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Understanding future changes to fires in southern Europe and their impacts on the wildland-urban interface

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ABSTRACT

Southern Europe is a highly fire-prone region where extreme fires have often disastrous consequences on both structures and people. Human activities and fire weather conditions favouring ignitions and propagation have always been the drivers of such fires but anthropogenic climate change alongside the extension of wildland-urban interface (WUI) that concentrates both assets and fire ignitions have the compounding effect of exacerbating fire risk. WUI are currently not adequately prepared to sustain events whose frequency and intensity are foreseen to increase in the future as shown during the extreme fires that occurred recently in Euro-Mediterranean countries. This work presents the context of WUI fires in the Euro-Mediterranean region, their driving forces and their impacts on society, with insights from three recent catastrophic fires that drew much attention. In this context, we propose a conceptual framework for understanding the WUI issue assessing the implications for fire risk and providing some guidance to mitigate this risk, updated management strategies as well as comments about gaps in our current knowledge and how we might address this problem in the future. A successful approach to reduce fire risk in the future will require building resilient landscapes and communities better prepared to face these extreme fire events in which WUI population, forest managers, land planners, civil protection, and policy-makers need to work together to improve the safety and resilience of these fire-prone areas.

1. Introduction

Besides the Mediterranean climate conditions (dry and warm summer) prone to fire ignition and propagation in a very flammable vegetation, Mediterranean regions are also characterized by areas where wildland vegetation intermingles with human settlements, the so-called wildland-urban interfaces (WUI). In the current context of climate change and demographic expansion, there is an increasing attention on the WUI. These areas are often considered as one of the main drivers of fire risk [1–5], as the risk to human lives and property, and therefore the stakes to defend, are the greatest [6]. As opposed to a fire that spreads only in the wildland, a WUI fire spreads across different types of flammable sources (not only vegetation) producing a range of impacts, eventually contributing to an extreme fire under specific conditions [7]. Among the new types of WUI fuels, ornamental vegetation is composed of both native and exotic species. This type of vegetation differs from wildland vegetation by its heterogeneous structure composed of isolated plants and groups of plants, sometimes lining up, thereby providing horizontal fuel continuity [8]. This WUI vegetation, which is not always properly managed (lack of regulations in some countries or lack of their enforcement when they exist), can act as a vector facilitating fire propagation from the wildland to structures (and then possibly from structure to structure, evolving in a conflagration fire) but also from the WUI towards the wildland. A fire spreading across the WUI can result in significant damage to structures, property losses and can lead to human casualties. According to [9], the WUI population is highly exposed to large WUI fires, which are undoubtedly more difficult to handle [10] as witnessed in the recent tragic fire events in Southern Europe (115 deaths in Portugal, 2017 and 102 deaths in Greece, 2018). During these fires, among citizens and firefighters involved in entrapment episodes, those that were directly exposed to a large amount of smoke particles, in combination with the extreme thermal radiation emitted by the fire and convection due to hot gases, suffocated and died in their home or on the roads [11].

In most Mediterranean regions, the current wildfire management policies are generally too focused on suppression and are no longer adapted to the on-going global change [5]. Global warming has been shown to increase the frequency and severity of fire weather conditions in both observed [12] and simulated [13] data, contributing to a lengthening of the fire weather season as well as an increased frequency of days with elevated fire danger. This trend has been attributed, to a large extent, to temperature increases in response to anthropogenic

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emissions but the signal may also be amplified in regions where precipitation is also expected to decrease. This is particularly true in the Euro-Mediterranean basin, where climate models project both a strong warming - the so-called Mediterranean amplification [14] - and precipitation deficit that collectively exacerbate fire weather conditions [15,16]. There is already emerging evidence of an increasing frequency of compound heat waves and drought episodes across Mediterranean regions in the observational record [17] and the confluence of the background warming trend with the occurrence of unusually dry years might alter the likelihood of extreme fire danger. For instance, a recent study indicates that the likelihood of extreme fire danger conditions such as those observed during the near-record breaking 2003 fire season in the French Mediterranean have increased by orders of magnitude in recent years due to anthropogenic climate change [18]. This trend is likely to continue given future climate projections ([15, 16]), which might facilitate fire spread despite suppression efforts and fire-fighting assets deployed [5]. Additionally, the aridification of the climate is thought to facilitate tree die back and mortality [19,20], enhancing the stands' flammability due to the resulting dead fuel amount. This aridification could also, over the long-term, entail changes in the distribution areas of species [21].

In addition to anthropogenic climate change, southern Europe has also experienced strong land cover and land use changes in recent decades, including a progressive abandonment of agricultural lands and activities. These changes alongside systematic fire suppression operations, especially in the surroundings of WUI areas, have contributed to a large-scale fuel build-up (increase in forested areas and therefore in fuel continuity and biomass) [22], thereby feeding fire spread [23], and eventually leading to the development of very intense and destructive fires. Moreover, in some countries such as Portugal or Chile, plantations of highly flammable species (e.g. *Pinus radiata* or *Eucalyptus globulus*) over extended areas have also increased landscape flammability and the risk of extreme fires [24,25]. At the same time, the steady urban sprawling in forested massifs (i.e. increasing the WUI areas) [1,26] has exacerbated the number of stakes to defend, posing a challenge for civil protection and firefighting teams [27]. In this context, fire managers and the general public (residents at the WUI, tourists, etc.) are confronted to unusual fast-growing and intense fires that neither the firefighting resources and tactics nor the protection strategies can suppress [28–31].

We here review the recent literature relating to WUI fires in Europe, the driving forces of these fires, their impacts on society together with insights from three recent catastrophic fires that drew much attention in Southern Europe. This allows us to propose a conceptual framework for understanding the WUI issue and to assess the implications for fire risk. Finally, we provide some guidance to mitigate the risk, update management strategies as well as comments about gaps in our current knowledge and how we might address these.

2. Fire and climate change

The last decade has seen an exceptional number of unprecedented extreme weather and climate events that are projected to be more frequent and more intense due to global warming. There are simple, physical reasons why fires would be expected to increase in a warmer climate. Indeed, a warmer atmosphere will increase the vapor pressure deficit and therefore atmospheric aridity. A drier atmosphere will be able to extract more water from soil and plants, thereby increasing landscape flammability. Beside this, fire activity is also responding to other meteorological variables such as wind bursts. Thus, a traditional approach to quantify fire weather conditions consists in computing fire weather indices summarizing the combined effects of different atmospheric variables on fire danger. One of the most widely used indices worldwide is the Canadian Forest Fire Weather Index (FWI) developed a couple decades ago [32]. Although initially developed in a jack pine forest of Canada, the FWI has been extensively used across the world, including across the Euro-Mediterranean basin [33]. The FWI integrates both current meteorological conditions (daily maximum temperature, minimum relative humidity, wind speed, and 24 h accumulated precipitation) as well as antecedent conditions and reflects the effect of fuel moisture and potential fire spread rate on fire behavior. A number of studies have thus focused on understanding how fire weather, viewed through the FWI, is responding to global warming [34,13].

Widespread increases in FWI values have been reported across the Euro-Mediterranean Basin due to anthropogenic climate change [18,35–37], mostly through increases in temperature and precipitation deficit. However, the relationship between fire weather conditions and actual fire activity is complex. It is not simple to relate changes in fire weather to changes in realized fire occurrence and fire spread as i) the climate-fire relation is strongly non-linear and ii) fires can also be influenced by a multitude of drivers ranging from land cover, fuel availability, human practices, or fire suppression strategies. Due to this complexity and diversity of processes, it is challenging to directly extrapolate the intensification of fire weather conditions to changes in fire activity.

A large body of studies have therefore sought to relate fire weather conditions to actual fire activity across a range of temporal scales [38–40]. The dryness of climate conditions in southern Europe has been found to be a good proxy of the amount of burned area in a given year [41]. On shorter timescales, studies detected two broad families of fires: fires mostly driven by heat waves and those mostly driven by wind bursts [42]. Interestingly, the relationships between fire weather, fuel moisture, and fire involve complex mechanisms and burned area often increases in a non-linear fashion with atmospheric aridity suggesting that critical thresholds in fire weather may trigger disproportionate responses in fire activity [43] (as seen in 2003 during the European heat wave).

Overall, climate-fire relationships are rather well understood and to some extent, well reproduced by statistical models, at least over broad geographical scales. Studies have therefore run climate simulations through empirical fire models to estimate future changes. These experiments suggest that anthropogenic climate change is likely to increase landscape flammability and, all things being equal, fire activity [17,16]), albeit the exact rate of increase remains unknown due to large uncertainties in climate models [37] and climate-fire model specification [44]. Additional uncertainties arising due to fire policy and fire management also complicate the realism of such simulations at regional scale and impair our ability to predict future fire activity. For instance, abrupt changes in fire policy have already been implemented in southern Europe and have contributed to a general decrease in burned area in recent decades [45,46]. However, the accumulation of fuel load, due to past fire suppression efforts within a long-term forest recovery context across the Mediterranean [47], is widely thought to have created favorable ground conditions for fire spread and the occurrence of large fires [46]. Indeed, suppression resources have historically limited fire activity but might be overwhelmed by climate change during critical seasons, as recently observed in Portugal or Greece [11], with the occurrence of extreme fires overwhelming current suppression capacities. This suggests that suppression resources may act with climate change through increased fuel to catalyze dramatic changes.

3. The wildland-urban interface

3.1. The WUI context

In recent decades, destructive WUI fires have resulted in the loss of life and property and have had dramatic socioeconomic impacts [48–51]. The problem is global and affects many countries all around the world, including Canada [52], the US [3,53,54], but also Australia – see the Black Saturday [55]. In southern Europe, recent WUI fires have contributed to fatalities in Portugal and Greece [11], drawing attention worldwide from both scientists and the general public.

WUI are complex areas where houses and other structures are built within or close to wildland vegetation. In the context of fire risk, the

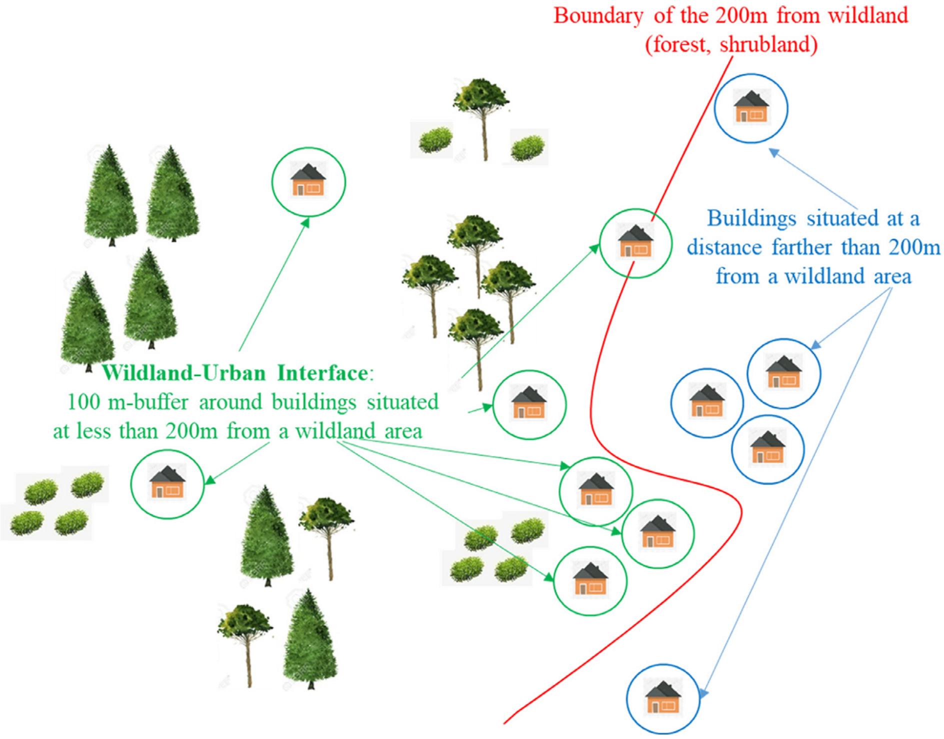

Fig. 1. The wildland-Urban Interface (adapted from [1]).

term is, most of the time, used to identify settlements that are potentially at risk [56–60]. Different types of WUI can be distinguished, such as intermingle areas, where natural forest vegetation, ornamental vegetation, and human infrastructures are separated by a line, and intermix areas where vegetation and human structures are totally intricated [61]. The WUI definition may vary from one country to another [62] but generally includes three variables: structures, vegetation, and a buffer distance (e.g. [63]). (Fig. 1).

WUI can be easily mapped using land cover data [64] to quantify their extent and dynamic. The WUI covered 9.5% of the conterminous United States in 2010 and had a 41% growth in the number of houses since 1990 [65]. Similar trends have been reported across Southern Europe [66,67]. In southeastern France, the WUI area has seen a 10% increase between 1999 and 2009 in the district of Bouches du Rhône where it covers 15% of the total surface [68]. Fire risk has been exacerbated by this rapid increase in WUI with simulations projecting a continued expansion in the future due to demographic trend, the attraction to areas with natural amenities, recreational activities, retirement to rural areas, and economic reasons [69–71].

This WUI expansion is expected to increase fire ignition. In rural areas, most fires are due to negligence during agricultural works while in more urbanized areas, fire causes can include arson or negligence during private works, for instance [72], since people moving into such areas are not always aware of the fire risk [73]. In the South of France, large fires are mostly due to arson, while smaller fires are due to negligence [74].

3.2. Vulnerability to fire hazard at the WUI

The risk is the highest at the WUI not only because the ignition hazard is high, but also because of the concentration of vulnerable populations, anthropogenic stakes, including houses, infrastructures and ecosystems (i.e. the vulnerability) [75]. Vulnerability is a complex concept with a large number of definitions [76,77]. Vulnerability represents potential consequences of the occurrence of a stochastic event, i.e. the hazard [78], including damages [79] and impacts on societies [80,81]. It depends on the number and variety of stakes exposed to fire hazard. [82] considered four classes of vulnerability: physical, social, economic, and institutional. Vulnerability at the WUI may refer to vulnerability of some particular classes of stakes, typically houses and their residents or to a more global notion of multi-stakes vulnerability of a whole area, including both human and natural vulnerabilities [83].

Assessing the global risk to improve the safety and resilience of communities requires the evaluation of both the probability of fire occurrence and the vulnerability of the threatened populations, exposed values, and ecosystems [84]. [82] suggested several methods providing qualitative, ordinal, or quantitative assessments of vulnerability. Qualitative methods include different types of matrix, such as the Vulnerability, Capacities, and Exposure matrix (VCE; [85]), while indicators-based methods, which are usually designed to provide vulnerability assessment for each element at risk, allow the ordination of the stakes in relation to their vulnerability for corrective actions prioritization. These qualitative methods relating damages to a local context are common practice [86,87]. On the other hand, curves, relating fire intensity to losses, aim at quantitatively assessing vulnerability. Fire intensity represents the power per unit of fire front width affecting the structures during the exposure time [88,89] but this metric is rarely available, unless in experimental conditions or in fire simulations. Quantitative approaches can also relate particular damages to some local variables, like topography or building materials, or global impacts including number of buildings destroyed and fatalities to some circumstantial variables, like the FWI over broad scale [90]. These latter methods require large samples of losses occurring in similar exposure conditions in order to identify statistically significant relationships between damages and local variables.

Expert opinion-based Multi-Criteria analysis and Modeling (MCM) is also used to calculate vulnerability indices [69], notably in case studies where observed damages in similar conditions are rare. These approaches aim at “objectiving” experts’ knowledge and experience, including firefighters but also forest and land managers, to hierarchize criteria of vulnerability by assigning to each of them a quantitative weight. In order to calculate an index of physical vulnerability of dwelling houses at WUI, [91] suggested considering criteria of internal vulnerability (building materials and modalities), criteria of contextual vulnerability (topography, wind exposure, spatial arrangements of the sur-

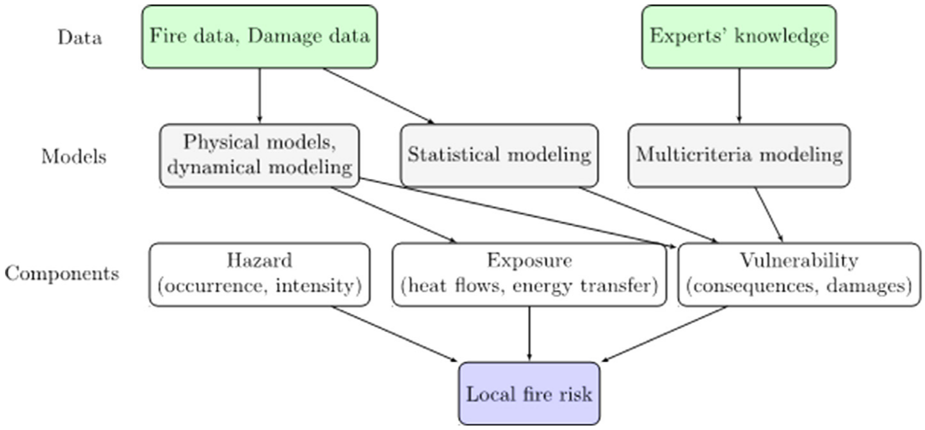

Fig. 2. Diagram framing the vulnerability modeling and assessment.

rounding vegetation), and proactive capabilities of residents (escape capabilities, self-defense). This approach uses the Ascendant Hierarchy Process [92] for experts' knowledge elicitation. Experts' opinion-based MCM is also used to assess the vulnerability of an entire WUI area, taking into account different human and natural stakes, by assigning a weight to each class of values present in the area at risk. For instance, a logistic regression model was able to explain damage occurrence based on vulnerability indices calculated with experts' opinions-based MCM [93]. This demonstrates the usefulness, but also the dependency to the context, of expert opinion-based modeling approaches for vulnerability mitigation decision making. Some of the modeling approaches for vulnerability assessment presented above are framed in Fig. 2. Vulnerability models are therefore key tools for fire risk management decision support and recommendations to populations [94] and contribute to improve WUI safety and resilience. Future change in vulnerability is closely related to WUI development throughout the landscape, due to both the discontinuous urban spread process and the forest encroachment on abandoned agricultural or pasture lands [95]. Urban land planning and forest management are the main tools at the disposal of decision makers to control these landscape changes [96].

4. How recent wildland-urban interface fires in southern Europe prefigure future challenges in managing wildfire risk

4.1. Mati, Greece 2018: how a poor urban arrangement can lead to a disaster

4.1.1. The context of the fire

At 12:03 on July 23, 2018, a first fire started on Mount Geraneia in western Attica, about 50 km West of Athens. The fire quickly spread in response to a strong wind reaching 90 km h^{-1} and swept through the WUI of Kineta [97]. This fire did not result in any human casualty but destroyed many houses and threatened by spotting an important oil refinery. Because of the high vulnerability of this stake, fire services were forced to dispatch a very large portion of ground and aerial firefighting resources to this specific area of Attica. While attention and resources were concentrated in western Attica, almost 5 h later, another fire broke out in a mountainous area of eastern Attica. The official cause of ignition was an unintended wood burning, although a damaged power line and arson were also initially advanced. The rapid spread of this second fire (rate of spread up to 5 km h^{-1}) towards the East affected the WUI of Mati where it finally stopped on the seaside (with a fire-front of approximately 1 km). The westerly flow (bursting at 100–120 km h^{-1} in several areas) blowing downslope in the eastern region of Attica [98] contributed to high temperature (up to 39 °C) and low relative humidity decreasing to 19%, creating ideal conditions for a rapid fire propagation. This rate of spread is however quite usual in Greece and despite the moderate final fire size (1,276 ha estimated by satellite data provided by the COPERNICUS Emergency Management Service – Mapping platform), the Mati fire toll was dramatic. A total of 102 people died in less than 3 h (making this event as the second-deadliest weather-related disaster in Greece) while more than 160 people were more or less severely injured and hundreds were affected by smoke and/or intense heat. Apart from human casualties, damages included approximately 3,000 houses partially or totally burned and 305 burned vehicles. Severe impacts on the built and infrastructure environment were also reported, e.g. damage in the low and medium voltage distribution networks, as well as in the water network [99]. No preventive evacuation was initiated in the first phase, when the fire started off, but only people in great danger were then rescued when it was possible.

4.1.2. Worsening factors

The topography and the town configuration contributed to a major traffic jam caused by the large number of people trying to flee. These people were often unaware of the geographical characteristics of the area such as the steep coastline that hindered access to the sea and led to their entrapment. Limited escape routes and the lack of visibility due to the smoke also contributed to the entrapment [97].

Multiple factors are held responsible for the human disaster of the Mati fire, including the management of firefighting and rescue resources and the WUI layout. The former was strongly constraint by the simultaneous occurrence of two critical fire events in Attica, as the strategic decision made at that time was to mobilize the maximum of means on the Kineta fire, for a flash massive attack, without leaving enough available teams and equipment in case of another fire (Antonis Mantzavelas, Omikron, pers. com., 2018). It is worth noting that, thanks to this strategy, there were no victim during the Kineta fire. The rate of fire spread, the delayed arrival of fire trucks due to the focus on Kineta, and the difficulty to employ aerial resources due to the strong wind, can therefore explain, among other factors, why suppression efforts were not successful.

The spatial distribution of the WUI is the second component that can explain the high casualty of the Mati fire. Indeed, the structures were directly intermixed with large patches of highly flammable pine forest, without any fuel break in between, putting the residents in a high fire risk situation. The part of the WUI located on the seacoast was sometimes on top of coastal cliffs, or in direct contact with a narrow beach. Moreover, the road network at the WUI was composed of very narrow lanes with many dead ends leaving no possibility of lateral escape. The lack of refuge areas (such as sports fields, squares, etc.) also participated to the entrapment.

Finally, the lack of warning or guidance from local authorities, along with the lack of any preparatory measures for fire protection (settlement fire plan, citizen education, or home preparation) were also aggravating factors. The fast rate of spread as well as the smoke and hot gases emitted by the fire surprised people, causing a general panic. Some people unwisely tried to escape at the last moment in their cars and were immediately caught in the traffic jam or trapped at the edge of the coastal cliff. Others managed to get into the sea but were exposed to heat and smoke for hours or drowned as rescue boats have only come hours later [100]. Fortunately, most people made quick decisions, either moving out in time or sheltering in their homes that are generally built with non-flammable materials as in most European countries.

The high number of destroyed buildings was mainly due to structure weaknesses (e.g. vulnerable roofs and frames, poor building materials) which allowed the fire to spread inside. Most affected residences and buildings included storied constructions, while ground floors or basements suffered statistically less damage, as often witnessed during a crown fire [99]. Moreover, it is worth noting that many of the affected homes were seriously damaged due to vegetation surrounding houses and to louvered shutters that provided an entrance for the flames into the buildings.

4.2. Pedrógão Grande, Portugal 2017: new challenges in fire management and evacuation of populations in the event of multiple fires

4.2.1. The context of the fire

The Pedrógão Grande complex of fire events (i.e. occurrence of several independent ignitions in a same region leading to the simultaneous propagation of several fires, eventually merging), as described by [101], occurred between June 17 and 22, 2017. This complex of fires involved two consecutive fires, the Pedrógão Grande and the Góis fires, spreading simultaneously and burning together 45,000 ha in central Portugal, near Coimbra. The former, caused by a failure of power line, reached intensities of 60,000 kW m^{-1} and, during 10 min, reached a rate of spread up to 15 km h^{-1}, provoking most fatalities. The fire exhibited an extreme phenomenon of vorticity (i.e. fire whirl as well as short and long-distance spotting activity) [101]. The Pedrógão Grande fire perimeter comprised 3,833 ha of WUI out of which 1,706 ha did not burn, eventually burning a total of 28,914 ha [102]. The Góis fire, caused by a lightning strike, was less intense and spread more slowly, with a rate of spread of 1.8 km h^{-1} and a maximum fireline intensity of 20,000 kW m^{-1} responsible for 17,521 ha burned. According to their intensity, these fires can be classified as impossible and virtually impossible to control, respectively [67].

Almost 98% of the area affected by the Pedrógão Grande complex of fires was burnt during the first 2 days. During this period, the two main fire fronts merged and the resulting firestorm produced an extreme fire behavior leading to fatal accidents when people tried to escape. In total, 66 people (among them 65 civilians and 1 firefighter) lost their lives, 31 trapped inside their cars and 30 on foot while trying to escape, while more than 200 people were more or less seriously injured. Only four civilians died at home, all having mobility difficulties. Additionally, more than 1,000 structures (buildings, infrastructures, etc.) were damaged or destroyed [103].

Besides the high temperature and dry conditions of the 2017 fire season in Portugal [40] (temperature ~ 38 °C and relative humidity ~ 20% at the time of fires; [101]), these fires spread on a rough topography and in a very dry and flammable forest vegetation. This vegetation was mainly composed of plantations of *Eucalyptus globulus* and *Pinus pinaster* as well as dense shrubland, providing high fuel continuity. The WUI extended over 3,833 ha, mostly characterized by isolated buildings [102], out of which 2,126 ha were burned affecting 1,043 structures.

4.2.2. Worsening factors

From a tactical shortcoming point of view, as [101] pointed out, the Portuguese Civil Protection warning system failed to inform citizens of the gravity of the on-going fires and the population was unprepared to respond effectively. The fires on June 17, 2017, and especially the Pedrógão Grande fire, happened to turn into extreme fires due, partly, to the wrong perception of their potential that ended up in underestimating the resources needed, notwithstanding the extreme weather conditions at the time of ignition. Moreover, firefighting resources were divided into several fires that occurred in the area, limiting the availability in firefighting means on the Pedrógão Grande fire. Indirectly playing on the extent of the damage, an important lack of adequate crisis communication during this event was underlined [104]. The communication systems collapsed and the high pressure exerted by politicians and media led to misevaluation, failures and errors in the command and control chain.

Basically, the lack of preparedness (physical and psychological) of the population was also an important factor explaining the high level of losses and damages, among which poor safety and difficult evacuation of people who were often aged and living in marginalized rural areas, therefore increasing the vulnerability of the stakes [104]. The lack of prevention measures regarding fuel management and defensible space aggravated the situation further. Moreover, the lack of collaborative work between central fire agencies, municipal governments, and local communities, the loss of the technical knowledge developed for decades by the Forest Service, and the minimization of its role and competences, as well as the restrictive legislation of the use of fire as a management tool, were other factors that exacerbated the situation.

The Pedrógão Grande complex of fires was, unfortunately, not the only dramatic fire of the 2017 season in Portugal. During the autumn 2017, more than 600 fires burned more than 200,000 ha throughout the Central Region of Portugal, killing 51 civilians, mainly in the northern half of the country, including 38 people on October 15 [105]. Once again, these fires were associated with severe meteorological conditions for the season due to the passage of Hurricane Ophelia off the Portuguese Coast, displaying temperatures above 30 °C and very strong winds. The early (June) and late (October) timing of these fires, on both ends of the typical summer fire season, illustrates the lengthening of the fire-prone season in southern Europe and the need to consider these changes in fire preparedness.

4.3. Rognac, France 2016: Usual firefighting strategies facing unusual fire behavior

4.3.1. The context of the fire

This fire occurred in Rognac, southeastern France, a highly fire-prone area (already impacted by six fires larger than 300 ha since 1967). With 2,669 ha burned in 10 h, the Rognac fire is actually the largest fire that occurred in 2016 in France.

The Rognac fire ignited in the afternoon on August 10, 2016, due to sparks emitted by an electric saw used by a resident working outdoors, despite the strong wind blowing at that time at 55 km h^{-1} on average, gusting up to 88 km h^{-1}. It is worth noting that relative humidity (32% at the time of ignition) and air temperature (27 °C) were rather moderate for the season due to a continental northerly wind (Mistral) that brings unusual cold air across the region [42]. However, the vegetation moisture content was very low due to the lack of significant rain for several months; the landscape was therefore very flammable.

The fire quickly spread in the wind direction (with a maximum rate of spread of 5.3 km h^{-1}) and was qualified as a convective fire, due to the particularly long spotting (up to 2 km). Eventually, the fire was extinguished almost 10 h after ignition, having burned 2,669 ha and more or less severely impacted seven different communities, especially Vitrolles (1,648 ha) and Les Pennes-Mirabeau (676 ha), threatening more than 2,000 buildings located at less than 50 m from the flame front (Fig. 3).

Besides its large size for a WUI fire, what mostly characterized the Rognac fire was its propagation through the WUI, towards the core of the urban area (2,200 ha were burned at the WUI and urban areas), acting sometimes more as a “suburban fire” than a “WUI fire”. In total, more than 2,000 structures were exposed to the fire and 181 (houses, other buildings, gardens and their equipment, etc.) were impacted, including 117 buildings out of which 26 were completely destroyed [106].

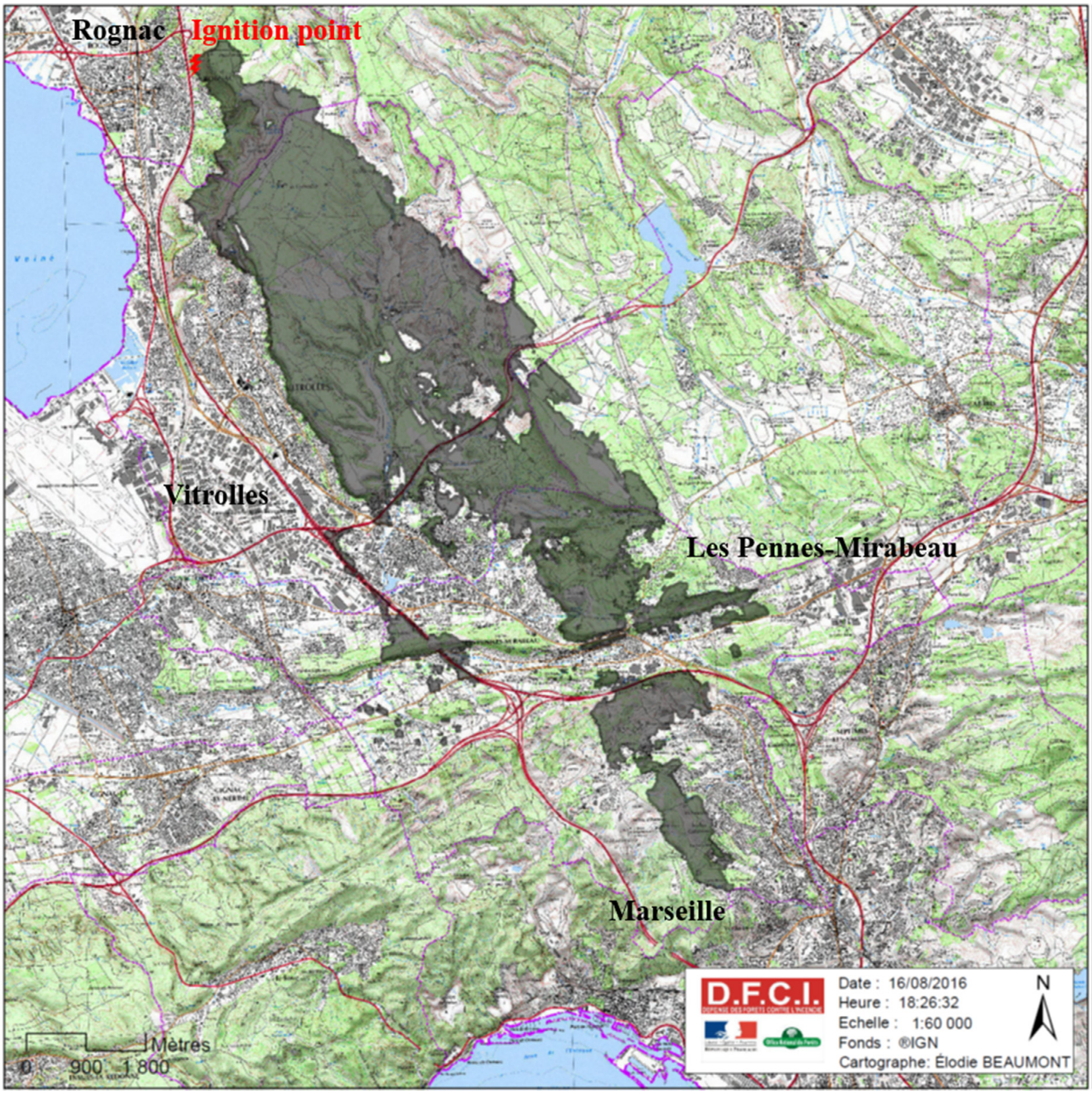

Fig. 3. Location of the ignition point and area burned by the Rognac fire (adapted from source: Office National des Forêts).

4.3.2. Worsening factors

Different reasons can explain the extent of the fire and the subsequent damages: (1) a limited suppression force, (2) a dry vegetation, (3) wind bursts, and (4) the extent of WUI complicating fire suppression strategies. When the fire ignited, the firefighting force available was reduced due to an unexpected firefighting aircraft maintenance that grounded most aerial resources. Moreover, several other fires occurred the same day in nearby locations, including a critical fire in Fos-sur-Mer (more than 1,000 ha burned) threatening an oil terminal (one of the main stakes of the area). These simultaneous fire outbreaks caused the splitting of the firefighting resources, preventing the early and massive attack of the fire (a strategy that consists of attacking the fire within the first 10 min after ignition with full force). With the fire attack delayed, the fire grew rapidly due to windy conditions interacting with topography, making the fire even more difficult and dangerous for firefighters [106].

The role of ornamental vegetation in fire propagation was paramount as the fire often spread using the horizontal fuel continuity provided by ornamental hedges located around residents' properties and along roads, destroying nearby buildings (76% of the burned area was located at the WUI) [107]. The role of ornamental vegetation was sometimes combined with a lack of clear-cutting around housing, though mandatory for buildings located at less than 200 m from wildland areas according to the French regulation at the WUI. One of the most significant examples was the “Château des Barnouins” which was completely destroyed due to tall trees overhanging the roof and two large cypress hedges located on each side of the house. The strong radiant heat emitted by the burning vegetation surrounding the buildings as well as the massive shower of firebrands generated by this vegetation, eventually contributed to the collapse of the roof and the burning of the mansion.

4.4. The same facts everywhere

Retrospective analyses of extreme fire events in southern Europe often reveal similar patterns among these fires.

- Weather conditions are major drivers of the occurrence, spread, and extreme behavior of these catastrophic fires. It is now obvious that these fires cannot be prevented only by an increase in suppression resources, in particular in the context of climate change that is expected to promote critical fire weather conditions in the future.

- Extreme fire behavior is also fueled by large amount of vegetation biomass due to past fire suppression strategies, agricultural land abandonment, lack of implementation of fuel reduction policies at the WUI, or large extents of unwise plantations of very flammable exotic species in some places.
- The suppression capacity is often overwhelmed, due to the occurrence of multiple fires at the same time [67].
- The rate of urbanization and population sprawl inside the forest over the past 20 years, combined to a poor land planning regarding wildland/rural-urban interfaces increased the vulnerability.
- The lack of awareness of fire risk as well as the lack of knowledge or guidance among residents regarding fire preparation and response added to the toll. The 2017 fires in Portugal, for example, highlight the need to better prepare and inform the population about fire preparedness and response [104].

Overall, the most important factors contributing to the increase in fire risk (i.e. climate change and land use/land cover changes but also change in fuel management) are not new given that these changes have begun decades ago and are gradual (albeit their effects are more and more pronounced with time). In contrast, some new socio-economic contexts have emerged, such as the increasing number of tourists or “new” residents without any awareness of the “culture of risk” in fire-prone areas. For the latters, solutions among promoting «Firewise communities», intensifying awareness and information campaigns through different channels including social networks, could be sought.

5. Mitigation of the risk and improvement of the socio-ecosystem resilience to fires

This section summarizes what could be done to mitigate extreme fire effects in southern Europe.

- The organization and preparedness of civil protection agencies must improve to face climate change. This could be tackled by a better understanding of the conditions contributing to extreme fires. An increase in weather data collection (including collecting data during fire events) and the improvement of modeling tools for forecasting fire propagation could be among the solutions [98], specifically within WUI areas. The civil protection agencies should also share experience-based tools and best practices particularly between Mediterranean countries and non-traditionally fire prone countries.
- Vegetation management has to be done at different scales: at landscape scale, in order to decrease the large amount of vegetation biomass accumulated due to past fire suppression strategies and land use change (agricultural land abandonment) or to limit the extent of plantations of very flammable exotic species (such as *Eucalyptus globulus* in Portugal), and at WUI scale, to implement fuel reduction policies that are, in general, poorly enforced.
- A change of perspective has to be considered instead of focusing on the reduction of burned area. [5] suggested reducing fire severity across large areas and in key locations in order to minimize negative impacts to society, ecosystems and their services.
- Fire policies have to be revised at different scales. Previous works (e.g. [11,5]) agreed on the need of a major revision of policies and practices to mitigate the number of fatalities in Mediterranean Europe, especially regarding prevention. As underlined by [108], the efficiency of fire management policies should not be assessed based on the burned area but rather on socio-ecological damages prevented by such policies. Rural development policies, whose lack of continuity and soundness was responsible for important damage in Portugal [104], also need to be revised.
- We need to better plan the WUI to develop resilient communities along with fire-resilient landscapes. Land use planning and landscape management have to be considered to regulate existing WUI and their surrounding [53,8] and better plan their extension taking into account current fire risk [3]. The land use planning has been identified as an important component of fire risk management and specific policies based on residential patterns would help reducing the risk [109]. This should also consider fireproofed structures to promote self-protection through specific regulations, incentives, insurance [5], as building construction materials have been found critical for structure survival during a fire, sometimes more than the defensible space distance [54,110]. In rural-urban interfaces undergoing agricultural land abandonment, encroachment of highly flammable vegetation and tree plantations around rural settlements ought to be contained and replaced by less flammable species such as oak species (*Quercus suber, Q. ilex*), in a buffer area around housing.
- Decision support systems based on model simulations can help taking into both climate change scenarios and land use land cover change scenarios (LULCC) in land management and planning strategies [111].
- For WUI residents, community preparedness is also a key component of a policy targeting reduced damage. The successful Australian strategy “Prepare. Act. Survive.” stresses the safer option of leaving early, as well as the dangers and significant level of preparation needed for successful defense compared to the previous Australian policy of “prepare, stay, defend, or leave early”. already showing that local communities have to participate in the design and planning of mitigation actions [93]. The American concept of Fire Adapted Community (FAC) is also an interesting approach to better mitigate the impact on human functioning or well-being when a fire occurs at the WUI [112]. The FAC includes residents, land management professionals, local politicians, emergency managers, and fire professionals who effectively collaborate to plan for, respond to, and recover from the evolving risks that fires pose to humans within or outside of the Wildland-Urban Interface.
- Residents, but also land planners, need to be more educated about fire risk as the role of fire prevention policies, such as the mandatory brush-clearing (the French fuel management regulation at the WUI), on fire mitigation is often misunderstood. Consequently, this regulation is often poorly implemented, resulting sometimes in catastrophic consequences when a fire occurs. People also need a better knowledge of the flammability potential of the ornamental vegetation and of how to use it around their home [8]. One of the lessons learned from past fires is to implement suitable designs of houses that will eventually serve as shelters in European countries, following the standards developed in Australia for instance [5].

6. Towards a fire resilient landscape design

At the wildland-urban interface, alongside an adequate and foreseen land planning, targeting the reduction of the amount and connectivity of fuels in a fire-wise landscape design, would reduce the fire severity, improving the effect of fire suppression strategies and therefore, mitigating fire damage. Forest management, including afforestation and reforestation, has to be improved keeping this in mind (i.e. considering in silvicultural practices the species’ flammability, often linked to their fire adaptation strategies) in order to decrease the fire risk. In some parts of southern Europe where agricultural areas intermix with urban settlement (rural-urban interface), agricultural policies should be better aligned with forest and fire policies to avoid vegetation encroachment around assets [5] promoting for instance livestock grazing and agroforestry [113] whenever possible. Others efficient tools to reduce fuel biomass, such as prescribed burning or use of fuel biomass for energy, have to be more efficiently promoted to gain acceptance with stakeholders and population and should be implemented and fostered wherever possible. Finally, an innovative model of fire management considering both the multi-scalar dimension of fire and the social root of fire [114] is needed to improve safety and resilience.

7. Conclusion

The extension of the wildland-urban interface that concentrates both assets and fire ignitions combined with anthropogenic climate change have been exacerbating fire risk in southern Europe, as seen throughout the world. In the past few years, the resulting catastrophic fire events took a heavy toll in human life and structure losses at the WUI, highlighting the fact that these areas are currently not adequately prepared to sustain events whose frequency and intensity are foreseen to increase even more in the future.

Better understanding the context of WUI fires in the Euro-Mediterranean region, their driving forces and their impacts on society, is needed to find sustainable solutions to tackle the fire risk issue at the WUI. Using insights from three recent catastrophic fires that occurred some years ago in southern Europe, we proposed a conceptual framework for understanding the WUI issue assessing the implications for fire risk and providing some guidance to mitigate this risk. We also provided insights on updated management strategies as well as comments about gaps in our current knowledge and how we might address this situation in the future. Indeed, a successful approach to reduce fire risk in the future will require building resilient landscapes and communities better prepared to face these extreme fire events. In this new context, WUI population, forest managers, land planners, civil protection, and policymakers will need to work together to improve the safety and resilience of these fire-prone areas of southern Europe.

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.

References

[1] C. Lampin-Maillet, Classifying the Relationship Between the Spatial Organization of a Region and Fire Risk: The Case of Forest-Dwelling Interface Areas in The South of France, PhD, Geography, University of Provence, Aix-Marseille, 2009.

[2] A.D. Syphard, V.C. Radeloff, T.J. Hawbaker, S.I. Stewart, Conservation threats due to human-caused increases in fire frequency in mediterranean-climate ecosystems, Conserv. Biol. 23 (2009) 758–769.

[3] A.D. Syphard, J.E. Keeley, A.B. Massada, T.J. Brennan, V.C. Radeloff, Housing Arrangement and location determine the likelihood of housing loss due to wildfire, PLoS One 7 (2012) e33954.

[4] A. Ganteaume, M. Long-Fournel, Driving factors of fire density can spatially vary at the local scale in SE France, Int. J. Wildland Fire 24 (5) (2015) 650–664.

[5] F. Moreira, D. Ascoli, H. Safford, M.A. Adams, J.M. Moreno, J.M.C. Pereira, F.X. Catry, J. Armesto, W. Bond, M.E. González, T. Curt, N. Koutsias, L. McCaw, O. Price, J.G. Pausas, E. Rigolot, S. Stephens, C. Tavsanoglu, V.R. Vallejo, B.W. Van Wilgen, G. Xanthopoulos, P.M. Fernandes, Wildfire management in Mediterranean–type regions: paradigm change needed, Environ. Res. Lett. 15 (1) (2020) 011001.

[6] A. Bar Massada, V.C. Radeloff, S.I. Stewart, T.J. Hawbaker, Wildfire risk in the wildland–urban interface: a simulation study in northwestern Wisconsin, Forest Ecol. Manage. 258 (2009) 1990–1999, doi:10.1016/J.FORECO.2009.07.051.

[7] E Ronchi, S.M.V. Gwynne, G. Rein, P. Intini, R. Wadhwani, An open multi-phys ics framework for Modeling wildland-urban interface fire evacuations, Saf. Sci. 118 (2019) 868–880, doi:10.1016/j.ssci.2019.06.0.

[8] A. Ganteaume, Ornamental Vegetation, in: S. Manzello (Ed.), Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires, Springer, Cham, 2018.

[9] J. Silva Sande, F. Rego, P. Fernandes, E. Rigolot, Improving fire management success through fire behaviour specialists, in: Towards Integrated Fire Management – Outcomes of the European Project Fire Paradox, EFI Research Report number 23. European Commission, Fire Paradox Project number FP6–018505, 2010, pp. 105–119.

[10] D.X. Viegas, Recent forest fire related accidents in Europe, European Comm. JRC Sci. Technical Reports (2009) JRC 56107, EUR 24121 EN. (Brussels).

[11] D.M. Molina-Terrén, G. Xanthopoulos, M. Diakakis, L. Ribeiro, D. Caballero, G.M. Delogu, D.X. Viegas, C.A. Silva, A. Cardil, Analysis of forest fire fatalities in Southern Europe: Spain, Portugal, Greece and Sardinia (Italy), Int. J. Wildland Fire 28 (2) (2019) 85–98, doi:10.1071/WF18004.

[12] W.M. Jolly, M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G.J. Williamson, D.M.J.S. Bowman, Climate-induced variations in global wildfire danger from 1979 to 2013, Nat. Commun. 6 (2015) 7537, doi:10.1038/ncomms8537.

[13] J.T. Abatzoglou, A.P. Williams, R. Barbero, Global emergence of anthropogenic climate change in fire weather indices, Geophys. Res. Lett. 46 (1) (2019) 326–336, doi:10.1029/2018GL080959.

[14] R. Brogli, N. Kröner, S.L. Sørland, D. Lüthi, C. Schär, The role of hadley circulation and lapse-rate changes for the future European summer climate, J. Clim. 32 (2) (2019) 385–404, doi:10.1175/JCLI-D-18-0431.1.

[15] J.L. Dupuy, H. Fargeon, N. Martin-St Paul, F. Pimont, J. Ruffault, M. Guijarro, et al., Climate change impact on future wildfire danger and activity in southern Europe: a review, Ann. Forest Sci. 77 (2020) 35, doi:10.1007/s13595-020-00933-5.

[16] M. Turco, J.J. Rosa-Cánovas, J. Bedia, S. Jerez, J. Pedro Montávez, M.C. Llasat, A. Provenzale, Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models, Nat. Commun. 9 (2018) 3821, doi:10.1038/s41467-018-06358-z.

[17] A. Russo, C.M. Gouveia, E. Dutra, P.M.M. Soares, R.M. Trigo, The synergy between drought and extremely hot summers in the Mediterranean, Environ. Res. Lett. 14 (2019) 014011, doi:10.1088/1748-9326/aaf09e.

[18] R. Barbero, J.T. Abatzoglou, F. Pimont, J. Ruffault, T. Curt, Attributing increases in fire weather to anthropogenic climate change over France, Front. Earth Sci. 8 (2020) 1–11, doi:10.3389/feart.2020.00104.

[19] C.D. Allen, A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H., Hogg, P. Gonzalez, R. Fensham, Z. Zhangm, J. Castro, N. Demidova, J.H. Lim, G. Allard, S.W. Running, A. Semerci, N. Cobb, A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, Forest. Ecol. Manag. 259 (2010) 660–684.

[20] J. Carnicer, M. Coll, M. Ninyerola, X. Pons, G. Sanchez, J. Penuelas, Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought, Proc. Natl. Acad. Sci. 108 (2011) 1474–1478.

[21] Fréjaville, T., Curt, T., Spatiotemporal patterns of changes in fire regime and climate: defining the pyroclimates of south-eastern France (Mediterranean Basin). Climatic Change 129 (2015) 239-251.

[22] C. Vega-Garcìa, E. Chuvieco, Applying local measures of spatial heterogeneity to Landsat-TM images for predicting wildfire occurrence in Mediterranean landscapes, Landscape Ecol. 21 (2006) 595–605, doi:10.1007/S10980-005-4119-5.

[23] F. Moreira, O. Viedma, M. Arianoutsou, T. Curt, N. Koutsias, E. Rigolot, A. Barbati, P. Corona, P. Vaz, G. Xanthopoulos, F. Mouillot, E. Bilgili, Landscape–wildfire interactions in southern Europe: implications for landscape management, J. Environ. Manage. 92 (2) (2011) 389–2402, doi:10.1016/J.JENVMAN.2011.06.028.

[24] S. Gomez-Gonzales, F. Ojeda, P.M. Fernandes, Portugal and Chile: longing for sustainable forestry while rising from the ashes, Environ. Sci. Policy 81 (2018) 104–107.

[25] F. De la Barrera, F. Barraza, P. Favier, V. Ruiz, J. Quense, Megafires in Chile 2017:Monitoring multiscale environmental impacts of burned ecosystems, Sci. Total Environ. 637–638 (2018) 1526–1536.

[26] G. Xanthopoulos, C. Bushey, C. Arnol, D. Caballero, Characteristics of wildland–urban interface areas in Mediterranean Europe, North America and Australia and differences between them, in: G Boustras, N. Boukas (Eds.), 'Proceedings of the 1st International Conference in Safety and Crisis Management in the Construction, Tourism and SME Sectors (1st CoSaCM)', 24–28 June 2011, Nicosia, Cyprus, Brown Walker Press, Boca Raton, FL, USA, 2012, pp. 702–734.

[27] D. Caballero, WUIWATCH White book on fire prevention and defense in the WUI. Directorate General of Humanitarian Aid and Civil Protection ECHO, Project Final Technical Implementation Report, Deliverable 9.9 (Madrid, Spain). (2017).

[28] Z Maditinos, C. Vassiliadis, Mega fires: can they be managed effectively? Disaster Prevent. Manage. 20 (2011) 41–52, doi:10.1108/09653561111111072.

[29] A Cardil, C.S. Eastaugh, D.M. Molina, Extreme temperature conditions and wildland fires in Spain, Theor. Appl. Climatol. 122 (2015) 219–228, doi:10.1007/S00704-014-1295-8.

[30] A. Cardil, D. Merenciano, D.M. Molina-Terrén, Wildland fire typologies and extreme temperatures in NE Spain, iForest – Biogeosciences and Forestry 9 (2016) e1–e6, doi:10.3832/IFOR1939-009.

[31] G.M. Jones, R.J. Gutiérrez, D.J. Tempel, S.A. Whitmore, W.J. Berigan, M.Z. Peery, Megafires: an emerging threat to old-forest species, Front. Ecol. Environ. 14 (2016) 300–306, doi:10.1002/FEE.1298.

[32] C.E. Van Wagner, Development and structure of the Canadian forest fire weather index system, Forestry Technical Report 35, Government of Canada, Canadian Forestry Service, Ottawa (1987) https://doi.org/19927.

[33] P. Fiorucci, F. Gaetani, R. Minciardi, Development and application of a system for dynamic wildfire risk assessment in Italy, Environ. Modeling Softw. 23 (2008) 690–702.

[34] M.D. Flannigan, B.M. Wotton, G.A. Marshall, W.J. de Groot, J. Johnston, N. Jurko, A.S. Cantin, Fuel moisture sensitivity to temperature and precipitation: climate change implications, Clim. Change 134 (1–2) (2016) 59–71, doi:10.1007/s10584-015-1521-0.

[35] M. Moriondo, P. Good, R. Durao, M. Bindi, C. Giannakopoulos, J. Corte-Real, Potential impact of climate change on fire risk in the Mediterranean area, Clim. Res. 31 (2006) 85–95, doi:10.3354/cr031085.

[36] J. Bedia, S. Herrera, J.M. Gutiérrez, Assessing the predictability of fire occurrence and area burned across phytoclimatic regions in Spain, Nat. Hazards Earth Syst. Sci. 14 (2014) 53–66.

[37] H. Fargeon, F. Pimont, N. Martin-StPaul, M. De Caceres, J. Ruffault, R. Barbero, J-L. Dupuy, Projections of fire danger under climate change over France: where do the greatest uncertainties lie? Clim. Change 60 (2020) 479–493.

[38] C. Hernandez, P. Drobinski, S. Turquety, J.-L. Dupuy, Size of wildfires in the Euro-Mediterranean region: observations and theoretical analysis, Nat. Hazards Earth Syst. Sci. 15 (2015) 1331–1341, doi:10.5194/nhess-15-1331-2015.

[39] R. Barbero, T. Curt, A. Ganteaume, E. Maillé, M. Jappiot, A. Bellet, Simulating the effects of weather and climate on large wildfires in France, Nat. Hazards Earth Syst. Sci. 19 (2019) 441–454.

[40] M. Turco, S. Jerez, S. Augusto, P. Tarín-Carrasco, N. Ratola, P. Jiménez-Guerrero, R.M. Trigo, Climate drivers of the 2017 devastating fires in Portugal, Sci. Rep. 9 (2019) 13886.

[41] M. Turco, J. von Hardenberg, A. AghaKouchak, M.C. Llasat, A. Provenzale, R.M. Trigo, On the key role of droughts in the dynamics of summer fires in Mediterranean, Europe Sci. Reports 7 (1) (2017) 81.

[42] J. Ruffault, T. Curt, N.K. Martin St-Paul, V. Moron, R.M. Trigo, Extreme Wildfire occurrence in response to Global Change type Droughts in the Northern Mediterranean, Natural Hazard. Earth Syst. Sci. Discussions 18 (2017) 847–856, doi:10.5194/nhess-2017-415.

[43] F. Pimont, J. Ruffault, N.K. Martin-StPaul, J.-L. Dupuy, Why is the effect of live fuel moisture content on fire rate of spread underestimated in field experiments in shrublands ? Int. J. Wildland Fire 28 (2) (2019) 127–137.

[44] Y. Boulanger, M-A. Parisien, W. Wang, Model-specification uncertainty in future area burned by wildfires in Canada, Int. J. Wildland Fire 27 (3) (2018) 164–175.

[45] M. Turco, J. Bedia, F. Di Liberto, P. Fiorucci, J. von Hardenberg, N. Koutsias, M.C. Llasat, F. Xystrakis, A. Provenzale, Decreasing fires in Mediterranean Europe, PLoS One 11 (2016) e0150663.

[46] T. Curt, T. Fréjaville, Wildfire policy in Mediterranean France: how far is it efficient and sustainable? Risk Anal. 38 (3) (2018) 472–488, doi:10.1111/risa.12855.

[47] J. Abadie, J.-L. Dupouey, C. Avon, X. Rochel, T. Tatoni, L. Bergès, Forest recovery since 1860 in a Mediterranean region: drivers and implications for land use and land cover spatial distribution, Landscape Ecol. 33 (2) (2017) 289–305, doi:10.1007/s10980-017-0601-0.

[48] G. Herrero-Corral, M. Jappiot, .C Bouillon, M. Long-Fournel, Application of a geographical assessment method for the characterization of wildland-urban interfaces in the context of wildfire prevention: a case study in western Madrid, Appl. Geogr. 35 (2012) 60–70.

[49] R.G. Rehm, W. Mell, A simple model for wind effects of burning structures and topography on wildland–urban interface surface-fire propagation, Int. J. Wildland Fire 18 (2009) 290–301, doi:10.1071/WF08087.

[50] A.M. Gill, S.L. Stephens, G.J. Cary, The worldwide “wildfire” problem, Ecol. Appl. 23 (2013) 438–454, doi:10.1890/10-2213.1.

[51] M.A. Moritz, E. Batllori, R.A. Bradstock, A.M. Gill, J. Handmer, P.F. Hessburg, J. Leonard, S. Mccaffrey, D.C. Odion, T. Schoennagel, A.D. Syphard, Learning to coexist with wildfire, Nature 515 (2014) 58–66, doi:10.1038/nature13946.

[52] L.M. Johnston, M.D. Flannigan, Mapping Canadian wildland fire interface areas, Int. J. Wildland Fire 27 (2018) 1–14, doi:10.1071/WF16221.

[53] A.D. Syphard, T.J. Brennan, J.E. Keeley, The role of defensible space for residential structure protection during wildfires, Int. J. Wildland Fire 23 (2014) 1165–1175.

[54] A.D. Syphard, T.J. Brennan, J.E. Keeley, The importance of building construction materials relative to other factors affecting structure survival during wildfire, Int. J. Disaster Risk Reduct. 21 (1) (2017) 40–147.

[55] B. Teague, R. McLeod, S. Pascoe, 2009 Victorian Bushfires, Royal Commission final report: summary, State Government of Victoria, Melbourne, 2010.

[56] S.I. Stewart, V.C. Radeloff, R.B. Hammer, T.J. Hawbaker, Defining the wildland-urban interface, J. For. 105 (2007) 201–207.

[57] J.D. Cohen, The wildland-urban interface fire problem. A consequence of the fire exclusion paradigm,, For. Hist. Today Fall 2008 (2008) 20–26.

[58] A.M. Gill, S.L. Stephens, Scientific and social challenges for the management of fire-prone wildland–urban interfaces, Environ. Res. Lett. 4 (2009) 034014, doi:10.1088/1748-9326/4/3/034014.

[59] W.E. Mell, S.L. Manzello, A. Maranghides, D. Butry, R.G. Rehm, The wildland–urban interface fire problem – current approaches and research needs, Int. J. Wildland Fire 19 (2010) 238–251, doi:10.1071/WF07131.

[60] S.E. Caton, R.S.P. Hakes, D.J. Gorham, A. Zhou, M.J. Gollner, Review of pathways for building fire spread in the wildland urban interface part i: exposure conditions, Fire Technol. 53 (2) (2016) 429–473, doi:10.1007/s10694-016-0589-z.

[61] V.C. Radeloff, R.B. Hammer, S Stewart, Rural and suburban sprawl in the U.S. Midwest from 1940 to 2000 and its relations to forest fragmentation, Conserv. Biol. 19 (3) (2005) 793–805.

[62] L.M. Johnston, R. Blanchi, M. Jappiot, Wildland-urban interface, Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires Manzello S., Springer, Cham, 2020.

[63] C. Lampin-Maillet, M. Jappiot, M. Long, C. Bouillon, D. Morge, J.P. Ferrier, Mapping wildland-urban interfaces at large scales integrating housing density and vegetation aggregation for fire prevention in the South of France, J. Environ. Manage. 91 (2010) 732–741, doi:10.1016/j.jenvman.2009.10.001.

[64] C. Bouillon, M. Fernandez Ramiro, C. Sirca, B. Fierro Garcia, F. Casula, B. Vila, F. Tedim, A tool for mapping rural-urban interfaces on different scales, Advances in Forest Fire Research. Chapter 3 - Fire Management Viegas D, Universidade de Coimbra, Coimbra, Portugal, 2014.

[65] V.C. Radeloff, P.H. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar–Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, S.I. Stewart, Rapid growth of the US wildland-urban interface raises wildfire risk, Proc. Natl Acad. Sci. 115 (13) (2018) 3314–3319.

[66] L. Galiana-Martin, G. Herrero, J. Solana, A wildland-urban interface typology for forest fire risk management in Mediterranean areas, Landsc. Res. 36 (2011) 151–171, doi:10.1080/01426397.2010.549218.

[67] F. Tedim, V Leone, M Amraoui, C Bouillon, M Coughlan, G Delogu, P Fernandes, C Ferreira, S McCaffrey, T McGee, J Parente, D Paton, M Pereira, L Ribeiro, D Viegas, G. Xanthopoulos, Defining extreme wildfire events: difficulties, challenges, and impacts, Fire 1 (2018) 9, doi:10.3390/fire1010009.

[68] M. Long-Fournel, D. Morge, C. Bouillon, M. Jappiot, in: La cartographie des interfaces habitat-forêt : un outil de diagnostic territorial dans la prévention du risque d'incendie de forêt dans le Sud de la France, Sciences Eaux & Territoires, INRAE, 2013, p. 8. 10.14758/SET-REVUE.2013.HS.05. hal-00824644.

[69] L. Galiana-Martin, O. Karlsson, Development of a methodology for the assessment of vulnerability related to wildland fires using a multi-criteria evaluation, Geogr. Res. 50 (3) (2011) 304–319, doi:10.1111/j.1745-5871.2011.00718.x.

[70] F. Tedim, G. Xanthopoulos, V. Leone, Forest fires in europe: facts and challenges, Wildfire Hazard. Risks Disasters (2015) 77–99, doi:10.1016/B978-0-12-410434-1.00005-1.

[71] D.M. Theobald, W.H. Romme, Expansion of the US wildland-urban interface, Landsc. Urban Plan. 83 (2007) 340–354, doi:10.1016/j.landurbplan.2007.06.002.

[72] A. Ganteaume, A.D. Syphard, Ignition sources, in: S. Manzello (Ed.), Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires, Springer, Cham, 2018.

[73] C. Wilson, Why start wildfires? The Motivation Behind Arsons and Accidents, Northland DOC, 2009 Unpublished report..

[74] A. Ganteaume, M. Jappiot, What causes LF in Southern France, Forest Ecol. Manag. 294 (2013) 76–85, doi:10.1016/j.foreco.2012.06.055.

[75] J. Birkmann, O.D. Cardona, M.L. Carreno, A.H. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, M. Keiler, D. Alexander, P. Zeil, T. Welle, Framing vulnerability, risk and societal responses: the MOVE framework, Nat. Hazards 67 (2013) 193e211, doi:10.1007/s11069-013-0558-5.

[76] R.L. Ciurean, D. Schroter, T. Glade, Conceptual frameworks of vulnerability assessments for natural disasters reduction,, in: Approaches to Disaster Management - Examining the Implications of Hazards, Emergencies and Disasters, 2013, pp. 3–32, doi:10.5772/55538. INTECH Open Access Publisher.

[77] L. Costa, J.P. Kropp, Linking components of vulnerability in theoretic frameworks and case studies, Sustain. Sci. 8 (2013) 1–9, doi:10.1007/s11625-012-0158-4.

[78] S. Oliveira, F. Fernando, L. Lourenço, G. Laneve, A. Sebastian-Lopez, Mapping wildfire vulnerability in Mediterranean Europe. Testing a stepwise approach for operational purposes, Environ. Manage. 206 (2018) 156–159 https://doi.org/, doi:10.1016/j.jenvman.2017.10.003.

[79] D.G. Neary, J.M. Leonard, Physical Vulnerabilities from Wildfires: Flames, Floods, and Debris Flows, IntechOpen, 2019 [Online First],, doi:10.5772/intechopen.87203.

[80] S. Tapsell, S. Mccarthy, H. Faulkner, M. Alexander, C. Kuhlicke, S. Brown, G. Walker, A. Scolobig, B. De Marchi, C. Bianchizza, Social Vulnerability to Natural Hazards, CapHaz-Net - WP4 Report. London (2010).

[81] E. Chuvieco, S. Martínez, M.V. Roman, S. Hantson, M.L. Pettinari, Integration of ecological and socio-economic factors to assess global vulnerability to wildfire, Glob. Ecol. Biogeogr. 23 (2014) 245–258, doi:10.1111/geb.12095.

[82] S. Fuchs, T. Thaler, Vulnerability and Resilience to Natural Hazard, Cambridge University Press, Cambridge, UK, 2018.

[83] D. Paton, F. Tedim, Wildfire Community, Charles C Thomas Publisher Ltd, Springfield, USA, 2012.

[84] F. Tedim, Enhance wildfire risk management in Portugal: the relevance of vulnerability assessment, in: Wildfire Community. Chap. 4, Charles C Thomas Publisher Ltd, Springfield, USA, 2012, pp. 66–81.

[85] A. Fekete, B. Montz, In.Fuchs Vulnerability, Thaler S., 2018 T., Vulnerability and Resilience to Natural Hazard, chap 1, Cambridge University Press, Cambridge, UK, 2018.

[86] C. Aragoneses, J.M. Rabade, Methodological proposal for analyzing the vulnerability and potential gravity of forest fires within the framework of civil protection, in: Armando Gonzalez-Caban (Ed.), Proceedings of the second international symposium on fire economics, planning, and policy: a global view. PSW-GTR-208, USDA Forest Service, Pacific Southwest Research Station, Albany, CA, 2008, pp. 147–158.

[87] R. Blanchi, J. Leonard, R. Leicester, F. Lipkin, F. Boulaire, C. McNamara, Assessing vulnerability at the urban interface, in: The 5th International Wildland Fire Conference, Sun City, South Africa, 2011, pp. 9–13. May 2011.

[88] M.E. Alexander, M.G. Cruz, Fireline Intensity, Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires Manzello S., Springer, Cham, 2018.

[89] J-L. Rossi, F-J. Chatelon, T. Marcelli, Fire intensity, Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires Manzello S., Springer, Cham, 2018.

[90] R. Blanchi, J. Leonard, K. Haynes, K. Opie, M. James, F. Oliveira, Environmental circumstances surrounding bushfire fatalities in Australia 1901-2011, Environ. Sci. Policy 37 (2014) 192–203.

[91] L. Pugnet, E. Maillé, Assessment of wildland–urban interface vulnerability to fire using a multi-criteria analysis, International conference on forest fire risk Modeling and mapping - Vulnerability to forest fire at wildland-urban interfaces, Aix en Provence, France, 2013 30th of September, 1st and 2nd of October 2013.

[92] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.

[93] E. Maillé, L. Pugnet, J. Hédan, Coupling multi-criteria analysis and GLM for Modeling houses vulnerability to forest fires at WUI, Advance in Forest Fire Reserach Viegas, D.X. (Edt.), ADAI/CEIF, Coimbra, Portugal, 2018.

[94] T.W. Collins, B. Bolin, Situating hazard vulnerability: people's negotiations with wildfire environments in the US Southwest, Environ. Manage. 44 (2009) 441–455, doi:10.1007/s00267-009-9333-5.

[95] M. Ortega, S. Saura, S. Gonzalez-Avila, V. Gomez-Sanz, R. Elena-Rossello, Landscape vulnerability to wildfires at the forest-agriculture interface: half-century patterns in Spain assessed through the SISPARES monitoring framework, Agroforestry Syst. 85 (3) (2012) 331–349.

[96] L. Galiana-Martín, Spatial planning experiences for vulnerability reduction in the wildland-urban interface in Mediterranean European countries, European Countryside 9 (3) (2017) 577–593, doi:10.1515/euco-2017-0034.

[97] N. Efthimiou, E. Psomiadis, P. Panagos, Fire Severity and Soil Erosion Susceptibility Mapping Using Multi-Temporal Earth Observation Data: The case of Mati fatal wildfire in Eastern, Attica, Greece, Catena, 2019, doi:10.1016/j.catena.

[98] K. Lagouvardos, V. Kotroni, T.M. Giannaros, S. Dafis, Meteorological conditions conducive to the rapid spread of the deadly wildfire in eastern Attica, Greece, Bull. Am. Meteorol. Soc. 100 (11) (2019) 2137–2145.

[99] E. Lekkas, P. Carydis, K. Lagouvardos, S. Mavroulis, M. Diakakis, E. Andreadakis, M.E. Gogou, N.I. Spyrou, M. Athanassiou, E. Kapourani, M. Arianoutsou, M. Vassilakis, E. Kotsi, P.D. Speis, J. Delakouridis, D. Milios, V. Kotroni, T. Giannatros, S. Dafis, A. Kargiannidis, K. Papagiannaki, The July Attica (Central Greece) Wildfires-Scientific Report (Version 1.0), Newsletter of Environmental, Disaster, and Crisis Management Strategies 8 (2018), Athens.

[100] G. Xanthopoulos, M. Athanasiou, Attica region Greece, July 2018, Wildfire 28 (2) (2019) 18–21.

[101] D.X. Viegas, M.F. Almeida, L.M. Ribeiro, J. Raposo, M.T. Viegas, R. Oliveira, D. Alves, C. Pinto, H. Jorge, A. Rodrigues, D. Lucas, S. Lopes, L.F. Silva, in: O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017, Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA), 2017, p. 238.

[102] F. Tedim, D. Royé, C. Bouillon, F.J.M. Correia, V Leone, Understanding Unburned Patches Patterns in Extreme Wildfire Events: Evidences from Portugal, VIII International Conference on Forest Fire Research, Coimbra, 2018 November 2018.

[103] L.M. Ribeiro, A. Rodrigues, D. Lucas, D.X. Viegas, The large fire of Pedrógão Grande (Portugal) and its impact on structures, Advances in Forest Fire Research 2018 - D. X. Viegas (Ed.), Chapter 4 – Fire at the Wildland Urban Interface, 2018 https://doi.org/, doi:10.14195/978-989-26-16-506_94.

[104] F. Tedim, Portugal's 2017 Pedrógão Grande disaster in context of extreme event analysis, California Fire Science Consortium Webinar, 2018 www.calfiresci.org.

[105] D.X. Viegas, M.A. Almeida, L.M. Ribeiro, J. Raposo, M.T. Viegas, R. Oliveira, D. Alves, C. Pinto, A. Rodrigues, C. Ribeiro, S. Lopes, H. Jorge, C.X. Viegas, Análise dos Incêndios Florestais Ocorridos a 15 de outubro de 2017, 2019 Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA)..

[106] P. Tissot, L'incendie de forêt de Rognac du 10 août 2016 2016 : une catastrophe humaine évitée », Forêt méditerranéenne,XL (2) (2019) 105–110.

[107] A. Ganteaume, Role of the ornamental vegetation in the propagation of the Rognac fire (SE France, 2016), Fire Continuum Conference, 2018 May 21-24, 2018, Missoula.

[108] E. Rigolot, J-L. Dupuy, F. Pimont, J. Ruffault, Les incendies de forêt catastrophiques, Respons. Environ. 98 (2020) 19–35.

[109] A.D. Syphard, A. Bar Massada, V. Butsic, J.E. Keeley, Land use planning and wildfire: development policies influence future probability of housing loss, PLoS One 8 (8) (2013) e71708.

[110] A.D. Syphard, H. Rustigian-Romsos, M. Mann, E. Conlisk, M.A. Moritz, D. Ackerly, The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes, Global Environ. Change 56 (2019) 41–55.

[111] A. Badia, P-B. Montserrat, N. Valldeperas, G Meritxell, Wildfires in the wildland-urban interface in Catalonia: vulnerability analysis based on land use and land cover change, Sci. Total Environ. 673 (2019) 184–196, doi:10.1016/j.scitotenv.2019.04.012.

[112] T.B. Paveglio, C.M. Edgeley, Fire adapted community, in: S. Manzello (Ed.), Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires, Springer, Cham, 2020.

[113] F. Moreira, G. Pe'er, Agricultural policy can reduce wildfires, Science 359 (6379) (2018) 1001.

[114] F. Tedim, V. Leone, G. Xanthopoulos, A wildfire risk management concept based on a social-ecological approach in the European Union: fire smart territory, Int. J. Disaster Risk Reduction 18 (2016) 138–153.