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Vulnerability analysis to wildland-urban interface fires in metropolitan areas: an integrated approach

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Abstract

Wildfires pose a growing threat to populated areas around the world and especially in the Mediterranean Basin. Numerous Mediterranean cities have typically developed neighbourhoods that expand into forest land in which basic aspects for an efficient WUI fire management have not been considered. In this paper, we present a holistic approach to analyse threats to metropolitan areas due to WUI fires, accounting for infrastructural, societal and ecosystems vulnerability at settlement scale. Based on design fires and the key parameters responsible of fire impact and percolation through communities of most probable WUI fire events, we define key indicators to describe how vulnerable structures are in WUI metropolitan areas. Following, urban and societal indicators are selected to account for population's vulnerability and, finally, ecosystems potential losses are accounted by ecosystem vulnerability indicators such as ecosystem sensitivity and adaptability. We have implemented this methodology to analyse vulnerability in Barcelona WUI areas and identified those that can be more threatened in case of wildfire. Results of this study will be key to inform risk-reduction public policies, as they provide particular insights on those WUI areas within Barcelona municipality that should be prioritized along with the specific issues that should be tackled.

1. Introduction

Wildfires pose a growing threat to populated areas around the world and especially in the Mediterranean Basin. In 2018, the residential area of Mati, Greece, suffered a fire that killed 102 people and reduced more than 600 buildings to ashes. In the summer of 2021, numerous fires ravaged southern Turkey, killing 9 people and destroying hundreds of homes. Algeria also suffered several fires, with 65 deaths, and Greece, southern France, southern Italy, Cyprus and Sardinia had also severe outbreaks with multiple affected towns and resorts (Figure 1).

Climate change is affecting the synoptic weather patterns in the Mediterranean, with episodes of more intense and lasting Saharan air advections involving high temperatures and very low relative humidity, as well as extreme weather events with episodes of strong winds and hurricanes (medicanes). Although the number of ignitions has not risen significantly, the consequences are observed to be more and more severe.

Figure 1- Left: fires in Athens – Greece, 2021 (source: Aggelos Barai); Right: fires in Marmaris – Turkey, 2021 (source: Yetkin Report)

Built-up areas located in the wildland-urban interface (WUI) are increasingly threatened. Buildings, facilities and infrastructure are in direct touch with or very close to vegetation, which, in the event of a fire, suffer the direct consequences of flame contact, radiation and smoke exposure. Numerous Mediterranean cities have typically developed neighbourhoods that expand into forest land. Those wild areas, which provide basic ecosystem services (e.g. biodiversity conservation, water availability, air quality improvement, recreation, etc.), are usually on high slopes and are frequently visited by non-residents and tourists. In the development of such districts, the basic aspects for an efficient WUI fire management have not been considered, such as access roads, fire-resilient urban planning, fuel-reduced fringes, water points, etc.

In addition, evacuation processes in WUI fires are often very complex and, in some cases, end in disaster. Education, awareness, and training are critical issues for building resilient communities, as well as trust, engagement and interaction between experts, managers, and communities (McCaffrey et al., 2013). Giving all parties the opportunity to express their opinions, exchange knowledge and clear up misunderstandings, are central to meet social needs and improve community preparedness, response, and recovery (Mort et al. 2020).

In this paper, we present a holistic approach to analyse threats to metropolitan areas due to WUI fires, accounting for infrastructural, social and ecosystems vulnerability indicators at settlement scale. Our method is applied to Barcelona WUI area as a case study showing great potential to be replicated to other vulnerable metropolitan WUI areas.

2. Methodology

WUI fire vulnerability can be defined by the characteristics and circumstances of a WUI area that make it susceptible to the damaging effects of a wildfire (Gaunteaume et al., 2021). The magnitude of wildfire effects (i.e. heat from flames and toxic dose of smoke components) depend on the spread and intensity of the fire, driven by environmental parameters such as weather, topography and fuel. In turn, wildfire effects can lead to tremendous consequences in urbanized areas, ruining assets and infrastructures, killing and injuring people, and destroying basic ecosystem services.

In line with this definition, our methodology to analyse vulnerability to fires in WUI metropolitan areas is based on two main grounds (Figure 2). On the one hand, WUI fire vulnerability is intimately linked to the type of wildfire that can potentially threat a WUI zone, which may be different depending on the synoptic weather conditions. Fires generally follow particular behaviour patterns according to weather and topography, which have led to the definition of the so-called design fires in many Mediterranean regions (e.g. Costa et al., 2011). Design fires are thus the basis to infer fire impact and effects in WUI zones, and have to be well understood and parametrized for a comprehensive vulnerability analysis. On the other hand, vulnerability of WUI areas has to be explored covering three main axes to account for all possible damages: vulnerability of structures and infrastructures, social vulnerability and ecosystem vulnerability.

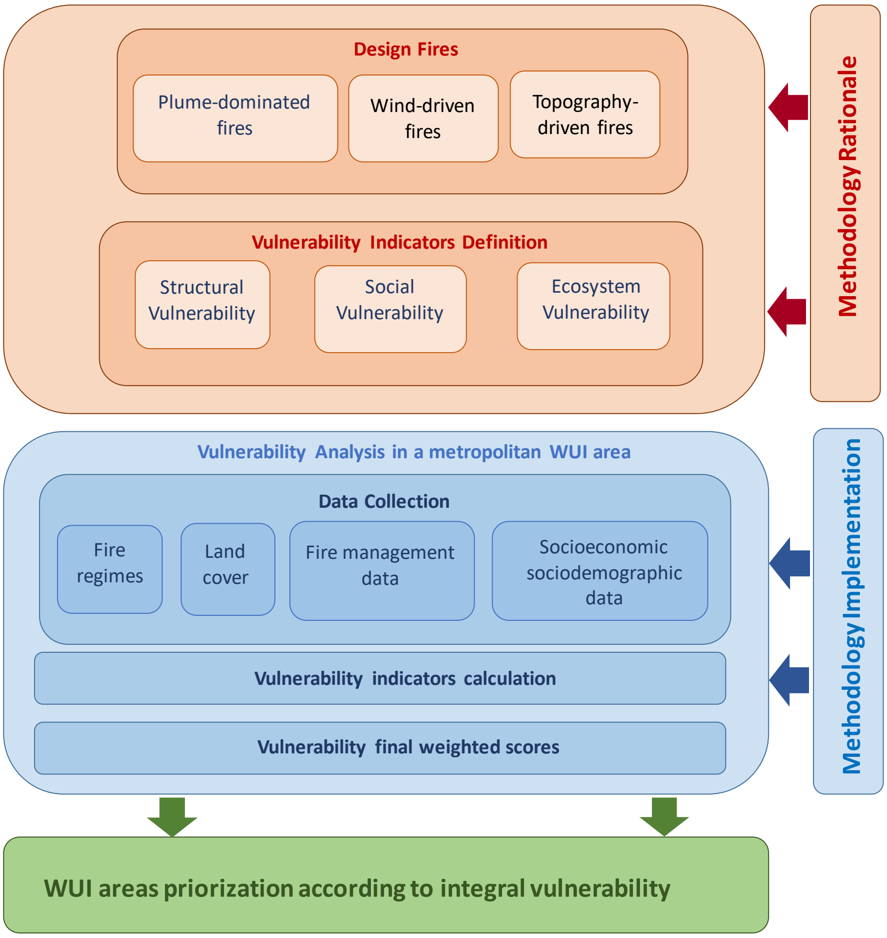

Figure 2- WUI fire vulnerability analysis. Methodology rationale

We have defined key indicators for structural vulnerability (Table 1) in line with the different fire exposure phases – pre-impact, impact and fire transfer (Vacca et al., 2020) that a WUI settlement faces in a fire incident. During the pre-impact phase, it is likely that firebrands will reach the settlement and initiate a spot fire within. This probability can be associated to the area of flash fuels (i.e. grasses and other fine fuels that ignite readily) present in the settlement, which will favour spot fire development. During the impact phase, the magnitude of the consequences in a WUI settlement due to direct flames/smoke exposure of the main fire perimeter will depend on the type of design fire and on the fire propagation mode (head, flank or back fire propagation). Fire permeability within the settlement (i.e. the easiness at which the fire propagates through the community) will largely depend on the type of WUI (e.g. interface, intermix or occluded, as defined by Mell et al, 2010) and is mainly driven by the vegetation continuity and channelling effects due to complex topography. Following, we have identified several severity-escalating factors that may increase fire risk, to account for *i)* the spatial arrangement of the structures with the surrounding vegetation (e.g. length of friction between structures-vegetation or roads-vegetation), *ii)* the presence of critical infrastructure that in case of fire impact may result in the escalation of the fire consequences; *iii)* the operation response (both regarding firefighting response and population response) and *iv)* the degree implementation of preventive measures. Finally, the last component of infrastructural vulnerability deals with the likelihood of a settlement to become itself a fire source term to consolidated adjacent wildlands.

Regarding social vulnerability, it is well known that socio-economic and socio-demographic variables closely correlate with levels of risk, vulnerability, and disaster within and between communities. Wildfires may be especially harmful to people who suffer from exclusion or discrimination on economic grounds, age (particularly the elderly, children, and young people), gender, origin, functional diversity, among others (Eriksen, 2014). According to this, we use these indicators to identify and further understand, in a more nuanced and qualitative examination, the social dimensions and intersections mediating and influencing WUI fire vulnerability

Table 1 – Infrastructural vulnerability components and indicators. (Qn) stands for quantitative indicator. (Ql) stands for qualitative indicator

Vulnerability component	**Indicators**
Pre-impact (firebrands exposure)	Area with flash fuels within the settlement (Qn)
Impact of the main fire perimeter (flames and smoke exposure)	Type of design fire (Ql)
	Propagation mode (Ql)
Fire transfer	Type of WUI (Ql)
	Degree of vegetation continuity (Qn)
	Presence of canyons within the settlement (Ql)
Severity escalating factors	Structure-vegetation and road-vegetation friction (Qn)
	Presence of critical infrastructure potentially exposed (Ql)
	Firefighting arrival time (Qn)
	Population response time (notification, decision and action) (Ql)
	Compliance with water network provisions (Ql)
	Compliance with fuel-reduced fringes provisions (Ql)
Fire source term potential	Perimeter length with flash fuels around the settlement adjacent to consolidated wildlands (Qn)

As for ecosystem vulnerability analysis within the wildfire context, it has to be highlighted that it has been receiving increasing attention during these last years. Several methods can be found in the literature (e.g. Chuvieco et al., 2010; Duguy et al., 2012; Tedim et al., 2013; Aretano et al., 2015) which basically differ on the components that make up ecosystem vulnerabilty and on the type of key issues under study, wether they mainly focus on habitats of greatest ecological value, on socioeconomic aspects or on a wider range of paramaters. In an holostic approach, ecosystem vulnerability analysis in WUI areas must integrate biodiversity indicators as well as other significant landscape and ecosystem values relevant for metropolitan areas, like residential areas, areas with historical-artistic heritage elements, and leisure equipment or infrastructure. In order to consider all these different aspects with a good trade-off between scope and computational cost, in our methodology we consider ecosystem vulnerability to be fairly represented by two basic indicators: sensitivity and adaptability. Ecosystem sensitivity represents the degree to which exposed elements may be affected by fire disturbances, while ecosystem adaptability considers the socioecological adaptive capacities of both ecosystems and communitties that allow to generate recovery and regeneration strategies when facing fire disturbance. Sensitivity and adaptabiltiy are usually infered by considering parameters such as types of habitat, forest cover and community facilities (Aleksandrova et al., 2021; Birkmann et al. 2013).

3. Case study: analysing vulnerability of WUI fires in Barcelona

Barcelona is a large metropolis with a WUI area of remarkable extension, coinciding with the urbanized perimeter within the Collserola Natural Park (NP). Inserted within or in contact with a continuous forest mass, buildings, streets and highways, facilities and infrastructure could be potentially threatened by large forest fires. WUI areas of Barcelona are densely inhabited with population with diverse socio-demographic and socio-economic characteristics. They are also frequently visited for recreational and sports purposes. It has to be highlighted that Collserola NP ecosystem has a direct impact on the health of the millions of people living around it, supplying key ecosystem services to the metropolitan area of Barcelona. The many functions that Collserola generates are air quality (through the absorption of CO_2 and the release of O_2), the regulation of water resources through uptake and evapotranspiration, and the regulation of the urban climate. In addition, Collserola provides habitat for valuable biodiversity.

3.1. Design wildfires

According to Ballart and Pagès (2021), the WUI area of Barcelona can be affected by two different types of wildfires: *A)* a plume-dominated fire, under a synoptic weather pattern of southern heat wave, involving synoptic westerly hot winds from the Iberian Peninsula; and *B)* wind-driven fires (sea winds) with upslope propagation which may occur under southern heat waves or anticyclones. The scenario involving higher risk corresponds to type A fires, as those would involve larger burnt areas with high intensity (Figure 3).

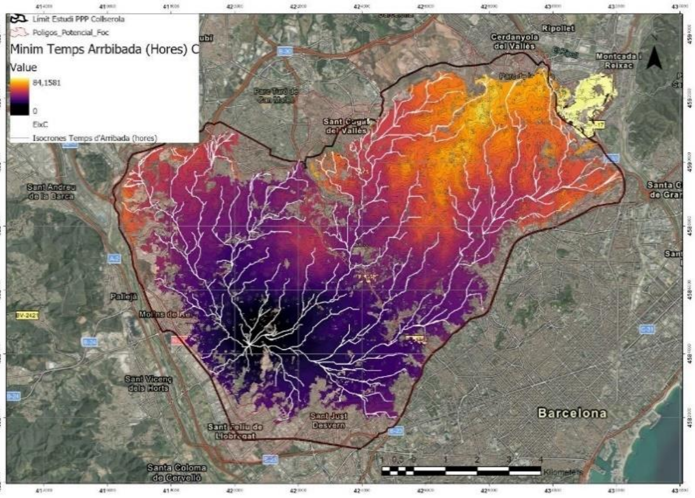

Figure 3- FlamMap simulation of a fire initiated in the metropolitan area of Barcelona (Molins de Rei) including all potential fire runs. The enormous destructive potential of the fire can be observed, as almost the overall Collserola NP area would be affected (Collserola NP perimeter is drawn with a brown solid line).

3.2. Vulnerability analysis

Vulnerability has been analysed in nine 1x1 km-areas of interest (AoI) within the WUI area of Barcelona (Figure 4) in which a preliminary screening of structural, social and ecosystems indicators has been done.

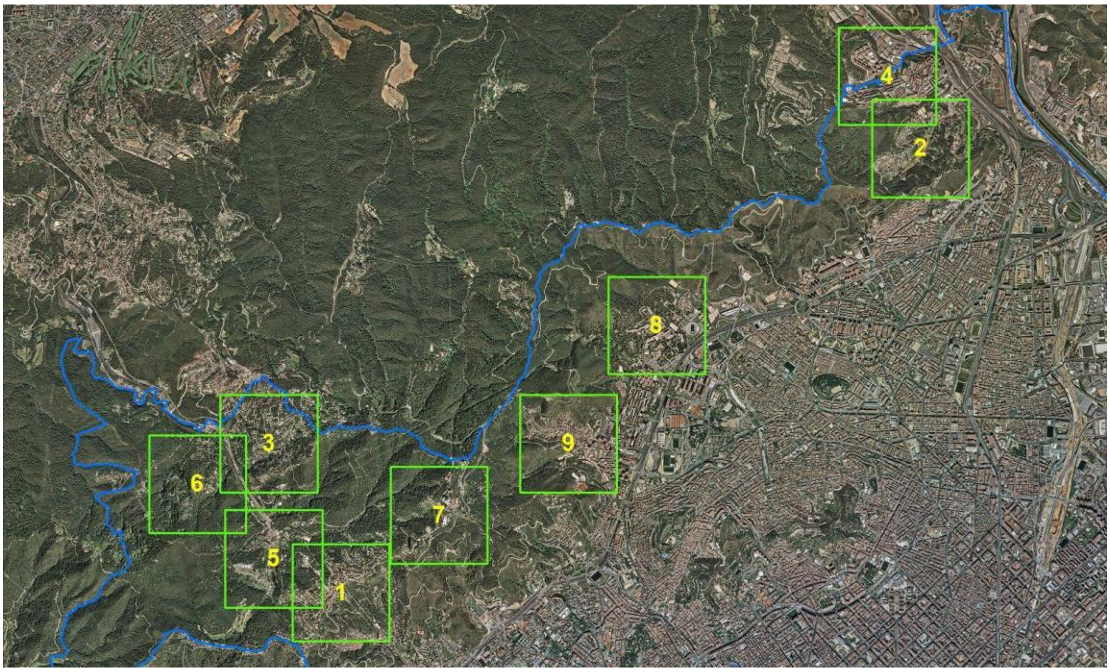

Figure 4- Location of the areas of interest within the WUI area of Barcelona. 1) Vallvidrera, 2) Torre Baró, 3) Can Rectoret, 4) Ciutat Meridiana, 5) Mas Sauró, 6) Mas Guimbau, 7) el Tibidabo, 8) Universitat de Barcelona Campus Mundet, 9) Sant Genís dels Agudells.

Regarding structural vulnerability, the indicators of the different components (i.e. firebrands exposure, fire and smoke impact, permeability, severity escalating factors and fire source potential) have been analysed and weighted across the nine AoIs. As for fire and smoke impact, the two design fires have been considered (i.e. plume-dominated fire with W-E direction and sea wind-driven fire with SE-NW direction) examining both potential head and flank impact. Permeability has been qualitatively analysed by classifying all AoIs in the study area in the two different types of WUI present in Barcelona (i.e. intermix and interface). Moreover, a quantitative analysis of vegetation continuity has been undertaken by using the WUIX algorithm (Caballero, 2019). The same software has also been used to compute the section of the WUI perimeter adjacent to consolidated grasslands or other wildlands with flash fuels, to obtain the potentiality of the AoI to become a wildfire source term egressing from the main fire perimeter. Firebrands' exposure has been inferred by computing the area of flash fuels in all AoIs. The main severity escalating factors have been investigated with data provided by the Barcelona fire agency (Bombers de Barcelona), and Barcelona city and provincial councils. As for structure-vegetation and road-vegetation friction length, again the WUIX algorithm has been used. The three AoIs with higher structural vulnerability have appeared to be Vallvidrera, Torre Baró and Can Rectoret.

In terms of social vulnerability, the main indicators of social and urban vulnerability most used to inform public policies at municipal and metropolitan level in Barcelona have been identified. These are indicators that are essentially based on socio-demographic and economic variables at neighbourhood level. In particular, we should mention the Social Vulnerability Index (SVI), based on three basic variables such as aging, migrant status and income (Ruiz et al, 2020) and the Urban Vulnerability Index (UVI, Antón-Alonso et al., 2021) that integrates information on social and residential exclusion. Mean normalized values of SVI and UVI have been calculated for the nine AoIs. Torre Baró, Ciutat Meridiana, UB Mundet and Sant Genís dels Agudells, have appeared to be the WUI areas with higher social vulnerability.

As for ecosystem vulnerability, Barcelona WUI area has been analysed both in terms of ecosystem sensitivity and adaptability according to the methodology developed in Moran (2020). Both parameters have been combined to obtain a final value of ecosystem vulnerability. The maximum ecosystem vulnerability corresponds to those elements of maximum sensitivity and minimum adaptability. In our case study, maximum values have been found in areas of scattered intermix or settlements surrounded by dense forest coverage. According to these criteria, Vallvidrera, Can Rectoret, and Torre Baró have appeared to be the WUI areas with higher ecosystem vulnerability.

4. Conclusions

A holistic methodology to analyse vulnerability to wildfires in metropolitan areas has been designed and implemented for the case study of the WUI areas of Barcelona. It considers three main vulnerability components: infrastructural, social and ecosystem vulnerability. Relying on different types of indicators, this integrated vulnerability analysis is key to inform risk-reduction public policies, as it provides particular insights on those WUI areas within a municipality that should be prioritized along with the specific issues that should be tackled.

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