Fire Safety Journal 140 (2023) 103853

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Methodology for the analysis of structural vulnerability of WUI settlements

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ARTICLE INFO

Keywords:
Vulnerability assessment
WUI mesoscale
WUI fire management
Case study

ABSTRACT

As WUI fires have become a global concern, there is a growing need for engineering methodologies that lead to proactive fire management not only at the landscape level, but at all WUI scales. This paper presents a quantitative methodology for structural vulnerability assessment at the WUI settlement level that is based on 10 indicators, established for the different fire exposure phases a WUI area experiences (pre-impact, impact and fire transfer) as well as on other factors that can escalate vulnerability. As output, a Structural Vulnerability Index (SVI) for the entire analyzed area can be obtained. The methodology can not only assess vulnerability of WUI settlements in a quantitative way, but it can also quantify the effect of measures employed for the reduction of this vulnerability. Additionally, the methodology is suitable for comparison between different settlements or neighborhoods of the same area. A case study for the city of Barcelona, Spain, is presented, in which 9 WUI neighborhoods are analyzed and vulnerability reduction measures are prioritized.

1. Introduction

Wildland-Urban Interface (WUI) fire events have been increasing in severity, frequency and impact [1], as cities are expanding towards forested areas and the urban population is moving towards suburban areas, resulting in an increase in urban fringes that are either in contact or mixed with wildland fuels [2]. The development of such settlements did not consider the basic aspects for an efficient WUI fire management (e.g., access roads, fire resilient urban planning, fuel reduced fringes, etc.) [3], causing them to be vulnerable to wildfires. Risk reduction strategies are therefore needed not only at landscape level, but also at community level or mesoscale [4], and local community involvement in planning, mitigating and reducing hazard and structural vulnerability to fire is a key factor [5,6]. Efforts have hence been placed in developing methodologies for risk and vulnerability assessment also at the WUI mesoscale (e.g., Refs. [7–11]). In this context, risk assessment methodologies determine the extent of risk by analyzing potential hazards of fire exposure and evaluating existing conditions of vulnerabilities, which are the characteristics of a WUI settlement that make it susceptible to the damaging effects of a fire [12]. Existing methodologies define the hazard by identifying fire exposure through variables such as environmental conditions (e.g., wind speed, temperature, humidity, etc.), topography, fuel type [10], used also to calculate burn and ignition probabilities [8,11] or ember deposition [9]. Meanwhile, the assessment of structural vulnerability of a WUI settlement is performed by using many different approaches. Alcasena et al. [8] assess structure susceptibility based on the fire intensity buildings are exposed to. This assessment only considers one variable, which is a function of the hazard each individual building is exposed to, therefore not considering the settlement as a whole. Menemenlis et al. [11] give a definition of vulnerability that is based on the exposure probability, thus only identifying what is the hazard buildings are subjected to. Galiana-Martin et al. [7] propose an assessment based on an *internal vulnerability* of the settlement, which depends on building density and vegetation aggregation, and an *external vulnerability* that depends on fuel type and terrain slope. In Hysa [10], vulnerability is given by the wildfire spread capacity within the settlement, which depends mainly on fuel properties (e.g., vegetation density, fuel type), environmental conditions, terrain slope and distance to water points, while Hakes et al. [9] consider indicators such as structure to structure and vegetation to structure distances.

Vulnerability assessment at the WUI mesoscale should entail variables that look not only at individual buildings, but at the settlement as a whole. Intrinsic characteristics of the settlement such as the spatial arrangement of buildings and vegetation, as well as its topography, should be considered in combination with variables that take into

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https://doi.org/10.1016/j.firesaf.2023.103853
Received 9 June 2023; Accepted 26 June 2023

account the prevention or management of a fire event. The methodology rationale presented by Pastor et al. [3] provides a holistic approach to vulnerability assessment at the WUI mesoscale, which includes structural, social and ecosystem vulnerabilities. This framework is the baseline for the work presented in this paper, which focuses on developing a structural vulnerability assessment methodology that identifies and categorizes the variables that contribute to vulnerability of a WUI settlement (both in intermix and interface areas i.e. with a housing density equal to or higher than 6.18 houses/km^2 [13]) during its different fire exposure phases (pre-impact, impact and fire transfer [4]), as well as recognizing factors that contribute in the escalation of the fire event, therefore increasing vulnerability. The methodology identifies a Structural Vulnerability Index (SVI) for the analyzed area, and is designed to detect which actions should be prioritized in order to reduce the value of this index. Additionally, the methodology, when used to analyze big settlements (e.g., metropolitan areas), can be scaled down to neighborhood level, allowing to make comparisons between different neighborhoods that might experience the impact of a fire in different ways.

2. Methodology and materials

The methodology entails the analysis of structural vulnerability at the mesoscale in relation to the different fire exposure phases of WUI communities. These are: (1) the pre-impact phase, during which firebrands and smoke reach the urban settlement well before the fire front; (2) the impact phase, when the main fire front reaches the interface and flames directly threaten assets located at the perimeter of the settlement; and (3) the fire transfer phase, during which the fire spreads through the different residential fuels (e.g., ornamental vegetation, structures, porches, outdoor furniture, fences, etc.) and the wildland vegetation in undeveloped areas present in the settlement [4]. During the pre-impact phase, firebrands transported by the fire plume and by the wind can reach urban areas and start secondary fires. The probability of this happening can be associated with the amount of flash fuels present in the settlement. This type of fuels (e.g. grasses, ferns, needles) ignite readily and are consumed rapidly when dry, favoring the initial development of a fire; therefore, the vulnerability of an urban area to fire will increase with the increasing presence of these fuels within its limits. During the impact phase of the main fire front, the degree of vulnerability of the settlement will depend on the type of fire and the section of the fire perimeter that is impacting (i.e., head, flank, back). Finally, the transfer or permeability of the fire throughout the urban area will depend on the type of WUI (interface or intermix) and will be influenced by the continuity of the vegetation and by the fire channeling effects derived from the topography. Additionally, several other factors can be responsible for a possible escalation of the severity of the fire event. These are the spatial arrangement of the buildings and infrastructures in relation to the vegetation (i.e., the presence of friction between vegetation and buildings), the operational response time, the degree of compliance with the prevention methods set by the legislation that are specific for the analyzed area, and the presence of particularly vulnerable infrastructures (e.g., industrial sites, places of public concurrence as schools, hospitals, churches, etc.).

The steps of the methodology for the structural vulnerability assessment are presented in Fig. 1. Data needed for the analysis includes land cover maps, meteorological and historical fire data (when available), orthophotos and a Digital Elevation Model (DEM) of the area of interest, cadastral maps, information on the fire brigade’s response time, water points map, maps locating fire breaks and their execution, and the location and type of vulnerable infrastructures. When this information is not publicly available, collaboration with local authorities is a key factor. With the collected information, the vulnerability analysis can be performed following the definition of the indicators given in Table 1, which are divided in 4 blocks. Each indicator considers the different factors previously described. Three categories of vulnerability have been established for all factors (high, medium and low), to which ranges of values are assigned accordingly. The value obtained for each block is then scaled to obtain a value between 0 and 1, with which the Structural Vulnerability Index (SVI) can be calculated by following a weighted approach.

2.1. Pre-impact and impact phase indicators

The amount of flash fuels present in the area of interest is an indication of how easily, during the pre-impact phase, firebrand showers from the main front can start a fire. The classification of the vulnerability of the area of study associated with this indicator is considered as follows: the vulnerability is low when the percentage of the area covered by fine fuels is 5% or less, it is medium when this percentage lies between 5% and 15%, and it is high when the percentage is 15% or higher (Table 1). This indicator does conservatively not consider the position of flash fuels within the settlement in relation to wind direction, as the

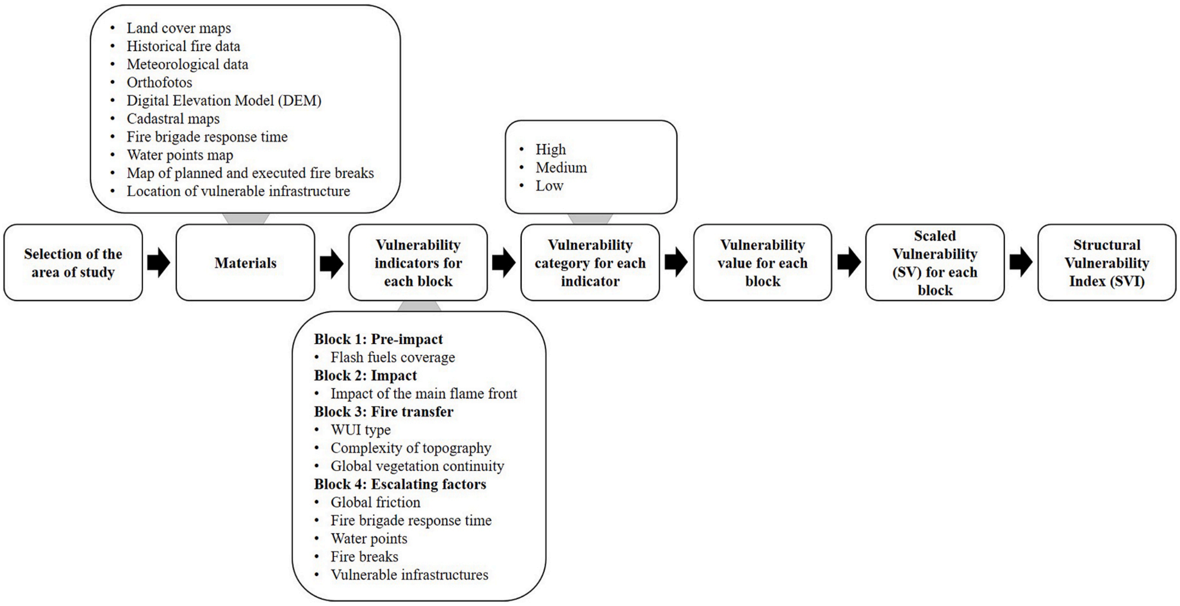


Fig. 1. Methodology of the structural vulnerability assessment.

Table 1
Definition of the vulnerability indicators.

Block	Indicators	Definition	Vulnerability category
Pre-impact	Flash fuels coverage	Percentage of area covered by flash fuels	High: area covered by flash fuels [15%–100%] Medium: area covered by flash fuels (5%–15%) Low: area covered by flash fuels [0%, 5%]
Impact	Impact of the main flame front	Potential number of head impacts of the fire	High: 2 head impacts Medium: 1 head impact Low: flank impacts (0 head impacts)
Fire transfer	WUI type	WUI category associated to vegetation cover	High: vegetation cover $\geq$60% Medium: vegetation cover (40%, 60%) Low: vegetation cover $\leq$ 40%
Fire transfer	Complexity of topography	Amount of critical topographic points (i.e., canyons, saddles, passes)	High: amount of critical points $>$3 Medium: amount of critical points [1,2] Low: amount of critical points = 0
Fire transfer	Global vegetation continuity C_{global}	Indicator associated to the ease of percolation of the fire due to vegetation continuity within the area	High: $C_{global} \geq 350$ Medium: C_{global} (250, 350) Low: $C_{global} \leq 250$
Escalating factors	Global friction F_{global}	Indicator associated to the degree of exposure of the buildings to vegetation	High: $F_{global} \geq 40$ Medium: F_{global} (20,40) Low: $F_{global} \leq 20$
Escalating factors	Fire brigade response time	Travel time from the closest fire station to the most critical location	High: time $\geq$12 min Medium: time (10, 12) min Low: time $\leq$10 min
Escalating factors	Water points	Coverage status and volume of water points	High: insufficient coverage of water points Medium: sufficient coverage, but volume needs to be increased Low: good coverage and adequate volume
Escalating factors	Fire breaks	Degree of execution (DE) of planned fire breaks	High: DE [0%, 75%) Medium: DE [75%, 100%) Low: DE = 100%
Escalating factors	Vulnerable infrastructures	Weighted and standardized account of infrastructures of particular vulnerability	High: normalized value [2/3, 1] Medium: normalized value (1/3, 2/3) Low: normalized value [0, 1/3]

latter, along with fire spread, may vary depending on the type of fire that impacts the settlement.

During the impact phase, the indicator that should be considered is the potential impact of the main fire front onto the perimeter of the urban area. Design wildfires can be identified based on the reconstruction of historical fire perimeters, the identification of meteorological situations at synoptic level for these back dated fires and the reconstruction of fire spread. The latter can be defined based on the Campbell Prediction System [14], which describes how the basic fire spread factors (fuel aspect, wind and slope) affect the fire front. These design wildfires should describe the maximal potential of a fire to become a large wildfire in a particular landscape [15]. When information on historical fire data is not available, design fires can be identified by simulating potential fire behavior characteristics with the help of fire analysis tools such as FlamMap [16]. Once design wildfires are selected, the type of impact onto the urban area can be identified (head, flank, back). As shown in Table 1, a high vulnerability is considered for those areas that due to their location and topography can be impacted by the head of two different types of fires (e.g., a plume dominated fire and a wind driven fire). Similarly, areas that can potentially be hit by the head of a single design fire are considered to be of medium vulnerability. Finally, those areas that can only be flanked (for any type of fire) are considered to be of low vulnerability. The determination of this indicator can be carried out in a qualitative manner, by observing the orthophotographs, the DEM and the historical fire data of the areas of interest.

2.2. Fire transfer phase indicators

Fire transfer or permeability indicators give an idea of the penetrability of the fire inside the urban area (i.e., how the fire can spread through the settlement). The WUI type indicator is indicative of the amount of land covered by vegetation within the area of study, which can be classified either as interface or as intermix. The difference between interface and intermix can be set at a threshold of vegetation cover of 50% (i.e., if vegetation coverage is less than 50% it can be considered interface and if it is higher, intermix), assuming that buildings are always present [13]. In this methodology, areas of high vulnerability have been considered to have a vegetation coverage of 60% or more (i.e., intermix), areas of medium vulnerability are covered by vegetation with values between 40% and 60% of the total area (intermediate position between interface and intermix), and areas of low vulnerability are those with a vegetation coverage of less than 40% (i.e., interface), as shown in Table 1. The calculation of the percentage of vegetation cover can be made by creating a mask of the vegetation in the orthophotos of the area of interest.

The complexity of the topography of the area of interest includes the presence of critical points such as canyons, saddles and passes. It is often responsible for local acceleration of the fire and it can be a good comparative indicator of the speed and intensity of flames that can be observed in the event of fire. The indicator associated with the complexity of the topography is defined as the number of critical topographic points located in the area of interest. The higher the number of critical points, the more extreme the fire behavior, therefore a high vulnerability is considered for those areas with 3 or more critical points, a medium vulnerability for those areas with 1 or 2 critical points, and a low vulnerability when there are no critical points within the boundaries of the analyzed area.

The last indicator of the fire transfer phase is the non-dimensional global vegetation continuity indicator C_{global}, inspired by the continuity variable of the WUIX index (Wildland-Urban Interface indeX) [17], which is an indicator of fire risk at the WUI. The indicator C_{global} has a purely topological character, given that the analysis of the relative position and the relationship between vegetation and buildings is two-dimensional, and it considers horizontal continuity. It is estimated by applying a cellular automata calculator that operated on a square mesh. The calculation of C_{global} depends on the values of the unitary continuity of each cell (C_i). This is calculated as the sum of the values assigned to the surrounding cells. A value of 1 is given to every neighboring cell of the mesh that is categorized as vegetation, while a value of 0.5 is given to cells located diagonally (i.e., that share a corner with the analyzed cell). A value of 0 is given to cells that are not categorized as vegetation. The unitary continuity (C_i) of the cell can therefore reach a maximum value of 6. This value is calculated for each cell of the mesh.

An example of the calculation of C_i is given by the green cells in Fig. 2. The non-dimensional C_{global} can then be calculated for the area of study based on its total surface (S_{tot}), expressed in m^2, as shown in Eq. (1), where R is the resolution of the mesh in meters and M is the number of cells of the mesh within one axis of the considered area. This indicator gives insight on the importance of the continued presence of vegetation within a settlement and therefore on how easily a fire could percolate through it.

$$C_{global} = \frac{100\ R^2 \sum_{i=1}^{M^2} C_i}{S_{tot}} \tag{1}$$

When the value of C_{global} is lower than 250, then the vulnerability of the analyzed area is considered to be low. A medium vulnerability is considered for values of C_{global} between 250 and 350, and a high vulnerability is considered for C_{global} values of 350 or more (Table 1).

2.3. Escalating factors

The first considered escalating factor is the non-dimensional global friction indicator relative to the buildings of the area of study (F_{global}). As for the C_{global} indicator, it is inspired by the friction variable of the WUIX index [17], therefore calculations follow the same approach. In this case, the unitary friction of one cell (F_i) that is categorized as building is calculated as the sum of the values of the neighboring cells that are categorized as vegetation. Cells that share a side with the analyzed one are given a value of 1, while cells located diagonally are given a value of 0.5 when the corner between building and vegetation cells is convex. Additionally, a value of 1 is added when the cell categorized as building is in the same location as one categorized as vegetation, making 7 the maximum value for the unitary friction. An example of the calculation of F_i is shown by the red cells in Fig. 2. F_{global} can be calculated as a function of the total surface occupied by buildings within the area of study (S_b), expressed in m^2, as given in Eq. (2). This indicator gives a very precise idea of the exposure of buildings to vegetation within the analyzed settlement. It considers the friction between buildings and vegetation in relation to the amount of buildings and their distribution within the settlement. Intermix zones will typically have a high value of global friction, while interface areas will have a lower value.

$$F_{global} = \frac{100\ \ R^2 \sum_{i=1}^{M^2} F_i}{S_b} \tag{2}$$

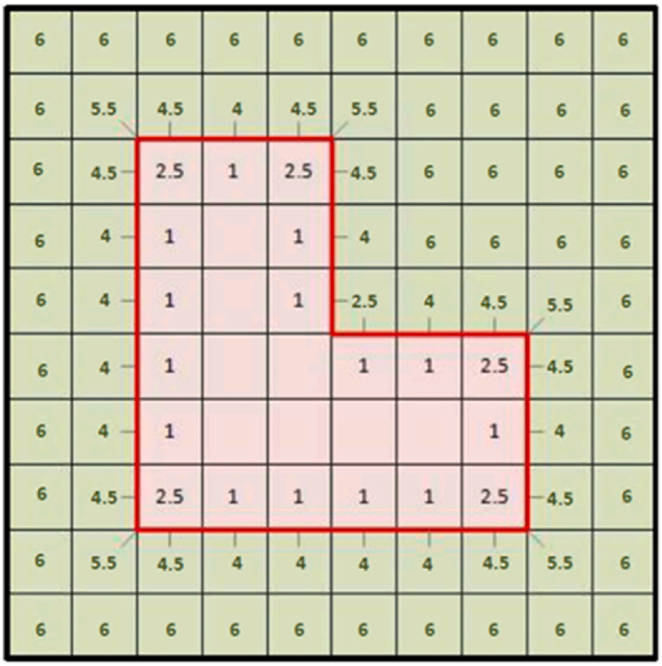
When the value of F_{global} is lower than 20, then the vulnerability of the analyzed area is considered to be low. A medium vulnerability is considered for values of F_{global} between 20 and 30, and a high vulnerability is considered for F_{global} values of 30 or more (Table 1).

Escalating factors also include the fire brigade's response time. This time is calculated as the sum of the alarm processing time, the turnout time, and the travel time, which depends on the route from the fire station to the point where the fire has been spotted. Given that the latter is the most variable one, it is the one taken as an indicator for the analysis. This time should be selected by consulting the local fire brigade to agree on the appropriate responding stations [18]. Consultation with the fire brigade of the city of Barcelona (Bombers de Barcelona) allowed setting vulnerability categories: when the travel time between the fire station and the location of the fire is less than 10 min, the vulnerability of that location can be considered to be low; when the travel time is between 10 and 12 min, the vulnerability is medium; when the travel time is above 12 min, then the vulnerability is high. Other locations may require a different set of reference values for the vulnerability level.

Another escalating factor is the coverage status and volume of the water points present in the analyzed area. This information can be found in water point maps of the area of study or in documentation of the municipality itself. The criterion for the evaluation of the vulnerability is set as follows: areas with adequate coverage and reservoir volume are considered to be of low vulnerability, areas with adequate coverage but needing more volume are of medium vulnerability, and zones with insufficient coverage are considered to be of high vulnerability.

The degree of execution of fire breaks around the urban area is another escalating factor. The presence of fire breaks depends on local legislation, and often it is the municipalities or local entities that are in charge of their implementation and maintenance. The degree of execution (DE) of the fire breaks is the ratio between the area of the executed fire breaks and the area of the planned fire breaks. The criterion established for the definition of vulnerability categories for this indicator is the following: areas with a DE of 100% are considered of low vulnerability, areas with a DE between 75% and 100% are of medium vulnerability, and areas with a DE of less than 75% are of high vulnerability.

The final escalating factor that is taken into account is the presence of vulnerable infrastructures (e.g., schools, hospitals, telecommunication and energy infrastructures, etc.) within the area of study. Vulnerable elements are selected according to the classification reviewed in the European project VESPRA (Vulnerable Elements in Spain and Portugal and Risk Assessment) [19]. This is a factor that can escalate the severity of an emergency either because it increases the complexity of an eventual evacuation or because failure of these infrastructures can have a serious impact onto essential services. Suppression and intervention actions might have to focus on these infrastructures and not on the wildfire. This aspect is considered based on the definition of an indicator that represents the sum of the number of vulnerable infrastructures weighted depending on the type of infrastructure. A weighting factor of 3 is given to infrastructures with the presence of vulnerable groups of people (e.g., hospitals, nursing homes, pre-schools), a weighting factor of 2 is given to infrastructures with a high occupancy, energy and telecommunication infrastructures and industries with the presence of dangerous substances, while a weighting factor of 1 is given to any other type of vulnerable infrastructure.



6	6	6	6	6	6	6	6	6	6
6	5.5	4.5	4	4.5	5.5	6	6	6	6
6	4.5	2.5	1	2.5	4.5	6	6	6	6
6	4	1		1	4	6	6	6	6
6	4	1		1	2.5	4	4.5	5.5	6
6	4	1			1	1	2.5	4.5	6
6	4	1					1	4	6
6	4.5	2.5	1	1	1	1	2.5	4.5	6
6	5.5	4.5	4	4	4	4	4.5	5.5	6
6	6	6	6	6	6	6	6	6	6

Fig. 2. Example of the calculation of C_i (green cells represent vegetation) and F_i (red cells represent a building) [17]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.4. Calculation of the vulnerability index

The calculation of the total structural vulnerability of the area of study is performed by prioritizing the different blocks of indicators. First, indicators are given different values depending on their identified vulnerability: indicators with low vulnerability are given a value of 1, those with medium vulnerability are given a value of 2, and those with high vulnerability are given a value of 3. Each exposure phase as well as the escalating factors are then considered as blocks, therefore block 1 (pre-impact phase) and block 2 (impact phase) can have a value between 1 and 3 (as these blocks only include one indicator each), block 3 (fire transfer phase) can have a value between 3 and 9 (this block includes 3 indicators) and block 4 (escalating factors) can have a value between 5 and 15, as it includes 5 indicators. Lastly, the value of each block is scaled to obtain a value between 0 and 1 (Scaled Vulnerability or *SV*). The Structural Vulnerability Index (*SVI*), expressed in percentage, is calculated as the sum of the scaled value for each block multiplied by its weight (*w*), as shown in Eq. (3). Due to the lack of data, this weight is based on the expert opinion of the authors. Blocks 1 and 4 are given a weight of 15% each, block 2 is given a weight of 40%, and block 3 has a weight of 30%. The impact phase is hence deemed to be the most influential component of the structural vulnerability of a WUI settlement. The fire transfer phase is the second most influential component, while the pre-impact phase and the escalating factors are given the same weight, which is the lowest one. An area is considered to be highly vulnerable when it has an $SVI > 65\%$, of medium vulnerability when $35\% \leq SVI \leq 65\%$, and of low vulnerability when $SVI < 35\%$.

$$SVI = \sum_{i=1}^{4} SV_i \, w_i \tag{3}$$

3. Case study

The presented methodology has been applied within the WUICOM-BCN project (“Barcelona Fire Resilient Communities”) to analyze structural vulnerability of 9 neighborhoods of the city of Barcelona, Spain (shown in Fig. 3), that are located within the area of the Natural Park of Collserola.

Values for each vulnerability indicator in each neighborhood are given in Table 2. The flash fuels coverage was calculated based on the information present in the land cover maps from the Geological and Cartographic Institute of Catalonia, considering fuel models involving grasslands, pastures and herbaceous croplands [20]. The impact of the main front was defined for each neighborhood based on the selection of two design fires (a plume dominated fire and a sea wind/topography driven fire) that were identified within the Homogeneous Fire Regime Zone number 68 of Catalonia [21], which includes the entire Natural Park of Collserola. The WUI type was identified based on the percentage of vegetation present in each analyzed neighborhood, which was calculated by creating a mask of the vegetation present in orthophotographs with a resolution of 25 cm [22]. The critical topographic points were identified thanks to a study performed specifically on the topography of the Natural Park by Ballart and Pagès [23]. The inputs for the calculation of the global vegetation C_{global} and the global friction F_{global} indicators with the WUIX2D software [24] were created by generating the vegetation mask used for the identification of the WUI type and the cadastral map of the city of Barcelona [25] (shown in Fig. 4). Calculations were performed with a fine mesh of 2×2 m^2 cells. When it comes to the other escalating factors, the fire brigade response time was calculated by the fire brigade of the city of Barcelona (Bombers de Barcelona); the coverage status and volume of the water points was found in the recently published project on infrastructures for wildfire prevention within the Natural Park of Collserola [26]; the degree of execution of the fire breaks was calculated based on the information given by the Consortium of the Natural Park of Collserola (CPNC), which collaborates with the Municipality of Barcelona and is responsible for the planning and execution of the fire breaks; finally, the presence of vulnerable infrastructures was identified by using the information given by the Municipality of Barcelona [27], supplemented with a search in Google Maps.

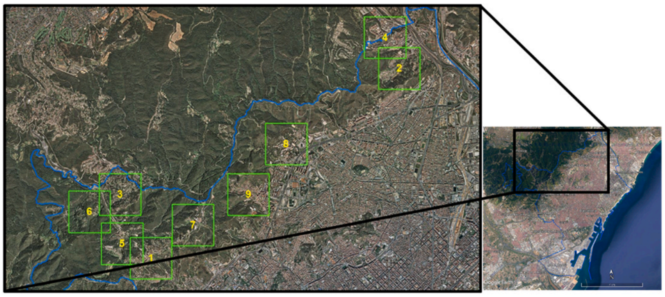


Fig. 3. Location of the analyzed neighborhoods (squares of 1×1 km^2). 1: Vallvidrera, 2: Torre Baró, 3: Can Rectoret, 4: Ciutat Meridiana, 5: Mas Sauró, 6: Mas Guimbau, 7: Tibidabo, 8: Mundet, 9: Sant Genís dels Agudells.

Results show that for the pre-impact phase, none of the analyzed neighborhoods exhibits an important vulnerability to the fast generation of secondary fires caused by firebrands landing during this phase, given that no large areas of croplands or grasslands are present. This does not exclude, however, the possibility of local combustion of other fuels such as wildland or ornamental vegetation, or residential fuels in case of firebrand showers. As for the impact phase, severe conditions are estimated for the neighborhoods of Vallvidrera (#1), Can Rectoret (#3), Mas Sauró (#5), Mas Guimbau (#6) and Tibidabo (#7), since a head impact is possible for both design fires. The neighborhoods of Ciutat Meridiana (#4) and Sant Genís dels Agudells (#9) present a medium vulnerability, given that a head impact is possible only for a sea wind/topography driven fire, while Torre Baró (#2) and Mundet (#8) can only be hit by the flanks of the selected design fires.

For the fire transfer phase, all neighborhoods but Ciutat Meridiana, Mundet and Sant Genís dels Agudells can be categorized as intermix areas (vegetation cover >60%), meaning that the fire can spread more easily through them. Moreover, the complexity of the topography can facilitate fire spread in all neighborhoods but Ciutat Meridiana, where there are no critical points. Mas Sauró and Vallvidrera are especially vulnerable due to the presence of three canyons for the first one and two saddles and a canyon for the latter. When it comes to the global vegetation continuity, the neighborhoods of Mas Guimbau, Tibidabo, Mas Sauró and Can Rectoret have the highest values and fall into the high vulnerability category, which exacerbates the issue of fire spread, given that these neighborhoods are also classified as intermix.

As for the escalating factors, the neighborhoods with the highest global friction indicator is Mas Guimbau, which is an intermix zone with very little urban area. Can Rectoret and Mas Guimbau also present a high fire brigade response time, although it is the neighborhood of Ciutat Meridiana the one with the longest response time. As for the water points, the network generally covers the needs of all neighborhoods, and only Can Rectoret, Ciutat Meridiana, Tibidabo and Sant Genís dels Agudells have a need for the increase of the diameter of the water points for the correct and safe loading for aerial firefighting. The degree of execution of the fire breaks is the highest for Torre Baró and Ciutat Meridiana (91% and 86% respectively), which have a low or moderate C_{global}. In contrast, more vulnerable neighborhoods (Vallvidrera, Can Rectoret, Mas Sauró) have execution degrees in the order of 70%. The Mundet area, despite being one of the neighborhoods with low or average vulnerability with respect to most indicators, has a very low degree of execution of fire breaks, with only 56%. The presence of vulnerable infrastructures is very high in this neighborhood, followed by Ciutat Meridiana, where several retirement homes, pre-schools and other educational establishments are present. These neighborhoods are

Table 2

Values of the vulnerability indicators for each neighborhood (Fig. 3). L: low, M: medium, H: high.

Indicator	Neighborhood								
	1	2	3	4	5	6	7	8	9
Fine fuels coverage [%]	0.4	3.6	0.2	5.6	0.9	0.6	0.3	0.6	2.3
Impact of the main flame front [# of head impacts]	2	0	2	1	2	2	2	0	1
WUI type [Vegetation cover %]	61.0	64.0	70.3	45.3	73.7	88.7	81.3	58.4	52.5
Complexity of topography [# of critical points]	3	1	2	0	3	1	2	2	1
Global vegetation continuity C_{global} [−]	306.6	340.2	371.3	233.6	398.2	512.5	456.5	313.5	260.1
Global friction F_{global} [−]	30.4	18.5	37.8	2.9	26.0	69.8	18.6	13.1	7.1
Fire brigade response time [min]	4′51"	11′14"	17′47"	21′34"	9′39"	12′26"	5′00"	7′14"	5′06"
Water points [Coverage status]	L	L	M	M	L	L	M	L	M
Fire breaks [DE %]	69	91	72	86	71	78	76	56	74
Vulnerable infrastructures [Weighted factor]	0.38	0.00	0.10	0.62	0.20	0.10	0.10	1.00	0.35

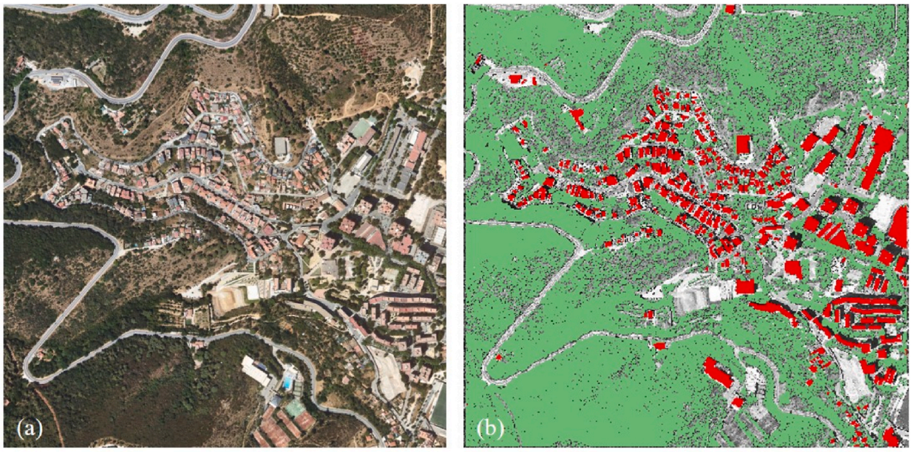


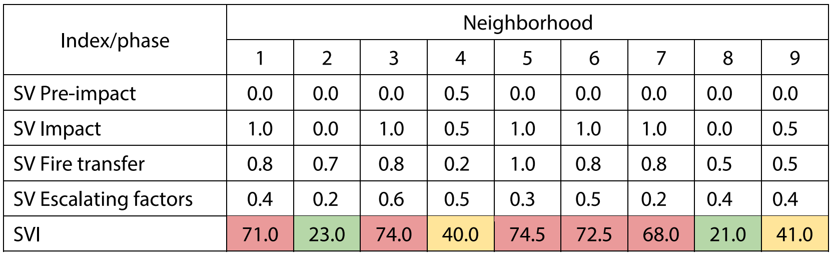
Fig. 4. (a) Orthophotograph of the neighborhood #9 of Sant Genís dels Agudells; (b) vegetation (green) and buildings (red) masks. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

those with the biggest urban area, along with Vallvidrera. Table 3 shows the overall results of the SVI for each of the 9 analyzed neighborhoods. These results point, in order, to Mas Sauró, Can Rectoret, Mas Guimbau, Vallvidrera and Tibidabo as those with a high structural vulnerability, followed by Sant Genís dels Agudells and Ciutat Meridiana with a medium vulnerability. Lastly, Torre Baró and Mundet can be considered as areas with low structural vulnerability.

Based on these results, the Municipality of Barcelona should prioritize its actions to reduce the vulnerability of the neighborhoods of Vallvidrera, Can Rectoret, Mas Sauró, Mas Guimbau and Tibidabo. All are intermix WUI areas that can be hit by the head of the two selected design fires, and, as previously stated, Vallvidrera and Mas Sauró are especially vulnerable due to the presence of three topographic critical points. These are all indicators that depend on the landscape and on the type of urban settlement, for which the vulnerability cannot be reduced. When it comes to the fire transfer phase, which has a high SV value in each of these neighborhoods, the only indicator for which vulnerability can be reduced is the C_{global}, by planning fuel breaks to reduce fuel continuity in the wildland (e.g., promoting agroforestry landscape mosaics) and fuel treatments close to buildings. The latter can reduce also the global friction indicator F_{global}, which is high for Mas Guimbau. Actions such as clearing the vegetation located close to the buildings are therefore recommended, and this involves also active participation of the residents of the neighborhoods. The SV value for the escalating factors is the highest for Can Rectoret and its reduction entails not only clearing vegetation close to buildings, but also the increase of the degree of execution (DE) of the fire breaks and the decrease of the response time of the fire brigade. This response time is high also for the neighborhood

Table 3

Structural Vulnerability Index (SVI) calculated for each neighborhood (Fig. 3) based on the Scaled Vulnerability (SV) of each phase and escalating factors. Colors identify the vulnerability categories as follows: red for high, yellow for medium, green for low..



Index/phase	Neighborhood								
	1	2	3	4	5	6	7	8	9
SV Pre-impact	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
SV Impact	1.0	0.0	1.0	0.5	1.0	1.0	1.0	0.0	0.5
SV Fire transfer	0.8	0.7	0.8	0.2	1.0	0.8	0.8	0.5	0.5
SV Escalating factors	0.4	0.2	0.6	0.5	0.3	0.5	0.2	0.4	0.4
SVI	🟥 71.0	🟩 23.0	🟥 74.0	🟨 40.0	🟥 74.5	🟥 72.5	🟥 68.0	🟩 21.0	🟨 41.0

of Mas Guimbau, which is adjacent to Can Rectoret. The reduction of this time would entail locating a fire station closer to these two neighborhoods.

To decrease of the SVI value from high to medium for each neighborhood entails different actions. In Mas Sauró the global vegetation continuity should be reduced so that the indicator C_{global} falls within the medium vulnerability category. Increasing the DE of the fire breaks will help in this reduction. In Can Rectoret two different strategies can be implemented. The first is to lower C_{global} to the medium category, the DE of fire breaks from low to high, and the fire brigade response time from high to medium. If it is not possible to reduce the latter, then C_{global} needs to be low and the DE of fire breaks medium. In Mas Guimbau, either the fire brigade response time should go from high to medium, or C_{global} is reduced from medium to low. In Vallvidrera C_{global} should be reduced from medium to low and the DE of the fire breaks increased from low to medium. In Tibidabo, the vegetation continuity indicator C_{global} should go from high to medium.

4. Discussion

As contemporary wildfire management is mainly suppression-oriented and focuses therefore on emergency response [28], the presented methodology is intended to implement proactive fire management within WUI communities that entails assessing and reducing structural vulnerability. This practical methodology can help local jurisdictions in the planning of mitigating actions that can reduce the settlement's vulnerability to wildfires.

Indicators that influence structural vulnerability are identified based not only on fire intensity, as for most existing methodologies, but also on factors that consider prevention and management of a fire event within the settlement. The impact of each of the 10 identified indicators on the vulnerability index of the analyzed area is quantified, therefore actions taken to reduce vulnerability based on these indicators can also be measured quantitatively. The quantification of the vulnerability category and the weight of each block of indicators is based, due to the lack of literature data (with the exception of the WUI type and the fire brigade response time), on the expert judgement of the authors and the stakeholders of the WUICOM Project, especially of the fire brigade (a total of 10 persons), which was gathered during a roundtable discussion. The weight of each block of indicators has been further investigated by performing a sensitivity analysis of the results obtained in the case study. The roundtable discussion highlighted that the impact and fire transfer blocks are the most critical ones when it comes to the vulnerability of a settlement, therefore they were given more weight. The chosen bracketing of the vulnerability category of the SVI has shown, within the analyzed case study, to highlight the differences between neighborhoods. These differences are not significantly sensitive to the bracketing choice.

The novelty of the methodology is the categorization of the identified vulnerability indicators in four blocks for each of the fire exposure phases and for the escalating factors, which are given a weight based on the expertise of the authors. Additionally, the methodology includes indicators such as C_{global} and F_{global}, fire brigade response time, the location and volume of water points, the degree of execution of fire breaks and the presence of especially vulnerable infrastructures, which are key aspects within the management of a fire event. Given that this is the first time the C_{global} and F_{global} indicators have been calculated for a specific case study, calibration for the assignment of a vulnerability category based on validation that includes more case studies is needed. This entails calculating the value of these indicators for areas that have been affected by wildfires, in order to compare the selected category values with real consequences of WUI fires. The threshold values of C_{global} depend on the total surface (S_{tot}) of the analyzed area, which is considered to be 1 km^2. It is therefore suggested to select target areas of approximately this dimension. Moreover, a further sensitivity analysis of the mesh size used to calculate these two indicators is needed, to identify the optimal resolution. A preliminary sensitivity analysis has been performed by comparing the results of the 2 m mesh size with a mesh size of 10 m (resolution of Sentinel-1 and Sentinel-2 satellite imagery): on average, the value of C_{global} for the 10 m mesh size is 13% lower compared to the one obtained for the 2 m mesh size, while the value of F_{global} for the 10 m mesh is, on average, 7 times bigger than the one obtained with a mesh of 2 m. In the analyzed case study, increasing the mesh size for the calculation of these two indicators will underestimate the value of C_{global}, and greatly overestimate the value of F_{global}. As the mesh size of 2 m accurately describes the location of the vegetation and the buildings and does not influence the computing time of the two indicators, it is suggested as the optimal size for this type of analysis.

When it comes to the selection of design fires, a deterministic approach is used to define the worst-case scenarios. In the analyzed case study, design fires had already been identified in previous studies based on historical fires. When no information on historical fires is available, wildfire simulations can be performed with softwares such as FlamMap [16], which require data on topography, surface fuels and canopy fuels.

As presented in the case study, the analysis of structural vulnerabilities of WUI settlements with this methodology can aid the decision-making process of local jurisdictions by identifying the areas that need to be prioritized, i.e., for which mitigating actions should be implemented with more urgency. Moreover, it is possible to identify which mitigating actions will have a bigger impact in reducing the vulnerability of the analyzed areas.

5. Conclusions

A methodology for structural vulnerability assessment of WUI settlements is presented in this paper, for which ten vulnerability indicators have been identified and quantified to calculate the Structural Vulnerability Index (SVI), which identifies the degree of vulnerability to wildfire of a WUI settlement. A case study of the city of Barcelona is presented, in which nine neighborhoods located at the WUI are analyzed. Out of these, four have been identified as highly vulnerable to wildfire, and vulnerability reduction measures have been proposed for each one based on the values of the vulnerability indicators. The proposed methodology can support WUI communities in the strategic planning of fire management actions that can reduce structural vulnerability to fire by measuring these actions in a quantitative way. Moreover, settlements of the same WUI area can be analyzed and compared in order to identify where mitigating actions should be prioritized.

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.

Acknowledgements

This research is funded by the Barcelona City Council and "La Caixa" Foundation (project WUICOM-BCN, 21S09274-001), the project PID2020-114766RB-100 of MCIN/AEI/10.13039/501100011033 and the project TED2021-130484B-100, funded by MCIN/AEI/10.13039/501100011033 and the European Union "NextGenerationEU"/PRTR. The authors also want to thank Bombers de Barcelona, the Consortium of the Natural Park of Collserola for their help in data gathering and the Pau Costa Foundation. A. Águeda is a Serra-Húnter fellow.

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