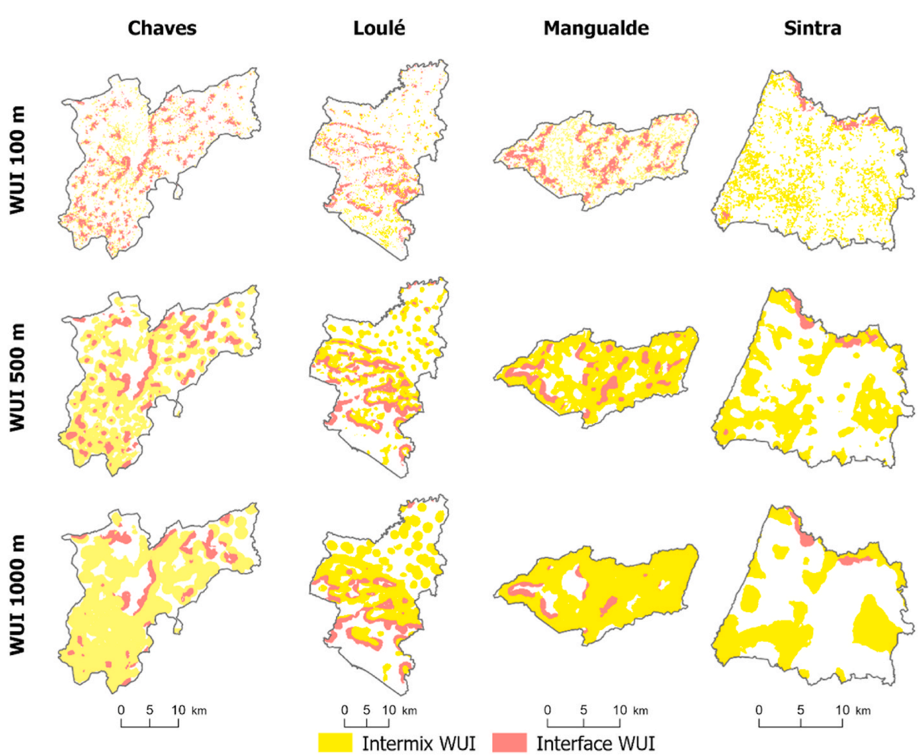

Fig. 2. Spatial patterns of WUI on the four municipalities for three radius size.

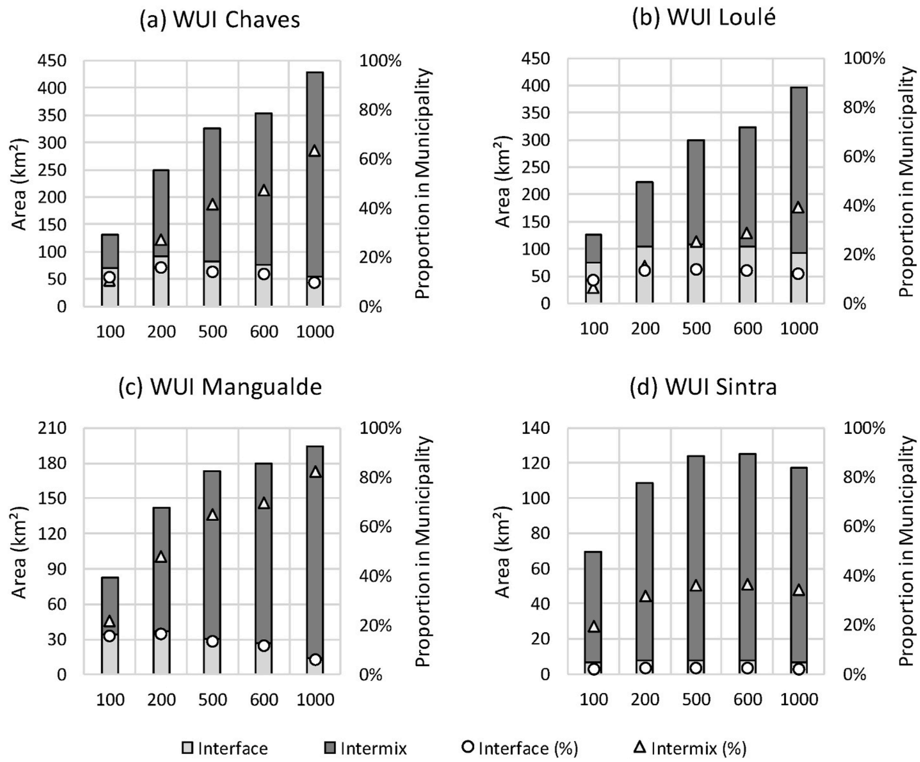

Fig. 3. – Total area and proportion of *intermix* and *interface* WUI by radius size, in the four municipalities of the study area.

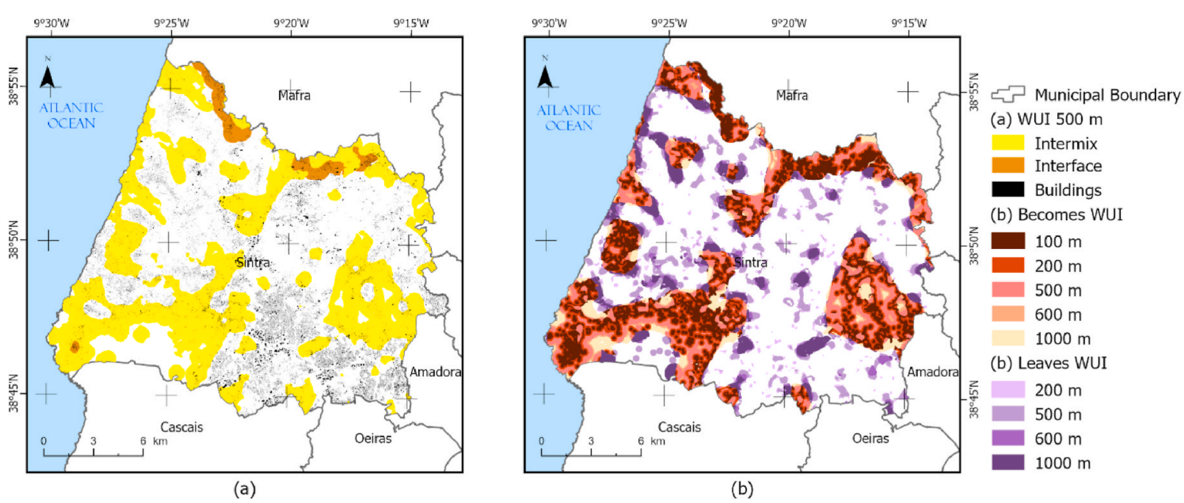

Fig. 4. – Wildland - Urban Interface in Sintra: (a) the spatial pattern of *intermix* and *interface* considering the radius of 500 m; (b) gains and losses in WUI area on each circular moving window radius size.

Table 3
Ratio between *intermix* and *interface* WUI.

Municipality	Circular moving window radius size				
	100 m	200 m	500 m	600 m	1000 m
Chaves	0.9	1.7	3.0	3.7	6.8
Loulé	0.7	1.1	1.8	2.1	3.3
Mangualde	1.4	2.9	4.7	5.8	13.0
Sintra	9.8	13.2	14.7	15.0	16.5
Total Study Area	1.2	2.0	3.1	3.6	5.7

moving window radii. Loulé showed the greatest similarity between mapped WUI areas, with *intermix* areas being at most approximately three times larger than *interface* areas in the largest radius analysed. Across the entire study area, the *intermix*-to-*interface* ratio ranged from 1.2 to 5.7.

3.2. Buildings in WUI

Out of the total 198,894 buildings in the study area, the proportion in WUI areas ranged from 39.4% to 45.5% as the radius size increased (Fig. 5a). Conversely, the buildings-to-WUI-area ratio decreased from approximately 192 buildings/km^2 (100 m) to about 80 buildings/km^2 (1000 m) (Fig. 5b). Only Loulé had a similar pattern to the overall study area, with consistent building proportions in WUI areas regardless of

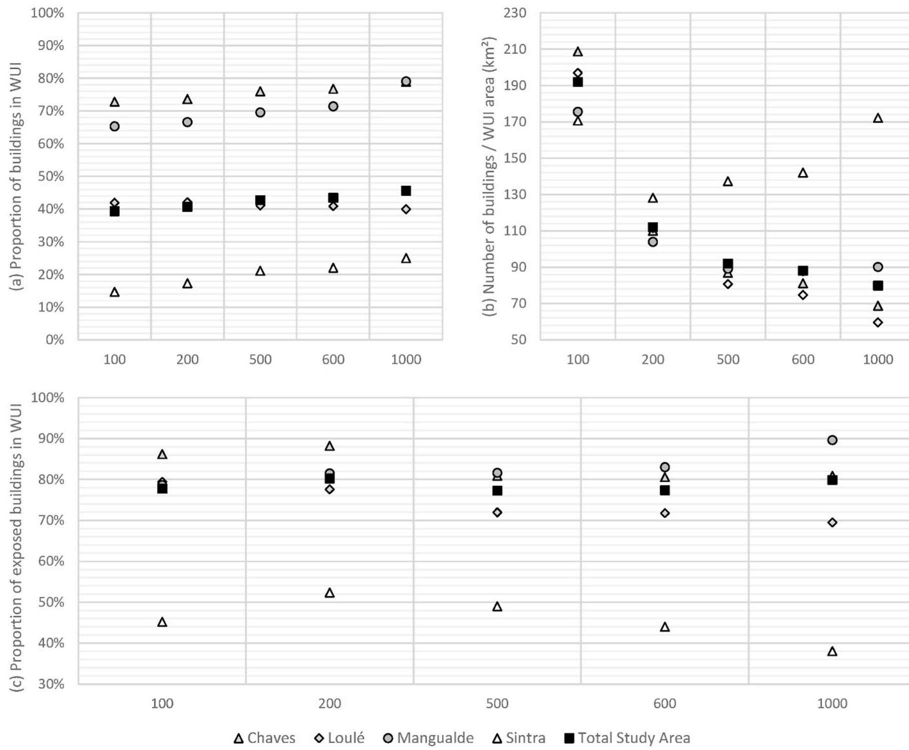

Fig. 5. Buildings inside WUI in each municipality and the total study area: proportion of buildings (a); the ratio between buildings and WUI area (b), proportion of exposed buildings within WUI (c).

WUI type. Chaves and Mangualde had over 65% of their buildings in WUI areas across all radius sizes. Sintra consistently showed lower values, with a maximum of 25% of buildings in WUI at the 1000 m radius. Notably, Sintra was the only municipality where the buildings/ km^2 ratio increased with radius size, except between 100 and 200 m.

We identified a total of 5436 buildings exposed to wildfires in all four municipalities, with Mangualde and Chaves accounting for 78.7% of this total. Fig. 5c shows the proportion of buildings located within WUI areas. Except for Sintra, all municipalities had more than 70% of the buildings located in interface areas, primarily in WUI *intermix*. Detailed information on buildings within each WUI can be found in Table S2 at supplementary materials.

3.3. Comparison between WUI maps

The resulting map from the combination of our WUI 100 m and the WUI_BM, Fig. 6a, and our WUI 500 m and the WUI_SC, Fig. 6b, identified areas of overlap between the maps, namely areas classified as WUI in both studies, areas identified as WUI in only one of the studies, and areas not considered as WUI by either. At supplementary materials Fig. S1 show the comparison for all municipalities.

Table 4 presents the confusion matrix with these two WUI mappings. The area not considered as interface by our study and the WUI_MB was approximately 1408 km^2 (74.4%). Meanwhile, the area identified as WUI in both studies was approximately 139 km^2 (7.3%), of which the areas classified as *intermix* by both were approximately 40 km^2 (2.1%) and identified as *interface* were approximately 50 km^2 (2.7%). However, approximately 22 km^2 (1.2%) were classified as *interface* in the WUI_BM and as *intermix* by us, and 26 km^2 (1.4%) of the area classified as *interface* by us were identified as *intermix* by the other study. Finally, there are approximately 77 km^2 (4.1%) of interfaces solely identified in the WUI_BM and approximately 268 km^2 (14.2%) of interfaces solely identified by us. Jaccard Index (0.38) and Agreement Score (0.79) are higher, suggesting a greater overall similarity and concordance with WUI_BM. This is because both classifications broadly agree on large areas classified as "Not WUI", which increases the index values.

The area not considered as interface by our study and the WUI_SC was approximately 611 km^2 (32.3%). The area identified as WUI in both studies was around 605 km^2 (32%), with approximately 407 km^2 (21.5%) classified as *intermix* by both and 6.7 km^2 (0.4%) identified as *interface* by both. Approximately 2 km^2 (0.1%) were classified as *interface* in the WUI_SC but as *intermix* by us, and 190 km^2 (10%) of the area classified as *interface* by us were identified as *intermix* by the other study. Lastly, approximately 359 km^2 (19%) of interfaces were solely identified in the WUI_SC, while around 318 km^2 (16.8%) of interfaces were solely identified by us. Jaccard Index (0.28) and Agreement Score (0.54) are both lower, reflecting a less overall similarity. However, the Agreement Score Intersection (0.68) is high, indicating good concordance in overlapping areas. Although there is a larger overlap between our WUI and WUI_SC, the presence of numerous differently classified areas contributes to lower overall similarity indices. For example, they identify more urbanized areas as WUI, whereas we identify more isolated areas as WUI (Fig. S2a).

In comparing our WUI maps with the existing DGT linear interface, Fig. 6c, d shows DGT interfaces within our WUI, and Table 5 details the relationship between DGT interface kilometres and WUI square kilometres. For *intermix* WUI, DGT's "Direct" interface consistently had a higher km/km^2 ratio across all window sizes and the entire study area. In *interface* WUI, the ratio of "Indirect 1″ interface was higher than "Direct" when considering the entire study area, despite local variations. "Indirect 2″ and "Null" interfaces were less prevalent in the WUI.

We observed that the relationship between the length of DGT interfaces and the area mapped as WUI decreased as the radius size increased. The most significant decrease occurred between the 100 and 500 m radii, where the WUI area approximately doubled while the length of DGT interfaces remained constant. Between the 500 and 1000 m radii, the growth was less pronounced. In some cases, such as in Sintra, the WUI area even decreased with the larger radius.

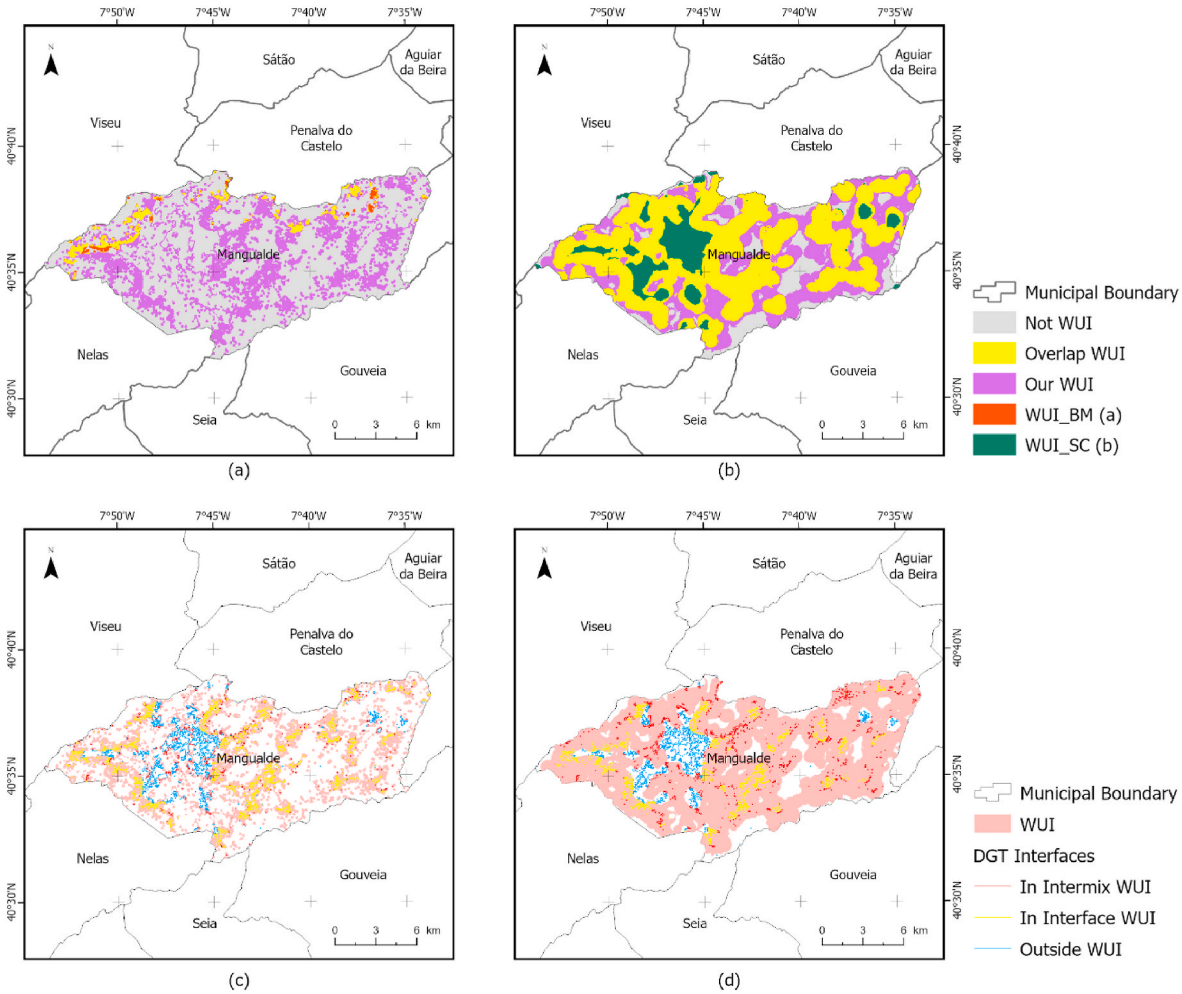

Fig. 6. – Overlaps in Mangualde between our WUI 100 m and WUI_BM (a); our WUI 500 m and WUI_SC (b). DGT's interface intersect our WUI at two moving window sizes: 100 m (c); 500 m (d).

Table 4
Confusion matrix of comparison between our WUI map and WUI_BM and our WUI map and WUI_SC in square kilometres. The bold numbers represent the interface overlaps between the maps. Values shown are in square kilometres converted from the count of the number of pixels in each class. Each pixel has an area of 100 m^2.

WUI	WUI_BM		
	Not WUI	Intermix	Interface
Not WUI	1408.1	25.6	51.8
Intermix	160.1	**40.4**	**22.2**
Interface	108.7	**26.0**	**50.5**
Jaccard Index: 0.38		Agreement Score: 0.79	
Jaccard Index Intersection: **0.48**		Agreement Score Intersection: **0.65**	
WUI	**WUI_SC**		
	Not WUI	*Intermix*	*Interface*
Not WUI	610.9	287.3	71.8
Intermix	288.2	**406.8**	**1.9**
Interface	30.2	**189.6**	**6.7**
Jaccard Index: 0.28		Agreement Score: 0.54	
Jaccard Index Intersection: **0.36**		Agreement Score Intersection: **0.68**	

4. Discussion

Given the increasing threat of wildfires in urban and peri-urban areas, mapping the Wildland-Urban Interface (WUI) plays a crucial role in understanding and mitigating fire exposure. This spatial characterization allows for the identification of vulnerable areas and the implementation of effective prevention and response strategies, ensuring the safety of communities and the preservation of natural resources. In this work, we mapped in detail the WUI for four municipalities in mainland Portugal, each exhibiting particular territorial conditions. Our approach considered the location of buildings and vegetation patterns based on a high-resolution land cover map of Portugal. The mapped WUI ranged from 21% to 60% of the total study area depending on the circular moving window radius size. Individually, the variation was high among municipalities, with a minimum of 16% of the Loulé area mapped as WUI for a 100 m radius and a maximum of 88% of Mangualde identified as WUI for a 1000 m radius. For our total study area, the area mapped as WUI by Bar-Massada et al. (2023) corresponds to 11%, while us mapped 21% of the total study area using 100 m radius size. With 500 m radius size Schug et al. (2023b) mapped 50% of the total study area as WUI, while us mapped 48% with the same radius size. Although both studies used similar general approaches to map the WUI and the same landcover map, they differed in the size of the moving window, the type of data on built-up areas, and the definition of flammable land cover types (Schug et al. (2023b) included grasslands while Bar-Massada et al. (2023) did not).

These discrepancies in mapping are expected and stem from the selection of input data and the methodological approach, such as the spatial resolution of the data and the parameterization defined (i.e. proportion of buildings in different scale levels, choice of combustible material and its proportion or the size of the moving window around the

Table 5
Ratio between DGT Interface and WUI represented by km/km^2. CV - Chaves; LL - Loulé; MG - Mangualde; ST - Sintra and TSA - Total Study Area.

Radius (m)	DGT Interface	*WUI Intermix*					*WUI Interface*				
		CV	LL	MG	ST	TSA	CV	LL	MG	ST	TSA
100	Direct	3.0	4.6	1.9	6.7	4.2	4.3	2.0	2.2	3.9	2.9
	Indirect 1	0.1	0.2	0.1	0.1	0.1	3.7	4.0	4.0	3.8	3.9
	Indirect 2						0.6	1.9	1.7	0.8	1.3
	Null										
500	Direct	1.1	1.0	0.8	3.4	1.4	2.9	1.3	2.0	2.9	2.0
	Indirect 1	0.4	0.4	0.4	0.4	0.4	2.3	2.2	3.3	2.6	2.4
	Indirect 2						0.5	1.3	1.9	0.6	1.1
	Null										
1000	Direct	1.1	0.6	0.9	3.4	1.2	2.2	1.3	2.1	2.6	1.7
	Indirect 1	0.5	0.5	0.8	0.6	0.6	1.6	1.9	3.0	2.3	1.9
	Indirect 2	0.1	0.1	0.3		0.1	0.3	1.3	1.8	0.5	1.0
	Null										

pixel in a point-based approach). Nonetheless, when compared to studies using a 100 m radius size, Lampin-Maillet et al. (2010) found that 30% of the territory near Marseille in southeastern France was identified as WUI, while for Baião, Northern Portugal, Santos et al. (2023) found that 26.7% of the municipality is classified as WUI. For Israel, Tikotzki et al. (2023) found that using the same data but with different parameterization, particularly at the national and regional scale levels, could result in different spatial patterns in the mapped WUI.

The ratio between *intermix/interface* WUI increased with the increase in the radius size of the moving window. This effect was expected because there is a direct relationship between the area mapped as *intermix* and the radius, while the area mapped as *interface* exhibits greater stability or even a decrease. This pattern has also been observed in other studies (Argañaraz et al., 2017; Bar-Massada et al., 2013; Carlson et al., 2022; Kaim et al., 2023). As pointed out by Kaim et al. (2023), WUI areas are highly sensitive to the size of the radius, especially near large patches of combustible material, where increasing the radius also increases the area of forest mapped as WUI, and conversely, near areas with small vegetation patches and dense built areas, smaller radii identify more *intermix* WUI fragments, which disappear when using larger radius sizes. Li et al. (2022), mapping the WUI for California, showed that changes in the distance to large vegetation patches do not abruptly alter the percentage changes in WUI area.

Considering the total extent of our study area, the percentage of buildings located within the WUI never exceeded 46%. However, there was a large variation among municipalities depending on the radius size. Mangualde and Chaves exhibited the highest values, consistently exceeding 65%, while Loulé consistently hovered around 41%, and Sintra showed lower rates of less than 25% of its buildings located in the WUI. Overall, the rate of buildings located in the WUI was consistently increasing with the increase in radius size, except for Loulé, which experienced a slight decline. Bar-Massada et al. (2013) observed an opposite pattern in in four U.S. locations (i.e. Santa Monica, CA; Grand County, CO; Huron NF, MI and Minong, WI), fewer buildings were within the interface area as the radius size increased, but over 80% remained in the WUI. In contrast, Kaim et al. (2023) observed that in Poland, about 60% of buildings were consistently in the WUI, regardless of radius size.

The spatial configuration of buildings in relation to combustible areas is crucial in determining wildfire exposure, with the intermingling of vegetation and built-up structures posing greater danger to population and assets (R. Oliveira et al., 2018; Radeloff et al., 2005; Stewart et al., 2007). To assess exposure in our study area, we examined the cumulative perimeter of burned areas for 22 years, identifying a total of 5436 buildings within this zone. Apart from Sintra, all municipalities showed over 70% of buildings exposed to wildfires within WUI areas, with *intermix* areas hosting most exposed buildings. These findings align with those of Argañaraz et al. (2017) and Caggiano et al. (2020), who observed that more than 60% of buildings in fire-prone areas are located within interface areas.

The different WUI patterns identified showed an increase in exposed buildings within WUI areas at a radius of 100–200 m, followed by a decrease between 200 and 500 m. In Sintra and Loulé, this decreasing trend continues in subsequent radius sizes, while in Chaves and Mangualde, the number of exposed buildings in WUI areas increases again. This reinforces the importance of effective land use planning in new developments to ensure building safety and establishing safer conditions for fire management (Taccaliti et al., 2023). Existing buildings in exposed WUI areas must be integrated in fuel management programs, and new construction should be constrained to less fire-prone areas. Despite existing regulations pointing to such measures (e.g. Decree-Law No. 82/2021, of 13 October), their enforcement is hindered by the socioeconomic context and land ownership structure in the country (Canadas et al., 2023). Mapping the WUI at the local level can assist in targeting the areas that require more urgent measures of protection. Additionally, construction practices must prioritize using fire-resistant materials (Lopes et al., 2023).

The comparison between our WUI, obtained for a 100 m circular moving window size radius, and those of Bar-Massada et al. (2023), as expected, did not show significant overlaps, around 7% of total study area. The differences found may primarily be related to the data and methodology used in both studies. Despite both adopting a 100 m moving window around built-up areas, there are some notable differences to highlight: Built-up areas: we used the Global-MLBuildingFootprints dataset as a base, whereas they utilized data from the World Settlement Footprint dataset of 2019 (Marconcini et al., 2020); Vegetation threshold: we accounted for a minimum of 50% vegetation within the same 100 m radius, while they used a 500 m moving window around the pixel; and Land cover map: we used the COSc of 2022, a map specifically developed for Portugal, whereas they used vegetation data from the 2020 European Space Agency (ESA) global land cover. But the main difference is that we choose to incorporate the grassland as combustible material.

Although Schug et al. (2023b) and Bar-Massada et al. (2023) have used the same LULC for mapping the WUI, the comparison between our studies showed more areas of overlaps, approximately 32%. However, our adopted methodology was able to avoid mapping urbanized areas as WUI, but we map more isolated areas as WUI (Fig. S2a at supplementary materials). The difference in methodologies was able to find a similar proportion of interfaces, but spatially the identified WUI may not be in the same local. This is mainly related to the thresholds adopted for building density and the source of the building data used in the two studies.

It is important to note that: despite the described differences, areas mapped as WUI were found in both approaches. This may suggest that these areas should receive greater attention from decision-makers for maintenance and fire control, since their classification as WUI does not vary with the methodology employed.

The built-up areas from DGT, used to create the interfaces, do not include all buildings from the Microsoft® database. Out of 198,894 building centroids in the study area, only 165,637 (83.3%) overlapped with DGT built-up areas. DGT considers only residential buildings and 'artificialized areas' from Costa et al., 2022, while our data is from 2023. We expected a stronger relationship between *intermix* WUI and "Direct" DGT interfaces, but this was only seen for the 100 m radius. For other radii, "Direct" and "Indirect 1" interfaces were more prevalent in WUI interfaces. Notably, (i) DGT classifies interfaces based on proximity to combustible material, whereas we use a percentage within a radius to classify WUI, and (ii) *intermix* WUI area increases with radius, while *interface* WUI area remains stable or decreases, reducing correlation in *intermix* areas. This highlights the need to focus on the most influential interfaces for management strategies in each WUI type.

The choice of the most appropriate moving window radius size is related to the purpose for which the map is made. In a point-based approach, the initial parameterization at the beginning of the mapping results in significant implications for the area and spatial distribution of WUI (Bar-Massada, 2021). As we have observed, overly large radii, i.e., 1000 m, can identify WUI in almost the entirety of a municipality, such as Mangualde, making it unfeasible for management by competent authorities. Similarly, overly small radii, i.e., 100 m, classify isolated structures as WUI (Bar-Massada et al., 2023).

We consider that the 500 m radius may represent a reasonable compromise, as it provides adequate spatial detail and avoids mapping isolated buildings. In the entirety of our study area, the proportion of the area mapped as WUI was less than 50%, whereas using larger radii increased this value. In addition, this radius allowed us to avoid mapping vegetation fragments located within urban zones and their surrounding areas as WUI (Fig. S2b at supplementary material). This value has also been considered suitable for analyses in other regions (Argañaraz et al., 2017; Carlson et al., 2022; Kaim et al., 2023), although Tikotzki et al. (2023) identified an entire village classified as WUI only when a 100 m buffer radius was employed, whereas a 500 m radius failed to designate it as WUI.

Therefore, for WUI mapping, it is important to consider that, as emphasized by Stewart et al. (2009) "the solution is not to declare a single map as the best, or conversely, to tell managers not to use a certain map because it is wrong, but rather to consider the purpose for which each map was developed and critically evaluate the quality of the data and analyses on which it is based". These purposes aim to effectively manage and mitigate wildfire risks in WUI areas. They must be tailored to the needs and abilities of the population and the territory (Oliveira et al., 2017) and involve strategies such as fuel management, implementing zoning regulations to restrict development in high-risk areas (Taccaliti et al., 2023), prioritizing construction practices (Lopes et al., 2023), educating residents about the risks associated with living in the interface areas, protecting natural habitats, and improving emergency planning efficiency.

5. Conclusion

This study underscored the relevance of mapping WUI for understanding differences between areas with distinct territorial features. By analysing four municipalities in mainland Portugal, we highlighted the need to consider the spatial distribution of buildings and vegetation patterns to identify the WUI areas, in order to assess it relation with wildfire exposure. Detailed analysis revealed variations in the extent and distribution of the WUI among the studied municipalities, emphasizing the need for customized approaches to fire management in different contexts. The use of programming routines, particularly the integration between ArcGIS Pro and Python, was essential for automating tasks, analysing large geospatial datasets, and ensuring the required flexibility to be used in different contexts. This approach can provide valuable information for technicians and decision-makers, especially given the prevalence of open data regarding building footprints and land cover maps with high resolutions in countries grappling with wildfire issues.

Although some differences were observed between the developed mapping and other existing cartographies, the study identified common areas classified as WUI, regardless of the approach used. This highlights the importance of prioritizing these areas for fire prevention and control.

The work conducted and the developed approach can significantly contribute to understanding further the distribution and patterns of the WUI in Portugal, providing crucial insights for wildfire risk management. Furthermore, as future approaches, new experiments could, for example, vary what is considered combustible to assess the patterns of the resulting new WUI, and the developed methodology could be adopted in other areas, such as across all of mainland Portugal, to enhance understanding of WUI dynamics and improve fire management strategies nationwide.

CRediT authorship contribution statement

Barbosa Bruno: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Oliveira Sandra:** Writing – review & editing, Supervision, Conceptualization. **Caetano Mário:** Writing – review & editing, Supervision, Conceptualization. **Rocha Jorge:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122098.

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