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Summary of Workshop Large Outdoor Fires and the Built Environment

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Abstract

Large outdoor fires present a risk to the built environment. Wildfires that spread into communities, referred to as Wildland-Urban Interface (WUI) fires, have destroyed communities throughout the world, and are an emerging problem in fire safety science. Other examples are large urban fires including those that have occurred after earthquakes. Research into large outdoor fires, and how to potentially mitigate the loss of structures in such fires, lags other areas of fire safety science research. At the same time, common characteristics between fire spread in WUI fires and urban fires have not been fully exploited. In this paper, an overview of the large outdoor fire risk to the built environment from each region is presented. Critical research needs for this problem in the context of *fire safety science* are provided. The present paper seeks to develop the foundation for an international research needs roadmap to reduce the risk of large outdoor fires to the built environment.

1.0 INTRODUCTION

Large outdoor fires are becoming an important research area across the world. Many cities are densely populated, and there exists the potential for large-scale urban fires. These may or may not be produced after the occurrence of strong earthquakes. The Great Hanshin earthquake in Kobe, Japan, in 1995 is one example. The recent 2016 Itoigawa City fire that occurred in Niigata, Japan, is an example where no earthquake was present, but a large-scale urban fire developed.

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In many countries, wildland fires that spread into communities, termed wildland-urban interface (WUI) fires, are frequently seen in media reports and have resulted in loss of life and property damage. The 2007 Southern California Fire forced 300,000 people to evacuate, destroyed over one thousand structures, and resulted in $1B paid by insurers [1]. In Europe, the 2007 fires in Greece destroyed several hundred structures, and resulted in the deaths of more than 70 people. In Australia, the 2009 fires in Victoria caused the death of 173 people and destroyed more than one two thousand structures [2]. More than 60 people perished in WUI fires in Portugal in June 2017.

WUI fires continue to burn in the USA and are rapidly getting worse with attendant increased economic costs [3]. Some recent examples include the Bastrop Complex Fire in Texas in 2011, the Waldo Canyon Fire in Colorado in 2012, and fires in Arizona, Colorado, and California in 2013. In 2016, WUI fires near the Great Smokey Mountains National Park in Tennessee claimed the lives of 14 people and destroyed more than two thousand structures. In October 2017, multiple WUI fires in California destroyed more than 6,700 residential structures and resulted in more than 40 deaths.

Fire safety science research has spent a great deal of effort to understand fire dynamics within buildings. Research into large outdoor fires and how to potentially mitigate the loss of structures in such fires is far less developed than other areas of fire safety science research. This is due to the fact that large outdoor fire spread is incredibly complex, involving the interaction of topography, weather, vegetation, and structures [4]. At the same time, common characteristics between fire spread in WUI fires and urban fires have not been fully exploited. Once a wildland fire reaches a community and ignites structures, structure-to-structure fire spread can occur under similar mechanisms as in urban fire spread.

On June 11, 2017, a workshop sponsored by the International Association for Fire Safety Science (IAFSS) was held. Seven panelists from around the world presented regional overviews of the large outdoor fire problem related to the built environment in their respective regions. Presentations explored common characteristics between these fires and were arranged as: European View, Asian View, North American View, South American View, and Oceania View. The presentations were reported in a recent report [5].

In this paper, an in-depth overview of the large outdoor fire risk to the built environment from each region is presented. Critical research needs for this problem in the context of *fire safety science* are provided. The paper includes an African perspective, as this was not presented at the workshop.

The authors seek to develop the foundation for an international research needs roadmap to reduce the risk of large outdoor fires to the built environment. Similar to the workshop, the various regions are presented in a random fashion as to not suggest any particular region in the world is more or less important than the other. The paper also highlights the start of a permanent working group approved under the umbrella of the IAFSS to start to tackle this enormous fire safety science challenge.

2.0 ASIAN VIEW

2.1 Historical Fires and Overall Problem in Asia

Asia is the largest region in the world, with a total land area of 44.5 million km^2 and a population of 4.2 billion (**see** Table 1). Asia covers vast areas, from Russia to Indonesia and Japan to Israel and includes many small islands. Due to its size, the weather, the topology, state of development, and culture vary extensively within Asia. Some countries are highly populated with most people living in urban areas while some are sparsely populated. Some countries have large portions of forest while some do not. The overall state of economic development differs significantly from country to country. Due to these differences, large outdoor fires in Asia include not only wildland fires, which are sometimes called mountain fires (in direct translation from various Asian languages), but also peat fires, WUI fires, as well as urban fires, where the forest itself plays no role. As a result, the reader should be not surprised that Asia is the hardest region to provide a succinct overall description.

The Black Dragon wildland fires in China and Russia in 1987 destroyed over 70,000 km^2 of forest, resulting in the loss of hundreds of lives. In recent years, Asia has started suffering from more WUI fires. The Mount Carmel Fires in Israel in 2010 destroyed over 50 km^2 of forest, resulted in 44 deaths, and destroyed 70 structures. In 2015, a series of WUI fires in Russia resulted in more than one thousand structures destroyed with 33 fatalities. Korea had two WUI fires in one day in 2013; Japan had two WUI fires in 2017. In WUI fires in Asia, cultural buildings as well as historic communities may be burned, which is an irreplaceable loss from a cultural point of view.

Peat fires are also one of the large outdoor fire problems in Asia, especially in Russia and in Indonesia where copious peatlands exist. One of notable problems with those fires is massive haze - emissions of particulates, CO_2, and CO, not only within these countries but also to nearby countries [6–8]. During fires in Russia from July to September 2010 many people suffered from smoke and combustion gases from peat fires [9]. Many out of control fires start from intentional fires, such as slash and burn methods for clearing land for agricultural purposes [10].

Because of developments in urban areas, it is more common in Asia to focus on urban fires [11–13]. The Niigata fires in Japan on December 2016 burned 40,000 m^2 of urban area and damaged 120 houses, with 120 of 147 destroyed. This fire was the worst urban fire in Japan for over 40 years, other than post-earthquake fires. The Great Hanshin earthquake in Kobe, Japan, in 1995 is one example of a post-earthquake fire. As Asia has many densely built communities, strong wind drives simultaneous fires that may easily overwhelm firefighting resources resulting in massive structure losses.

The other problem in Asian cities is old buildings [14–16]. Over recent decades, many Asian countries have developed in many ways, including applying better codes and standards for fire protection; however old buildings, constructed before such codes and standards, still exist in cities. In most cases, several city blocks contain mostly old buildings, and as those buildings are more ignition-prone than new buildings, it is easy for fires to propagate from structure-to-structure. At the same time, informal settlements may exist in urban areas in

Asia. The Philippines suffers from fires in shanty towns which force people to evacuate [17]. Those fires receive less attention than most other fires, as economic losses are much smaller, and those buildings do not follow any codes or standards [18].

While each country has statistical information on fires, it is not standardized and not easy to compare such as [19–22] so no detailed discussion on the fire statistics among countries is provided here. It may be obvious that these problems are due to the large differences among countries, such as differing stages of economic development. The overall lack of statistical data in Asia results in severe difficulties to make overall assessments of the magnitude of the problem.

For example, average fatalities per population are relatively low in China, yet the absolute number of fire casualties was high [23]. Indonesia's peat fires do not kill people quickly but may affect people's health in the short and long-term. The full extent of health risks from haze remains unknown. Peat fires in Indonesia have an impact on the economy, and the haze crisis in 2006 was estimated to cost 50 million USD [24]. The 2017 shanty town fire in the Philippines was not an economically huge loss, yet left 15,000 people homeless. As large outdoor fires in Asia include urban fires, economic loss of urban fires may be larger than those of wildland fires especially for developed, densely-populated-urban countries, yet peatland fires have huge impact on forest destruction and health.

2.2 Current Research in Asia

Most of the research on wildland fires and WUI fires in Asia has been conducted in China, Japan, and Russia [25–28]. The Korean government designated WUI areas by defining 30 m from forest, and they attempt to make a hazard map for protection [27]. In China, a major focus has been on the fire dynamics of wildland fires, such as fire whirls. In Japan, extensive work has been performed in collaboration with the USA to explore common features for mitigation of structure ignition from firebrands which is common in WUI fires and Japanese urban fires [26]. Extensive fire whirl research has been ongoing in Japan for decades as well [25]. Russia has conducted much research as well, but few studies are published in English, as is also the case in Japan [28].

Ignition mechanisms, smoldering combustion, and emissions from peat fires have been studied in Asia [8, 29–32]. Little research has been performed on mitigation of peat fires so far. Researchers experimentally investigated how much water is needed to mitigate peat fires, which was found to be more than anticipated [33]. Soap-based firefighting foam developed originally for structure fires, then experimented for forest fires [34], is being experimentally investigated for peat fire suppression in Indonesia.

Because of developments in urban areas, it is common in Asia to focus on urban fire simulations [14–16]. Some models include spot fires, while others may include firefighting resources. Urban fire simulations may be used not only for research but also for urban planning or firefighting training, thus the focus is on great visualization as well as ease of use [16]. Much experimental research, small-scale or large-scale, has been done for validation. Some of research simulations were good matches with past disasters [14, 15].

While safe evacuation is important, evacuation modelling on urban fires has been separately developed or considered and not incorporated in most cases [35–36]. If there were estimates of fire propagation in real-time, it would be possible to better navigate people to safe places. Currently, people still evacuate without specific guidance. Some people head to predesignated places, which may endanger them more, or other people head to 'safer places' where there is actually no place for evacuees. When wind shifts and a fire heads in a different direction, evacuees are often forced to move around to safer places.

3.0 SOUTH AMERICAN VIEW

3.1 Historical Fires and Overall Problem in South America

South America is a continent of the Americas and is located mainly in the southern hemisphere. Sparsely populated (**see** Table 1), the majority of the population dwells in urban areas which are expected to attract more rural inhabitants searching for better opportunities. Although the native populations are diverse, the countries of South America share a common Spanish/Portuguese influence. Economically, the continent can still be considered as part of the developing world with a significant percentage of the population living under the poverty line and with economies which are mostly based on the export of commodities. National governments and public policies still have much progress to make to become more effective and efficient, including topics related to public safety and risk management.

Geographically, South America is split in two by the Andes, a mountain range that runs in a north - south direction from Colombia to Patagonia. Forests occupy about 22 % of the South American land area, while agricultural land covers approximately 19 % of the surface. The forest cover represents 27 % of the world's total forest cover with the tropical forests of the east of the Andes playing a major role in the Earth's CO_2 cycle and biodiversity. Forestry is an important economic activity, and significant parts of Argentina, Brazil, and central Chile have large plantations of several *Pinus* and *Eucalyptus* species.

Most wildfires in South America are caused by humans. In general, the South American ecosystems have not evolved facing natural wildfires which implies that the biota in the continent is particularly vulnerable to the effect of fires. This is particularly true for the tropical rainforests east of the Andes and the temperate rainforests in Patagonia. In the former, although thunderstorms are frequent, it appears that the normal precipitation rates naturally prevent fires [37]. In the latter case, the presence of the South Pacific High anticyclone prevents thunderstorms in most of Chile's lowlands and coastal areas, thus eliminating this natural ignition source from these ecosystems [38]. Exceptions are the savannas and shrublands on the eastern part of South America which normally face fires of natural origin and show higher adaptation and resilience [39].

Statistics on wildfires are not readily available, and there are concerns about their quality and uncertainty. The reasons for this can be attributed to the political context of some countries and, in some cases, to the remoteness of the areas where the fires occur. The Brazilian space agency, INPE, has done extensive work on the remote detection of wildfires and the estimation of the burned area using satellites [40]. The data for Argentina, Brazil, and Chile indicates that both in terms of burned area and number of fires, the wildfire problem in South America is significant and in the case of Brazil, is larger than that of the USA and Europe combined (Figure 1). The data points to a gap in the effectiveness of the response to wildfires in South American countries compared to that in the developed world which can be exemplified by comparing the situation in Argentina and Europe: while the number of fires in the South American country is an order of magnitude lower, the total burned area is similar.

Readily available specific statistics of WUI fires are non-existent for the countries analyzed. This constitutes a major disadvantage when trying to characterize the WUI fire problem and can lead to the implementation of policies which do not focus on the right aspects of this problem. Table 2 presents a compilation of recent incidents carried out by the authors. While most of the documented WUI losses have occurred in Chile, the Argentinean population living in the WUI is also exposed to fire hazards. The city of Valparaiso in central Chile is particularly affected by WUI fires [41]. This city is a clear example of the WUI situation in South America which features a high proportion of low- to mid-income neighborhoods with houses that are built of light materials which are easily ignitable and with the presence of illegal landfills that contribute to the general fuel load and fast fire propagation at the WUI. Additionally, the topography of the city, with neighborhoods built on steep hills cut by deep ravines with difficult access to fire brigades, challenging egress of residents, and poor water availability is also a significant contributor to the overall fire risk at the WUI. Given the population density in Valparaiso, fires are frequent and very often affect many houses. The Great Fire of Valparaiso in 2014 claimed the lives of 15 people and burned 2900 houses [41], being the most severe WUI fire in Chile and possibly South America in recent years. In several cases, the affected residents live in villages or small rural communities, which do not have appropriate fire brigades or emergency response plans to adequately face these incidents. An unfortunate example of this is the town of Santa Olga in Chile, a community of 2600 inhabitants which during the severe fires of early 2017 was almost completely destroyed when the Las Maquinas fire spread through the town, burning 1000 houses, the local fire station, and the local high school, among other public buildings.

Several factors help make this problem more severe. There is a lack of clear jurisdiction in the WUI areas which results in undefined responsibilities regarding fire safety management at the interface. The management of safety at the WUI requires knowledge of the fire risk at different locations which in turn requires knowledge on the fire behavior of the different wildland and urban fuels and predictive capabilities that allow to estimate the magnitude of different fire scenarios. Laws and regulations should evolve to incorporate risk in the decision-making process. Additionally, during the response phase of severe incidents, urban fire brigades typically play a major role. The tactics employed by these fire brigades, which have been developed for normal structural fires, are very often rendered ineffective in large outdoor fires.

A note must be made on the building codes in South America which in general only present basic fire safety requirements. In terms of building material performance, these requirements are strongly biased towards fire resistance and lack provisions regulating reaction to fire. The inclusion of reaction to fire requirements, including precise provisions regarding the flammability and flame spread performance of building materials, can contribute to the mitigation of fire risks, not only at the WUI, but in the general built environment in South America.

Aside from regulations that establish clear responsibilities regarding the management of the WUI fuels and the improvement of building codes, education is a key aspect to mitigate the risk of WUI fires. Efforts should be focused on creating awareness of the fire hazards on the WUI communities, on fire prevention, and on the local management of the WUI fuels. These actions should have a positive impact particularly on low-income communities which are the most affected by these incidents.

3.2 Research Activities in South America

Research activities regarding forest fires in general, and WUI fires in particular have been carried out for decades in South American countries although they appear to be decoupled from either national or regional strategies to address the problem. The highest activity is concentrated in Argentina, Brazil, and Chile, but other countries like Colombia [42], and Bolivia [43] have produced scientific output on the topic. Research related to fire science, however, is more limited, and only recently the WUI fire problem has received attention.

The flammability of local/native species has been studied using less detailed techniques for ranking species [42, 44] or using more comprehensive techniques including fire calorimetry and soot production measurements [45–47]. Fire spread testing has been carried out on forest fuel beds in different forest types and in field and laboratory conditions [48–50]. Work also includes ignition studies by idealized firebrands [51], a key fire spread mechanism at the WUI.

Modeling of wildfires includes work on Amazonian forests [49] using WFDS, work on fire propagation using small world networks, and wildfire forecasting using inverse methods [52]. FARSITE has been used to model grassland fires in Argentina and Brazil [53–54]. The modeling effort has not focused on WUI fires. Finally, researchers in Chile have developed KITRAL, a firefighting decision support system that includes limited wildfire modeling capabilities [55–56].

4.0 OCEANIA VIEW

4.1 Historical Fires and Overall Problem in Oceania

In Australia, fire is a defining part of the ecosystem, and plays a role in shaping its landscape and the biodiversity within it. However, uncontrolled and intense fires, often referred to as “catastrophic fires”, present threats and challenges to both human communities and the environment. The Australian Climate Council reported an estimated cost of $375 million per year related to bushfires [57]. This cost includes bushfire management, fire suppression, recovery efforts, and damaged and lost infrastructure and properties. The total economic cost of bushfires could reach $800 million annually by mid-century. In addition to the cost of human life and property, Stephenson *et al.* [58] reported an increased cost on agriculture, industry, and ecosystem service. The environmental cost of these fires is realized when fire intensities much higher than the level achieved prior to European settlement are experienced.

This is mainly due to the influence of fire exclusion which has allowed fuel levels to accumulate well beyond pre-European levels in certain areas.

Australia experiences different fire regimes across the country resulting in different impacts on human communities and the built environment [59–60]. In the northern part of Australia, fires frequency approach an annual occurrence rate across the savanna grasslands (Figure 2). The southern regions, characterized by dense forest and significantly higher accumulated fuel loads, experience less frequent but more intense fires that often have catastrophic consequences on life and properties (Table 3). The southern regions are also more populated than the North with people living in close proximity to forests, defined as the wildland urban interface (WUI), or rural-urban interface (RUI). In those areas, large fires occur on days which approach the most severe fire weather experienced anywhere in Australia. These weather occurrences are infrequent and result in fires that are impossible, or extremely difficult to control. Once they have fully developed, these fires result in widespread destruction and damage.

The impact of fire on life and property is considerable in Australia. Over the last 100 years, 840 people lost their lives in bushfires, and almost 14,000 houses were lost (Figure 3). Victoria is the state that has been the most affected by bushfires and has experienced more losses than all other states together. More than 60 % of life losses, and 80 % of house losses have occurred during 10 iconic bushfire events including Black Friday in 1939 and Ash Wednesday in 1983 [61] (Figure 4). The most recent and most devastating bushfire was Black Saturday in 2009 resulting in 174 fatalities and more than 2000 houses lost with an estimated net cost of $942 million [58]. All of these fires have ocurred during catastrophic weather conditions which contributed to both the severity of the fire behavior and the vulnerability of the building in the fires path [62].

New Zealand experiences a different fire regime than Australia due to extensive deforestation following human settlements. Here, fires were extensively used to clear forest and indigenous vegetation. According to Yeates *et al.,* [63], the forest area was reduced by 40 % with the Polynesian settlement and a further 20–30 % with European settlement. Wyse *et al.* [64] reported that New Zealand has a low fire frequency, and fires are rarely as destructive as those in Australia. On average 4000 ha are burnt each year (over the last decade) with a small impact on the built environment (Table 3). The Port hills fire in 2016 resulted in 11 houses being destroyed. It was the most significant and destructive fire occurring in New Zealand, which had not experienced a fire this size since early settlers.

4.2 Research Activities in Oceania

Research is performed by a number of organizations: Australasian Fire and Emergency Service Authorities Council (AFAC), providing advice on policies and standards for Australia and New Zealand; Universities; the Bushfire and Natural Hazards Cooperative Research Center (BNHCRC); Commonwealth Scientific and Industrial Research Organization (CSIRO); other government research organizations and departments at state and local level; and the private sector such as contractors, and insurance companies.

Many research projects have been carried out in Australia and New Zealand to improve understanding of the impact of large bushfires on the community and the built environment. These range from engineering projects that examine better house design and material performance to social research projects that look at community perception, preparedness, and awareness. For this paper, an exhaustive overview is not provided, but rather a cross section with examples of the research performed. These include research from post-bushfire surveys and historical fire datasets, experimental work, measurement of fire impact on communities, modelling and risk mapping, and response of community to bushfires (socio-economic research).

Post bushfire surveys have been useful to better understand the mechanisms of fire spread and the vulnerability of the urban area. These surveys collect data that enables analysis of the impact of fires on the communities and buildings affected including the sequence of events that lead to the ignition of structures. This information is critical for improving community safety into the future. The research studies focused on the building materials and design, the immediate landscape, the human activity, and how these factors influence the risk of loss. The surveys were performed after iconic bushfires and have taught many lessons with each fire providing its own unique perspective and learning [65–69]. The researchers have highlighted the role of fire weather condition, as well as the main fire growth mechanisms involved in the ignition and destruction of buildings in bushfires (firebrands, radiant heat flux, flame contact, and wind). House design and material, the amount of vegetation around a house, and any combustible elements at the interface are identified as key factors in defining the vulnerability of house to these attack mechanisms. The role of resident and fire brigade defensive actions was identified as being one of the most significant factors in reducing house losses.

In addition to studies of specific fires, historical fire datasets on fatalities and house loss have been developed to better understand bushfire impact on life and structure loss. The information captured by historical datasets provide an evidence-based approach and has been used to improve the fire danger rating system and community education [61–62, 70].

Experimental work is used to study the flammability of material or vegetation at the WUI [64] and to better understand performance of building materials and systems when exposed to bushfires. Studies on material and systems performances are done at small-scale using the cone calorimeter to study individual materials; at medium scale studies use a radiant panel to study, for example, the performance of glazing systems [71], and decks [72]. At the large-scale, experiments were used to assess the performance of large elements and whole systems including house, water tank, and fencing system [73–74]. Results are used to develop revised building codes.

Fire behavior modeling have been developed in Australia since the 1950’s. Several models and mapping tools (not detailed in this paper) are now used to assist managers and the emergency services [75]. The study of fire spread into rural-urban interface areas is less developed because of its complexity and the number of variables involved [59]. Combustible fuel at the interface (e.g. outbuilding, vegetation, stored material) contribute to the propagation of the fire through the urban interface. Field measurements, post-bushfire surveys, public records, and spatial datasets form an important basis for fire behavior modelling and house vulnerability assessment in the urban interface. However, the accuracy and detail of this information can vary greatly, especially when it is manually collected. Remote sensing methods can provide useful data over broad regions to supplement manually collected data.

Spatial analysis, modelling, and mapping have been used in Australia and New Zealand to better understand the risk at the WUI. Examples of studies include risk assessment and mapping at landscape level [76], at the structure level [77], loss modelling [78–79], and implication of fuel treatment on house loss [80].

Fire at the WUI impacts people's health. The combustion of a range of combustible materials present in urban areas (e.g. synthetic products, wood and manufactured products, polymeric materials or plastics, paper, electrical appliances, paints) release potentially toxic chemicals into the air resulting in increased health risks for residents and firefighters in the vicinity of the fire [81].

The influences of human intention and preparedness on community safety have been extensively studied using information from post bushfire surveys [82–83]. Specifically, studies have been conducted on community response to bushfires in the context of "Prepare Stay and Defend or Leave Early" policies [84–85]. Recent studies have looked at community response during bushfire including the challenges and experiences of residents sheltering during bushfire [86]. The information supports policy reform and community education initiatives.

5.0 EUROPEAN VIEW

5.1 Historical Fires and Overall Problem in Europe

Europe is exposed to various types of disaster risks that, to a certain extent, could eventually lead to large outdoor fires affecting the built environment. Disaster risks are usually classified into two main types: natural and man-made. Natural disaster risks include extreme geophysical events (earthquakes, tsunamis, volcanic eruptions), meteorological events (storms, flooding, extreme weather), climatological events (forest fires, drought), and biological events (pandemics). Man-made disaster risks can be non-malicious, of technological origin such as industrial accidents, or malicious such as terrorism [87]. Although many of these risks might directly affect the built environment, few of them can in fact cause a large outdoor fire as a secondary effect.

As anecdotal examples, it can be recalled that, in the past, Europe suffered big fires in cities (e.g. London 1666 [88]), some of them induced by earthquakes (e.g. Lisbon 1755[89]). However, the rather low incidence of this type of geophysical risk together with the current building materials and designs used in Europe, make building environments less prone to this type of scenarios at present. In contrast, forest fires associated with climate change certainly represent a serious threat to some urban and suburban areas throughout the continent.

In Europe, climatological and meteorological events account for 92 % of the total reported disasters and 83 % of the total losses [90]. These events have been continuously increasing worldwide since 1980 [91], and future projections suggest that climate change will upsurge the likelihood of extreme climate events (especially those related to heat waves, droughts, wildfires, and heavy precipitation) [92]. According to the European Environment Agency (EEA) [93] climate change will affect European forest fire regimes mostly in the Mediterranean and continental regions, increasing the length and severity of the fire season, the area at risk, and the probability of occurrence of large fires. These effects, together with the fact that urban sprawl has led to a growing intermixing of wildland and urban areas, have increased the risk of forest fires spreading over residential areas, notably in Southern Europe even threatening large cities (Figure 5).

Meaningful data on the impact of WUI fires in Europe during the last decades is scarce. European Forest Fire Information System (EFFIS) provides, among other services, data on forest fires occurrences and area burned by country as well as a collection of related news from the press on fire incidences. Although this information has undoubtable value, it does not allow performing relevant analysis of forest fires impact on the WUI. There are two fundamental causes of this situation, the former is the lack of a harmonized definition of WUI in Europe [94], and the latter is the way in which information is currently gathered in each EU country which does not include particular information on the wildfires effects at the WUI (e.g. number of damaged/destroyed homes, evacuated/injured/dead people, economic losses, etc.). A recent study analyzing the relationship between large fires and the presence of WUI in Europe [94] has shown that a strong correlation exists mostly in the Mediterranean regions.

Forest fire statistics over the last 25 years in Mediterranean Europe seem to show a slight gradual decrease of the average values of both the number of fires and area burned (Table 4). However, it has to be highlighted that a strong inter-annual variability exists depending on the seasonal meteorological conditions. Moreover, the percentage of large fires (i.e. fires with more than 500 ha of area burned) and the percentage of area burned by large fires seem to increase over the last 15 years in Portugal, Spain, and Greece (see the values for Spain in Figure 6). It is these large fires that mostly affect the WUI.

Recent WUI fires which occurred in Mediterranean Europe have revealed important management and research needs that will have to be considered in the near future to increase WUI communities’ safety and resilience. In this section, details of three recent examples of WUI fire accidents are provided, paying particular attention to the prevailing meteorological conditions, and to the main consequences to people, assets, and infrastructure.

The first example is the forest fire that occurred in Madeira Island (8–10 August 2016) with flames reaching and spreading through the old quarter of the capital Funchal. Because of this blaze, 300 houses were damaged (177 destroyed), 3 people were killed inside their homes, and around 1000 people were evacuated with a total of more than 150 million euros of estimated damage [95]. The analysis of the weather variables indicates that the island was suffering the effects of a heat wave with strong winds that favoured the development of several simultaneous fires. Funchal is a hilly city with houses built on slopes and surrounded by vegetation which contributed to the spread of the fire. In addition, the presence of many combustible materials stored around the houses contributed to the fire spread throughout the city. It is also worth mentioning the poor accessibility to certain ignited buildings that prevented efficient firefighting and the ill preparedness of the population to cope with these kinds of events

A second example can be found in Catalonia (north eastern part of the Iberian Peninsula) near the French border (July 22–24, 2012) which illustrates the complexity of managing multiemergency situations generated by WUI fires. The fire burned 13000 ha and caused four deaths, 20 people injured, around 2000 evacuated, and 140000 people unable to evacuate. Moreover, the fire provoked serious problems in transport infrastructure (the main roads and the train line to France were closed). The weather was characterized by strong northerly winds that accommodated a fast spread rate and the appearance of multiple spot fires caused by a high production rate of firebrands. The area affected is highly touristic, and the closure of roads entrapped many vulnerable people who panicked when flames approached. Firefighters were overwhelmed during the first hours of the emergency because 17 villages were affected and had to be evacuated, 600 vulnerable elements (hospitals, critical infrastructure, etc.) had to be protected, 70 alarms for fires in houses had to be attended, and all this happened in a situation of a total road collapse.

The last example concerns the Vitrolles forest fire (August 10, 2016) which also occurred in a highly touristic zone of the Provence-Cote d’Azur province and close to one of the most crowded cities in France, Marseille. It burned 3300 ha, caused five injured and 5000 evacuated people, and destroyed 25 houses. The area was experiencing the highest rainfall deficit since 1969 and a high winds episode. Multiple fires were burning simultaneously. The dense smoke cloud generated by the fire significantly affected critical infrastructures. The airport activity was seriously disrupted, and a petrochemical complex needed to be protected because of the proximity of the flames.

5.2 Research Activities in Europe

A great deal of research has been put in place during the last years in Europe to understand the factors and processes involved in fire spread through the WUI, firefighting personnel and population safety, home survivability and infrastructures and services affection. Most of it has been done through the European Commission Funding Programs, but there are also some notable national research initiatives as well [96–101].

Research projects dealing with different aspects related to WUI fires are being mainly coordinated by Southern European research and innovation entities of different nature such as technical universities, small and medium enterprises, or national institutes devoted to environmental sciences which reflects the mainstreaming and multi-disciplinary European approach to the WUI fire problem. Among others, it has to be highlighted the leading role of ADAI (Universidade de Coimbra, Portugal) with a worldwide recognized expertise of 30 years dedicated to the applied research in the field of forest fires and WUI fires and hosts the largest and more experienced laboratory for forest fire experimentation in Europe. In addition, it is worth mentioning the contributions by the French institute IRSTEA (Institut National de Rechearche en Sciences et Technologies pour l’environement et l’agriculture) which develops frontline research on ornamental vegetation flammability and combustibility and by CERTEC (Universitat Politècnica de Catalunya- Barcelona Tech) whose approach based on fire protection engineering methodologies (i.e. Performance Based Design) aims at analyzing home survivability and sheltering capacity by CFD (Computational Fluid Dynamics) modelling. It should be also noted that the involvement of northern universities is increasing which illustrates that the WUI fire problem is already becoming a concern throughout the continent. Evacuation modelling at the WUI is, as an example, a hot topic being developed by research groups traditionally devoted to fire safety engineering, (e.g. Lund University and University of Greenwich), who can provide complementary expertise needed to handle the enormous complexity of a WUI emergency.

These projects are also supplemented by other research activities which indirectly help preventing/protecting the WUI from fire hazard. On the one hand, Europe has been active on wildfire behavior modelling, both from a physical (e.g. [102]), and semi-empirical (e.g. [103]) perspective over past decades. On the other hand, socio-economic factors related to forest fires are also being intensively addressed [104]. All these research efforts are usually linked to a strong commitment towards technology transfer. In this regard, it has to be highlighted the existence of certain European platforms (e.g. Pau Costa Foundation) that convey dissemination of results towards fire practitioners, managers and communities.

6.0 AFRICAN VIEW

6.1 Historical Fires and Overall Problem in Africa

Africa is the second largest continent in the world, with a total land area of 30 million km^2 and a population of 1.2 billion. Similar to Asia, Africa covers vast areas with many diverse countries and landscapes. The overall state of economic development differs significantly from country to country. Large outdoor fires in Africa include not only wildland fires, which are also called veld fires, but also recent WUI fires, as well as informal settlement fires, where the forest itself plays no role. The challenge here is the general lack of reliable statistics to characterize the overall nature of large outdoor fire problem in Africa.

Africa is comprised of vast deserts in the north and tropical rainforests in the center. Significant wildland fires occur across the vast savannas in Africa, and most significant cause of these fires are humans. These savannas are typically large areas of grasslands that are intermixed with shrubs or trees. Greenhouse gas emissions from these wildland fires burning in the savannahs have been known for some time [105]. Notable wildland fires have been reported in Bostwana, Zimbabwe, Sierra Leone, and South Africa [106]. Recently in South Africa, WUI fires have been reported, resulting in the destruction of property and the loss of lives. The Knysna fires in June 2017 resulted in the evacuation of some 10,000 residents with some 400 structures lost in these fires. There is, however, no uniform WUI definition across Africa.

Areas in Africa, specifically the country of South Africa, are prone to many fires in informal settlements. These are also referred to as shantytown fires. It is estimated that nearly a third of Cape Town’s population lives in informal settlements, and each year significant fires occur that result in significant numbers of deaths [107]. Similar to the situation in Asia, these fires generally do not receive much attention since such areas are not governed by building codes and standards.

6.2 Research Activities in Africa

Considerably less research has been conducted in Africa in the context of fire safety science pertaining to large outdoor fires. A review of the IAFSS proceedings over the past 12 symposia reveal only a handful of papers from researchers in Africa. A recent review of wildland fires in Zimbabwe looked at various factors to suggest better fire management practices from wildland fires [106]. The interested reader is referred to this study as work in South Africa is referenced as well.

Most recent studies have focused on attempting to better deal with the large informal settlement fire problem in South Africa. While this research is in its infancy, it has shown the complex fire problem of attempting to help improve the fire safety situation in these informal settlements [107].

7.0 NORTH AMERICAN VIEW

7.1 Historical Fires and Overall Problem in North America

Over the past ten years in the United States, about 80,000 fires were reported per year which burned on average of 1.6 to 4 million hectares [108]. As shown in Figure 7, while the number of fires reported per year appears to have remained relatively constant over the past few decades, the area burned appears to be increasing [108–109]. Though data before about 1985 is suspect, the fire exclusion policy and advances in firefighting technology kept the area burned between the 1950s and 1980s at historically very low levels (about 1.5 million ha/year [108]). To put these numbers in context, several studies have shown that up to 86 million hectares used to burn annually before European settlement [110–113]. About 95 % of the area is burned by 3 % of the fires indicating that big fires are still a relatively rare event. Similar to the number of fires per year, this ratio has surprisingly stayed relatively constant for the last 100 years [114]. Many of these fires are ignited by humans in more developed areas; however, lightning tends to dominate in other regions, such as the Rocky Mountains, which are generally more rural and prone to dry lighting [115]. Suppression of these fires by federal, state, and local resources is an overwhelming expense. The federal suppression cost can be upwards of 2 billion dollars (US) per year [116]; however, that does not include local costs, recovery, insurance losses, etc. One issue commonly cited related to budgeting is “fire borrowing” in which major fires are funded from within the same funds that are responsible for wildfire prevention. One of the most disturbing trends is that suppression costs have increased by an order of magnitude between 1985 and 2016 [116]. Sadly, the wildlands are not all that burns in these fires. There are also about 3,000 home losses per year in the wildland-urban interface. Examples of major fires include the 2016 fires around Gatlinburg, Tennessee, which burned more than 2500 structures, and caused up to $2 billion US in damage [117], and the 2003 Cedar Fire in San Diego, California which caused over $1 billion US in insured losses and destroyed 2,200 homes [118]. Each disaster also caused 14 fatalities.

Canada holds 9 *%* of the world's forests with over 8,000 forest fires reported per year and burning on average 2.8 million hectares annually since 1970 [119–120]. About half of this area is burned in remote "modified suppression areas" where fires are allowed to burn naturally [119–120]. Lightning accounts for about half of all fire starts and almost 80 *%* of the area burned in Canada [119–120]. The boreal and taiga ecosystems account for a large portion of the area burned as they are prone to lightning ignition, are far from the main population centers, and require fire for regeneration, thus falling into the "modified suppression areas" [121]. Suppression costs are around 500 million - 1 billion Canadian dollars per year over the last 10 years [122]. Similar to the United States, 97 % of the area is burned by 3% of the fires [121]. Examples of major WUI fires in Canada include the Ft. McMurray fire which burned nearly 600,000 ha and over 2,400 structures [123]. The direct and indirect costs of the fire were estimated to be 9.5 billion Canadian dollars [124].

Mexico reported about 8,000 fires per year from 1988 to 2004, burning on average about 266,329 ha/year over the same period [125]. The average fire size from 1988 to 2005 was 33 hectares. Eight four percent are human caused, and about 43 % are due to agricultural activities [125]. Interestingly, Mexico does not report major losses of homes and other infrastructure due to WUI fires because communities are usually surrounded by farming zones, or the fuel loads have been reduced enough to avoid intense fires that threaten structures [125].

Contrasting the fire problem among the United States, Canada, and Mexico shows great disparities in the problem. In general, longer, hotter, drier fire seasons have been reported in recent years throughout North America. This has been shown to be due, in part, to climate change, which is projected to get worse for some ecosystems [126]. The growth of the WUI, with people moving their homes close to forests and other flammable vegetation also contributes to this problem not only increasing ignitions but also suppression costs [108,115]. Finally, the US in particular has a long history of fire exclusion, essentially removing fire from the landscape. While this has been incredibly effective in suppressing small fires in mild to moderate conditions, 2 % to 5 % of fires still escape initial attack and burn [127]. This has been described as the "fire paradox" - by suppressing fires, the wide natural and historic variability in fire frequency and severity [128] has been replaced by only high severity fires burning in the worst possible conditions [129–130]. In other words, by suppressing fires we unknowingly self-selected for only the largest, most severe fires.

Because most of the WUI fire disasters, in the US, start in undeveloped areas that are often ecologically fire adapted, addressing the impact of large outdoor fires on the built environment must include addressing wildland fire. How to solve the "fire problem," particularly in the United States, has no clear answer. The landscape has changed over the last 100 years. Because of fire exclusion, forests are denser, fuel loads higher and more continuous (horizontally and vertically), species distributions have shifted to favor more shade tolerance, and the stands are more homogeneous in age leaving them more vulnerable to widespread disturbance (fire, insects, and disease) [22].

7.2 Research Activities in North America

In both the United States and Canada, research into wildland and WUI fires is very broad and diverse, involving many entities including governments, universities, private companies and consultants. The US and Canadian government agencies often act as both researchers and as funding sources. In the US, these agencies include the National Institute of Standards and Technology (NIST), US Forest Service (USFS), Department of Interior, Department of Homeland Security, US Geological Survey (USGS), National Park Service (NPS), Bureau of Indian Affairs (BIA), Bureau of Land Management (BLM), Desert Research Institute (DRI), Environmental Protection Agency (EPA), and National Aeronautics and Space Administration (NASA). In Canada, these agencies include National Resources, Canada and the Canadian Forest Service. Research in Mexico seems to largely take place at universities and by outside government agencies and Non-Government Organizations (NGOs). To put some perspective on the how active wildland and WUI fire research is, the Joint Fire Science Program (jointly funded by the Department of the Interior and the USFS) lists approximately 150 actively funded research projects in 2017. Needless to say, a comprehensive listing of ongoing research in North America is not attempted here. In general, however, common research areas include experimental fundamental fire behavior, fire behavior model development and validation, fuels management effectiveness, fire fighter safety, risk, economics, emissions, remote sensing (pre- and post-burn fuels measurements, active fire behavior), human behavior and social science, and ecology (post-fire effects, mortality, seasonality, climate change, and resilience). It is very important to point out that few studies in the US have focused on WUI fires from a fire safety science view point.

Based on years of wildfire research, fire managers have dozens of models, tools, maps, and data sources available to them in the United States (ex: [131]). These include tools for fire behavior predictions such as BehavePlus (1D) [132], FlamMap (2D hazard mapping) [133], FARSITE (2D fire front predictions) [134], FSPro (2D ensemble fire probabilities) [135], and NEXUS (crown fire) [136]. Decision-support tools for federal managers are also available such as WFDSS [137] and WFAS [138] which incorporate risk management techniques [130]. Some of these tools incorporate surface-level wind distribution from Wind Ninja [139]. There’s a wide variety of data available such as fuel maps from Landfire [140], area burned and severity maps from Landsat [141], and fuel moistures from the National Fuel Moisture Database [142]. This data is often out of date due to the long time to assemble information but is still incredibly useful for land management and fire behavior predictions. Remote fire detections are also available from MODIS, VIRRS, AVHRR, GOES, and airborne mapping [143]. There is even a tool to help predict fire effects and tree mortality from both prescribed and wildland fires (FOFEM [144]). These existing tools are primarily used for planning (~98 %) including risk analysis, spatial fuel planning, and fire management plans [145]. Other uses include operations, training, historical reconstruction, and research. Again, as compared to wildland fires, WUI fire tools are far less advanced [146].

Many more complex research tools are in development often incorporating computational fluid dynamic simulations (CFD). These include WFDS/FDS [147], WRF-Fire [148], and FireTEC [149] in the United States. WRF-Fire couples an atmospheric boundary-layer model (ABL) to an empirical fire spread model, FireTEC couples an ABL model to a CFD-based surface model, and FDS is a large eddy simulation (LES)-based fire simulation tool. Several tools are also available for modeling smoke impact such as BlueSky [150], VSmoke and VSmoke-GIS [151], and HYSPLIT and NOAA's Smoke Forecasting System [152].

In Canada, similar tools are available. The Canadian Wildland Fire Information System (CWFIS) uses the Fire Behavior Prediction (FBP) and Fire Weather Index (FWI) systems to create daily fire weather and fire behavior maps [153]. CWFIS also uses satellite images to map hot spots during the fire season. CWFIS is also responsible for generating a National Wildland Fire Situation Report. Similar to the US, the Canadians have the Canadian Forest Fire Danger Rating System (CFFDRS) for rating the risk of fires. For predicting fire effects, there is the Canadian Fire Effects Model (CanFIRE) [154].

In Mexico, there is a national Wildland Fire Information System built on the Canadian CWFIS that is maintained by the National Forest Commission (CONAFOR) and the Secretariat of Environment and Natural Resources (SEMARNAT) [155]. There are several programs for fire detection, including those run by the National Commission of Knowledge and Use of Biodiversity (CONABIO), CONAFOR's Forest Management Office - National Forest Fire Control Center (CENCIF), and the National Commission of Water (CNA) - National Weather Service along with cooperation with the US National Oceanic and Atmospheric Administration (NOAA) which provides MODIS and other satellite imagery.

Though there are many tools available to fire managers to help with such planning, restoration, and mitigation tasks, they may not be adequate. Most of these tools from the United States are based on the Rothermel model which is a semi-empirical model for fire spread through continuous, dead fuels [156]. The head-fire rate of spread, which is calculated as a constant, onedimensional quantity, is then applied to the task at hand such as fire risk mapping, fire spread predictions, or fire effects. In Canada, a fully-empirical model is used instead [157]. Both systems have major deficiencies such as being unable to predict fire behavior in situations outside of those used to develop the models. This includes extreme fire behavior such as fire whirls, flow attachment on slopes, fire and atmosphere interactions, and, because both systems assume that the fire is spreading at a constant rate, whether or not the fire will even spread. Better prediction of fire behavior cannot be achieved, either for management or in a research context, without a theory of *how* it spreads [158].

8.0 COMMON CHARACTERISTICS OF LARGE OUTDOOR FIRES ACROSS REGIONS

Over the course of the previous sections, large outdoor fires and the built environment have been delineated across the globe. WUI fires appear to be an emerging topic in all regions, and while each region is engaged in research, it is rather obvious it is not as well advanced as traditional building fire research. For more than 50 years, the fire safety science community has developed a detailed body of knowledge on fire dynamics within urban building structures. Due to great strides in traditional building fire research, for lack of a better term, *fire in the box,* the fire safety science community now has zone models and most recently, computational fluid dynamics (CFD) models [159]. In the case of FDS, many hours have been put in to validate the model against experimental results. While challenging, this is much simpler than trying to validate models that must be able to resolve physical processes over the disparate range of scales needed for WUI fires, from kilometers to resolve fire spread processes down to centimeters to capture individual firebrand ignitions [159].

Thus, WUI fires present unique challenges and opportunities for the fire science community. Unlike traditional fires which spread within a structure, WUI fires combine outdoor fire spread through vegetative fuels, ignition and involvement of structures, and finally structure-to-structure fire spread. This complexity is both challenging, because it incorporates a wide range of scales and processes, and a great opportunity, as no tools yet exist that are explicitly tailored to model fires within the WUI. As discussed in the research needs section below, the salient physics have yet to be elucidated for many of these important phenomena, therefore it is not surprising there exist no validated models to predict fire spread and structure ignition in WUI fires

In some regions, urban fires are prevalent and, in many cases, are not the result of interactions with burning forests. It is obvious that common characteristics between fire spread in WUI fires and urban fires have not been fully exploited. These commonalities were the subject of a special section in this very same journal; the interested reader is referred to Manzello and Himoto [160]. Another interesting similarity between the regions reviewed above are the dangers of fires in informal settlements.

9.0 PERMANENT IAFSS WORKING GROUP

A significant discussion outcome of the workshop was the desire of the participants to make this topic a permanent working group under the umbrella of the International Association for Fire Safety Science (IAFSS). So far, this has been done for only one other topic, the Measurement and Computation of Fire Phenomena (MaCFP) working group, supporting modeling, a far more well-characterized and studied topic in fire safety science [161].

Due to the structure and organization of the workshop, it was apparent that large outdoor fires and the built environment encompass far more than only wildfires, and the working group will address problems with key phenomenological shared characteristics relevant to wildland fires, urban fires, *and* wildland-urban interface (WUI) fires. Overall, the workshop was considered a fruitful endeavor and clearly highlighted that much needs to be done in this research area, as it is far behind the *well-studied* topics that have been around in fire safety science for decades. Many *next generation researchers* attended and were encouraged to work in this area, as a high research impact is possible.

Sara McAllister, Sayaka Suzuki, and Samuel L. Manzello joined together as co-leaders of the working group. The objectives and goals of the permanent working group are delineated. It is proposed that the group consist of three subgroups, *prioritized* into the following topics: Ignition Resistant Communities (IRC), Emergency Management and Evacuation (EME), and Large Outdoor Firefighting (LOFF). The IRC subgroup will be focused on developing the scientific basis for new standard testing methodologies indicative of large outdoor fire exposures, including the development of necessary testing methodologies to characterize wildland fuel treatment effectiveness adjacent to communities. The EME subgroup will be focused on developing the scientific basis for effective emergency management strategies for communities exposed to large outdoor fires. The LOFF subgroup will provide a review of various tactics that are used, as well as the various personal protective equipment (PPE), and suggest pathways for research community engagement, including environmental issues in suppressing these fires. The overall objectives are to bring the full depth of knowledge of the IAFSS community to work on these priority topics (see table).

Proposed Subleader	Topic
Elsa Pastor (Spain)	Ignition Resistant Communities
Enrico Ronchi (Sweden)	Emergency Management and Evacuation
Raphaele Blanchi (Australia)	Large Outdoor Firefighting

As a starting point for the permanent working group, the combined research needs across all regions were collected from the workshop. Clearly, all the research needs cannot be tackled by the permanent working group but all are listed below.

10.0 IMPORTANT RESEARCH NEEDS FOR ALL REGIONS

10.1 Understanding Fire Spread in WUI and Urban Fires and the Mechanisms of Structure Ignition both from Vegetation and Other Structures

The fire spread in WUI and urban fires is a rich and complex scientific problem which involves different types of solid fuels, a large range of spatial and temporal time scales, and a strong dependence on environmental and topographical conditions. To define a global research strategy, it is thus desirable to break the phenomenon into smaller problems to design the relevant experimental and theoretical work which can then be used to produce adequate numerical models and applied correlations for the practicing engineers. As pointed out during the workshop, a one strategy to consider is the approach taken by the fire safety science community during the 1960s and 1970s by defining “canonical problems” to address the building fire problem [162].

Large urban fires are typically caused by the attack of a wildfire front which firstly causes the ignition of structures in the WUI. Ignition can be caused directly by the flame front by radiation or flame impingement or by the transport of firebrands to structures which are not directly exposed to the flame front [163]. However, large urban fires can also be caused by the rapid structure to structure propagation of a fire originally enclosed in a single structure, e.g. after large earthquakes, during armed conflicts, or in areas with a large clustering of structures.

10.1.1 Ignition Phenomena—Although the radiant ignition of structural fuels has been studied extensively, the test methods developed for building fires should be revised to test their relevance as applied to the action of a wildfire front, including direct flame impingement and coupled radiant and convective heat fluxes. To adequately quantify the continuous ignition risks posed by large urban fires, extensive testing of building materials needs to be performed, with the added difficulty of specific variations in fuel properties imposed by the national building regulations. The theories for continuous ignition of solid materials should be revised to take into account the effect of coupled radiative and convective heating, surface orientation and strong velocity gradients in the boundary layer in order to produce applicable engineering correlations. The discontinuous ignition of structural fuels by firebrands has received recent attention, particularly in the development of new experimental methods to study ignition under firebrand showers [4]. Additional research is required to investigate the ignition vulnerabilities of coupled building components to firebrand showers, as most of the recent research has considered individual elements separately. While the experimental apparatus has been cloned by many research organizations worldwide [4], a globally accepted standardized test methodology for material classification to firebrand showers is required.

The onset of ignition is dependent on many parameters associated to the fuel (material, morphology, geometrical configuration, moisture content) and the hot particles, including its energy release and interactions with other particles [163]. The available theoretical and numerical models, however, are still unable to provide accurate and quantitative predictions of the phenomenon. Given the degree of parameters involved, statistical approaches have been suggested [163].

Much work has been devoted to studying the ignition of wildland fuels, and to a lesser extent, ornamental vegetation. During the past decade, testing of wildland fuels using fire calorimeters with adapted sample holders has allowed the ability to conduct experiments which are more representative of certain wildfire ignition and propagation scenarios. However, fire calorimeters cannot reproduce all the ignition configurations found in wildfires. More experimental and theoretical research is required to develop representative test methodologies for all ignition scenarios to obtain fuel properties which are relevant to the ignition phenomenon, with a special focus on live fuels.

10.1.2 Sustained Burning—The fire hazards posed by both forest and structural fuels are mainly related to the sustained burning of these objects and the ability of the flames to transfer heat to target fuels. The burning rates, flame heights, and flame emissive powers need to be quantified for live vegetative fuels and structural fuels, including structures fully involved in flames. The buoyant plumes generated by these fires and their interaction with wind, topography and other environmental parameters, needs an adequate characterization. Additionally, the effect of fuel treatments to change the morphology or fuel load of vegetation in the WUI on the fire behavior should be studied. To accomplish these requirements, the approach of developing and solving canonical problems seems particularly appropriate but is nevertheless a daunting challenge, considering the variability in morphology and material characteristics found in biomass species and structures all over the globe. Finally, additional research on the production of firebrands from burning vegetation and structures is needed to produce quantitative predictions of exposure conditions. Better characterization of exposure from firebrands is needed, such as quantitative predictions of particle production rates, size distributions, morphology, and energy release-rates. Although theoretical models of lofted firebrand transport have been formulated decades ago, the development of numerical models needs to take into consideration the burning of the particles, with time dependent variations in size and mass [4,163].

10.1.3 Urban Fire Propagation—Fire propagation in urban and WUI environments is a multi-scale and multi-dimensional problem, making it a more complex phenomenon than building fire or wildfire propagation [160]. Although the initiating causes of large urban fires are varied, there are similarities in the subsequent fire propagation. The fires in burning structures involve external cladding and structural elements, in contrast with fire inside buildings where at the time of fire brigade intervention the post-flashover fire is typically contained within the structure. Large outdoor fire spread does not always occur over a continuous fuel surface, and the heat transfer mechanisms that control the spread rate can vary. Radiation from the flames is a dominant mode of heat transfer, particularly in urban areas where the adjacent structures are close together, but research in wildland fire propagation has also pointed out, that at least in the small-scale, thermally thin fuels convection can play a major role [158]. It remains to be experimentally determined whether convection plays a major role in structure to structure propagation. This not only requires an ambitious experimental and theoretical research program, but also the results on flame and fire plume interactions with environmental parameters and topography as mentioned previously. Fire spread over discrete fuel surfaces can also be controlled by radiation, but for longer length scales firebrand transport is the dominant mode of energy transfer. Apart from all the inherent difficulties in predicting spot ignition by firebrands discussed in the previous paragraph, the modeling of far field outdoor fire propagation faces challenges of its own, which include solving the problem through a combination of deterministic (e.g. plume transport phenomena) and stochastic (e.g. ignition of solid fuels due to firebrands) approaches over a broad range of time- and length-scales. This large variability in scales will need to be addressed in development of detailed fire propagation models for research purposes, particularly if fluid dynamics, heat transfer and chemical processes are to be resolved numerically. Furthermore, the building of the large databases required for such modeling efforts adapted to specific regional or national realities will demand a significant amount of work. The databases should include property data on both vegetation and structural fuels, but also PDFs of specific flammability parameters, particularly for spot fire predictions.

It is important to highlight that there are various mitigation techniques proposed, such as foams, gels, and coatings intended to reduce structure ignition. Significant research is needed to quantify the performance of these techniques to standardized representative urban fire exposures.

10.1.4 Field Data Collection—The data requirements which have been discussed in the previous sections will demand applied research work into pre- and post-fire data surveys of vegetation and structural fuels, particularly to standardize the studies and so that the data is relevant for use in modeling. Extensive flammability testing of surveyed fuels should be carried out, following the test methodologies to be developed (cf. Sections 10.1.1 and 10.1.2), to develop the flammability databases. Research should also be devoted to carrying out detailed measurements of relevant variables during fire events, which would yield important information for model validation, firefighting tactics and forensic purposes. Remote sensing carried out from unmanned aerial vehicles, aircraft, and satellites is a convenient choice to perform most of the required measurements. Detailed forensic studies are key to understanding the factors that favor or preclude catastrophic outdoor fire incidents. There should be an active engagement of the fire science community in these studies, to collect information on topics like structure to structure fire spread rates, firebrand collection, and effectiveness of defensive actions and firefighting tactics. While recent reports have made progress, these studies lack comprehensive forensic analysis [164–165].

An ultimate goal of fire safety engineering is to develop tools to prevent the occurrence of catastrophic events. The development of large outdoor fire propagation models as mentioned in Section 10.1.3 would help in consequence and risk analyses at the WUI level, thus helping decision makers and urban planners. Real-time fire propagation models should be less detailed versions of the comprehensive models, and could be used during the emergency response phase. Much research is required to make the transition from the mostly empirical wildfire models which are in use today to models based on first principles which are applicable to both wildland and urban environments.

10.2 Impact of Fire and Smoke on Climate and Health

While studies on large outdoor fires have focused more on the spread of the fire and its potential for destruction, there are also serious environmental and health impacts from smoke and other effluents from these fires to both surrounding populations and the entire earth system. Smoke from large wildland fires has been known to cause health impacts to both wildland firefighters and the public [166]; however, these studies have mostly focused on wildland fires, not fires that burn into or within communities, e.g. WUI fires. The diverse makeup of chemicals released from wildland fires would certainly change in these situations, with elements of structures and other urban materials igniting and adding to the spectrum of effluents. For WUI fires, these may affect a smaller area than the atmospheric-scale plumes from large wildland fires, however their effects on first responders may be significant as wildland firefighters, unlike structural firefighters, typically do not wear any breathing apparatus [167]. Studies have already shown that there are significant health impacts to the public from large wildland fires [168–169] and have investigated exposure to wildland firefighters [167], however it is important to further understand these effects, determine ways to mitigate exposure, and particularly extend this knowledge to WUI fire situations.

The effect of fire emissions on climate is an issue that has been of growing interest and importance in the era of climate change [170]. Currently, the most common method to estimate global fire emissions is via radiometric fire detections from satellites, coupled with emissions factors for different fuels, represented as g of pollutants over kg of fuel burned. Determining the amount of fuel available to burn and considering the different possible burning conditions in different fires, however, is difficult and represents incredible inaccuracies into these calculations. Smoldering fires, such as those in Indonesia in 2015 that burned primarily through peat produce an incredible amount of emissions compared to their flaming counterparts. Large-scale “haze” events have been documented for months after these fires, exposing both populations and the earth system to an incredible amount of emissions that are not yet well understood [171]. Increased understanding of fire emissions under different burning conditions (e.g. different fuels, moisture content, live/dead state, smoldering/flaming, wind, etc.) is essential to improve these estimates in the future.

These emission factors are also used when initializing plume models of smoke and other effluent transport [172]. Improvement of these models, therefore, can have an impact not only on climate modeling but also on local and regional health impact modeling for both prevention and post-fire understanding. In general, the costs of fires in terms of both financial and environmental impacts is not yet fully considered when calculating these costs. Post-fire emissions can also manifest itself in means other than atmospheric emissions. Agents used to suppress fires can sometimes pollute the local environment and even waterways after being washed down from eventual floods after the surface layer of fuels is burned away. The impact of burning whole communities during WUI fires has also not been considered much in terms of the environmental impacts. All of these issues, together, should be considered when determining whether or not to perform mitigation methods such as prescribed burning, fuel treatments or upgrading structures that would reduce the likelihood of future fires in these areas.

10.3 Emergency Management Strategies for Communities Exposed to WUI and Urban fires

The size and magnitude of these incidents requires emergency management strategies more akin to natural disaster such as hurricanes and tornados than structure fires. Key considerations include: alerting populations and their response, pedestrian movement in evacuation, and vehicle traffic that involves evacuees and emergency responders. Emergency management involves active management during incidents as well as planning and preparation efforts, both of which can be aided by modelling and simulations.

Human response, pedestrian movement, and vehicle traffic are all critical components in fire safety for large outdoor fires. Extensive work has been done in each of these three topic areas, however there is a need for future work to address the specific hazards and scenarios for outdoor fires. For example, a body of knowledge exists for vehicle travel through fog which is similar to the smoky conditions present during wildland fires but lacks other hazards such as transported firebrands and spot fires that may affect traffic. The need to model these phenomena, as well as the spread of fire and smoke, for such events requires a framework that allows coupling inputs and outputs between various models. To achieve this level of emergency management an integrated modelling approach is needed. A recent study reviewed current models and provided a framework and recommended future work toward the development of such a system [173].

Response involves resources and equipment that play an important role in incidents and affects the overall emergency management. Post-incident studies have shown that responders and their actions affect the outcome of these incidents, however more work is needed to fully understand how response impacts the human response and traffic aspects.

10.4 Understanding WUI and Urban Fire Exposures to Design More Ignition Resistant Structures and Communities

While WUI building codes and standards exist, there are significant gaps in these recommended protection measures, most of all because of a lack in current understanding in how structures are ignited, mainly by firebrands [174]. As a wildland fire approaches a community, understanding the exposure that such a fire presents to that community is needed. Within the community, understanding the actual exposures generated from ornamental fuel and structural fuel combustion is required, especially with respect to firebrand production. Over the years, knowledge on radiant heat and flame impingement has been gathered due to research focused on urban fires. Once a wildland fire penetrates into a community, applying scientific knowledge from urban fires to WUI communities may be useful to understand radiant heat and direct flame impingement for structure-to-structure fire spread. Yet, again, without the coupling of firebrand exposures, communities would still be vulnerable to firebrand penetration into buildings that have been overlooked due to improper quantification [4]. It is necessary to develop representative new test methods indicative of actual WUI fire exposures.

It is also important to investigate existing structures and their ignition vulnerabilities. By investigating vulnerabilities of existing structures, especially to firebrand showers, it is possible to suggest scientific-based retrofitting methods. This approach may also be considered for communities which do not follow building codes and standards. Informal settlements which are often seen in developing countries possess potential risks to devastating fire spread due to construction methods. It is nonetheless important to evaluate the risk scientifically and apply proper methods to prevent large outdoor in informal settlements.

10.5 Large Outdoor Firefighting

Various firefighting equipment and tactics are used globally to respond to large outdoor fires (wildfires or fires that have reached the WUI). For example, when a fire is approaching a WUI community, the fire services' efforts are dedicated to optimal deployment of resources to reduce fire impact on the community. In such scenarios research is needed to better target investment and to optimize emergency service resource deployment and response planning. Situational awareness, namely for incident commanders to know the location of firefighters and where the fire actually is in near-real time is an important aspect where research could greatly assist.

Protective Personal Equipment (PPE) is a firefighter's last layer of protection and is fundamental for firefighter safety. Most countries stipulate their safety requirements via standards and regulations to provide this level of protection for firefighters. In order to investigate the performance of PPE as systems, some research organizations have designed tests to expose the PPE to a thermal environment. However, an updated understanding of fire exposure and how novel materials behave under these conditions is needed to design more effective and functional PPE (how the PPE maintain their protective capability). The biggest challenge is that there is wildland firefighter PPE and there is traditional structure firefighter PPE but in a WUI fire, both the wildlands and the structures are involved, so significant research is required to address PPE for these combined exposures [159].

Protection of the fire crews in vehicles is another important aspect of operational safety. This is complex as fire services use a range of vehicle sizes and designs to serve in different types of firefighting situations. While some research has been conducted to understand and validate the performance of vehicles and their protection systems, these approaches are not globally adopted as best practice.

It is also noted that the IAFSS requires improved outreach to the fire services. As large outdoor firefighting is major component of the permanent working group, it is hoped the

IAFSS group may translate important research findings to improve firefighter safety and better attract fire service interest.

10.6 Risk Assessment Methods in WUI Communities

WUI fire prevention and protection should be planned and implemented locally according to scientifically-based WUI fire risk assessment methods, either quantitative or qualitative. Quantitative methods should account for the evaluation of the probability of WUI fire occurrence and its subsequent damage. Although there are well accepted and applied fire risk quantification methodologies developed within the technical field of risk engineering for other types of fire scenarios (e.g. industrial fires), no methods have been yet developed for WUI fires. There are also methodologies developed for wildland fires at the landscape level but these do not include the influence of WUI fuels, firebrands, or the response of structures to a potential fire [175]. At this stage, there is a clear lack of standard methodologies to undertake a detailed vulnerability evaluation of communities. Based on an improved understanding on fire spread, ignition mechanisms and fire exposures, these methods could ultimately estimate through standard procedures the probability of a wildfire reaching a community boundary, the fire propagating inside the community, and the fire damaging houses and structures. These probabilities should then be coupled to the magnitude of the consequences on people, assets and environment to have an overall quantifiable risk measure. On the other side, WUI fire risk indices of a qualitative nature are also lacking. Based on significant parameters regarding community intrinsic properties (e.g., occupation, accessibility, fuel nature and continuity, buildings exposure, prevention infrastructures) and extrinsic properties (e.g. topography, wildland fuels, fire weather) risk indices should be developed, tested an applied as basic fire management tools for prevention and emergency planning.

10.7 Sharing Knowledge Across All Regions

Many of these challenges are not unique to one geographic area, so it imperative that scientists, researchers, practitioners, and managers work together and share existing knowledge across all regions. This must include outreach to the African research community, where to date their work has not reached global attention. This global collaboration will save time, effort, and the limited financial resources available by preventing one region from duplicating the work of another. Though it is clear that many regions suffer from many of the same problems, standardized reporting of fire statistics will help quantify the magnitude of each problem within each region, allowing more clear collaboration potentials. The possibility of globally standardizing WUI building codes may also arise as a better understanding of the wildland fire behavior potential, structure exposures, and mitigation strategy effectiveness becomes available. Yet, even before this, a complete understanding of current global large outdoor fire standards is required and such an effort is underway in ISO TC 92 [176].

11.0 CONCLUSIONS

Large outdoor fires present a risk to the built environment. In this paper, an overview of the large outdoor fire risk to the built environment from each region of the world was presented.

Critical research needs for this problem in the context of *fire safety science* were provided. A new permanent working group has been approved for this topic by the IAFFS and participation in this activity is strongly desired and great hope for lively discussion at the kickoff meeting at the Asia- Oceania IAFSS meeting in Taiwan occurring October 21–25, 2018.

12.0 REFERENCES

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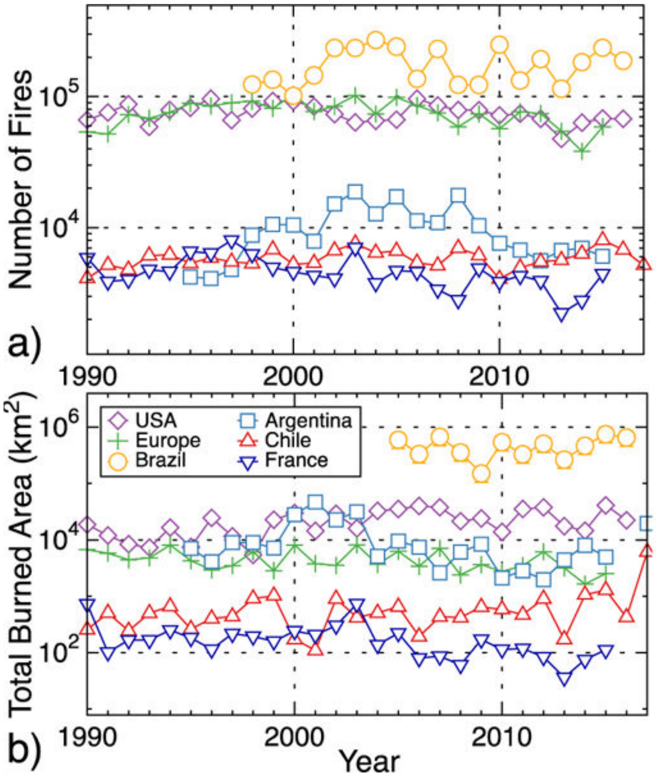

Figure 1.

Wildfire statistics for Argentina, Brazil, and Chile, 1990 – 2017. a) Total number of wildfires b) Total burned area (km^2) Data for the USA, Europe, and France are also shown for comparison.

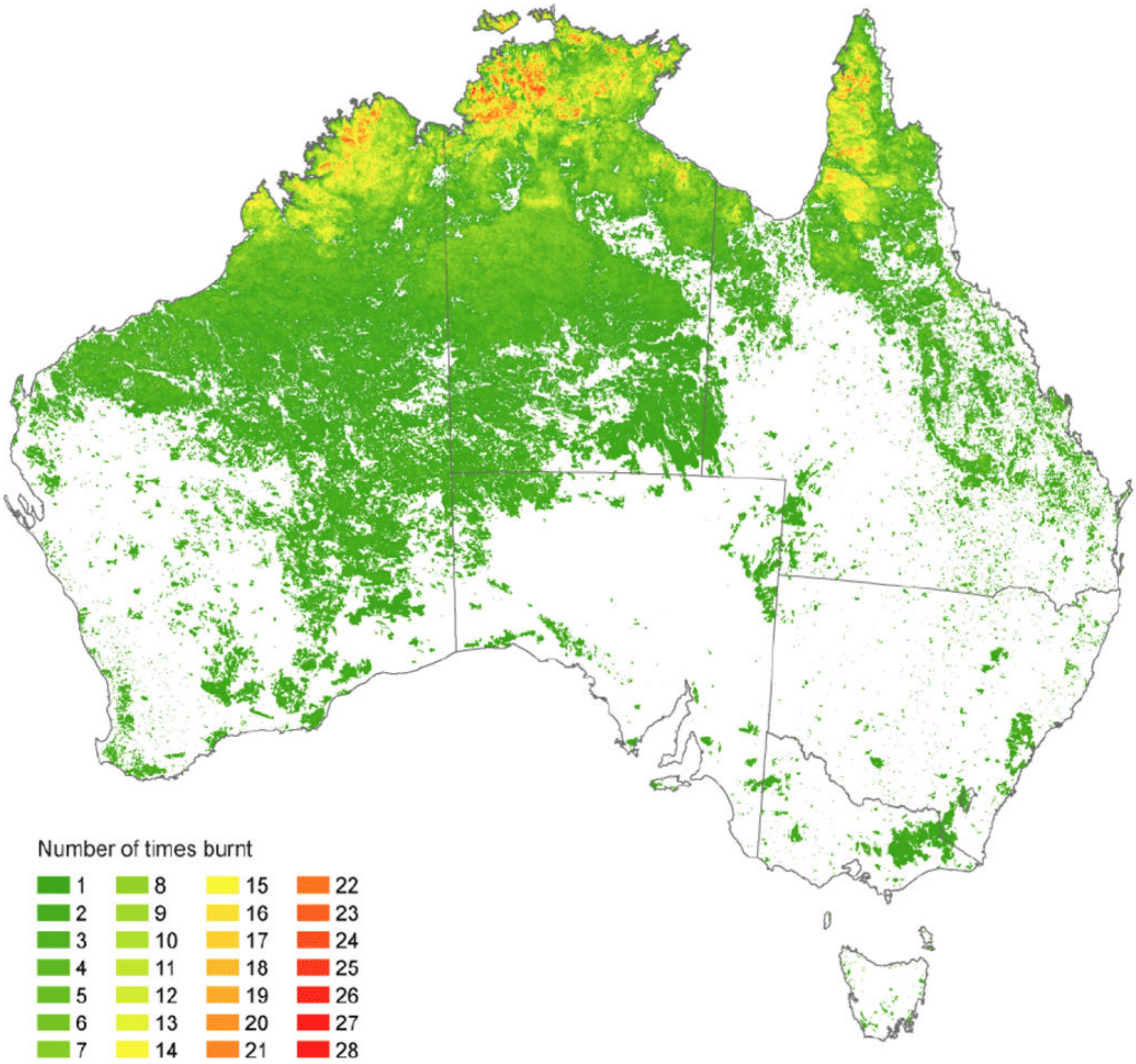

Figure 2.

Fire Return Frequency from Western Australian Land Information Authority (Landgate) 1988–2016 (unplanned and planned bushfire from MODSIM).

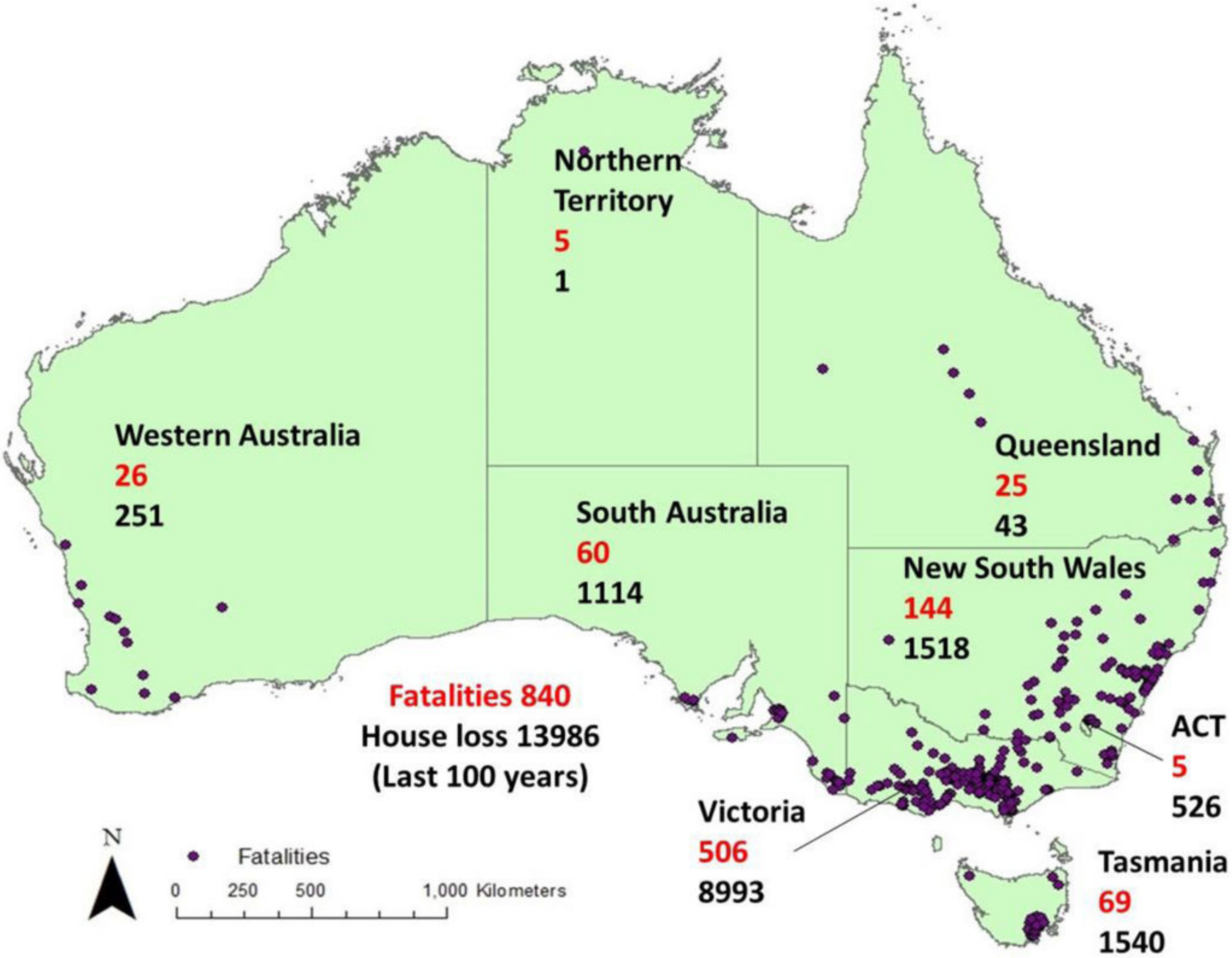

Figure 3.

Fatalities and house loss in Australia by state and specific location (purple dots) of all fatalities in Australia (taken from Blanchi *et al.,* [61].).

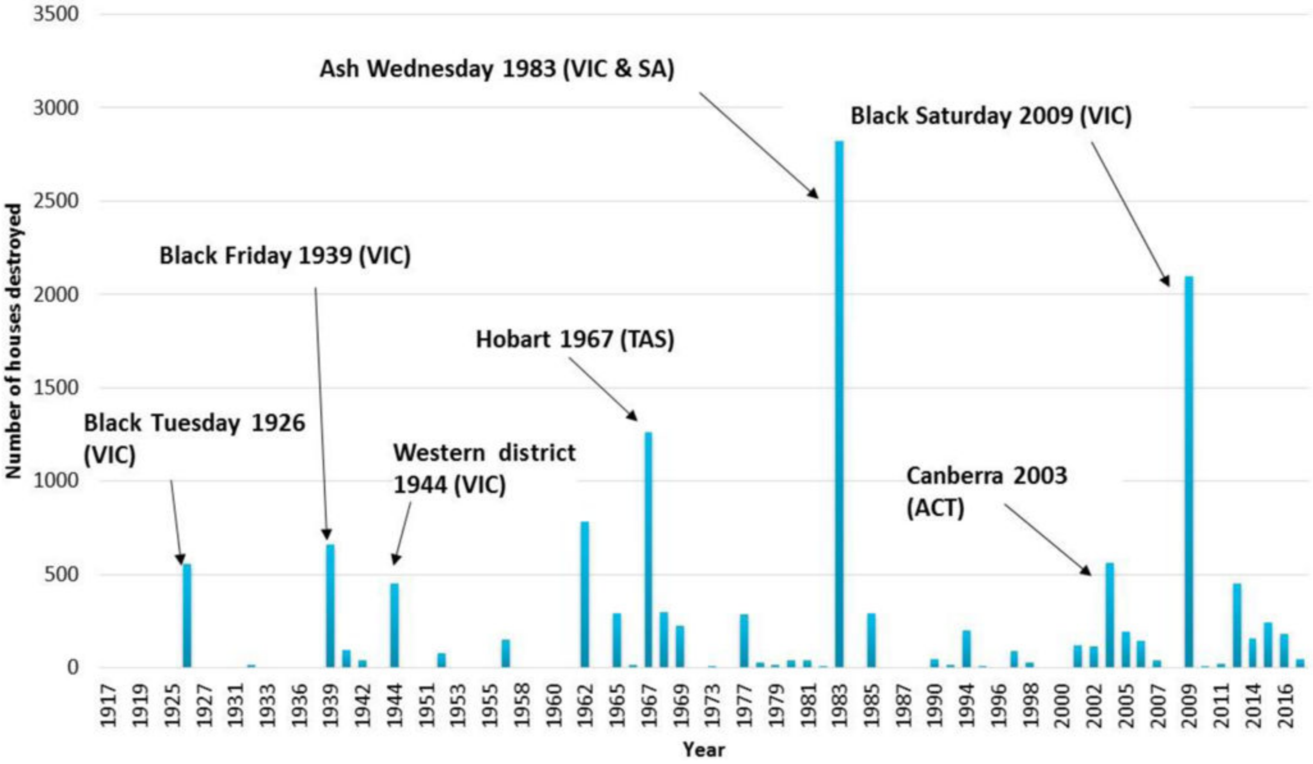

Figure 4.

Number of house loss per year, net cost of major bushfires (taken from Stephenson *et al.,* [58]).

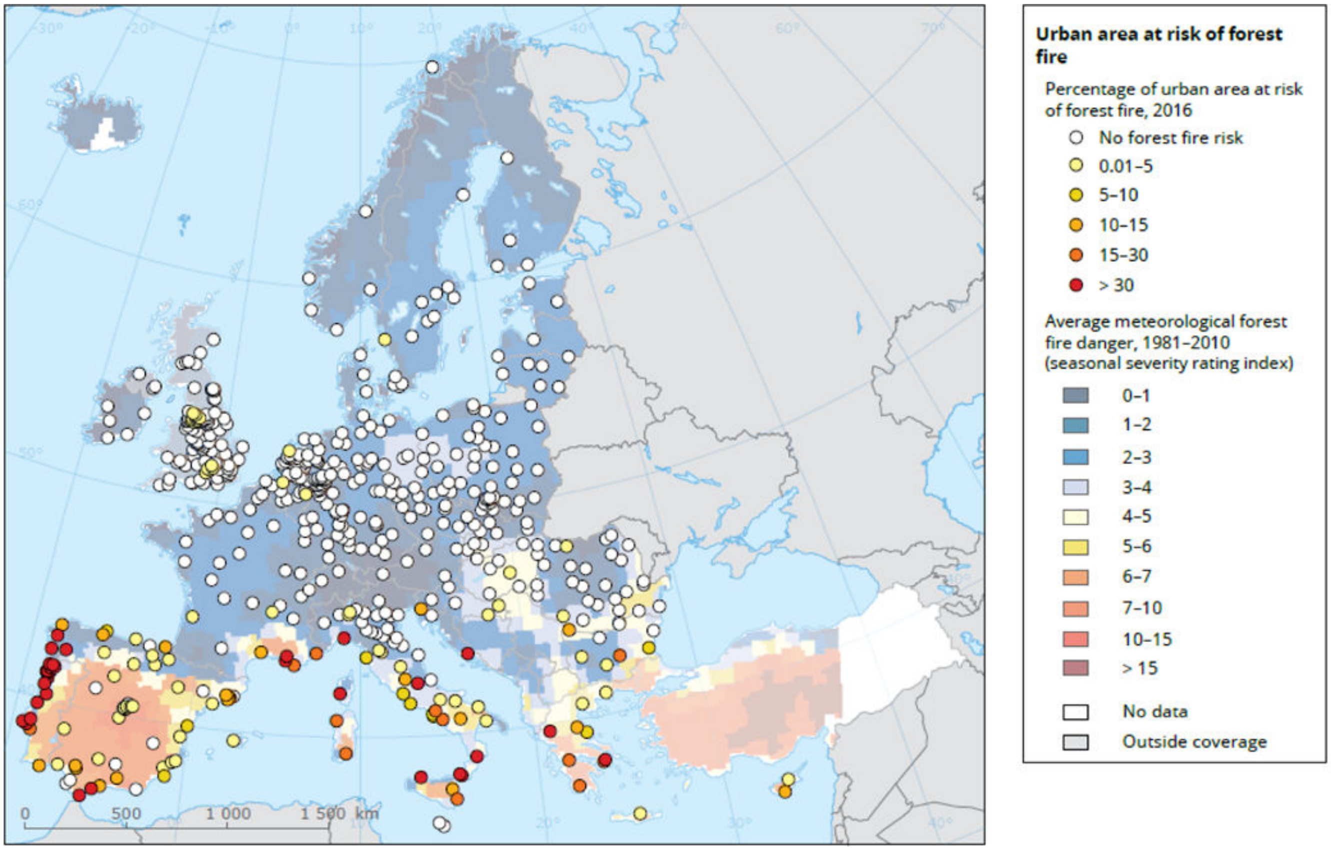

Figure 5.

Urban area at risk of forest fires (taken from [88]http://climate-adapt.eea.europa.eu/knowledge/tools/urban-adaptation/climatic-threats/forest-fires/exposure).

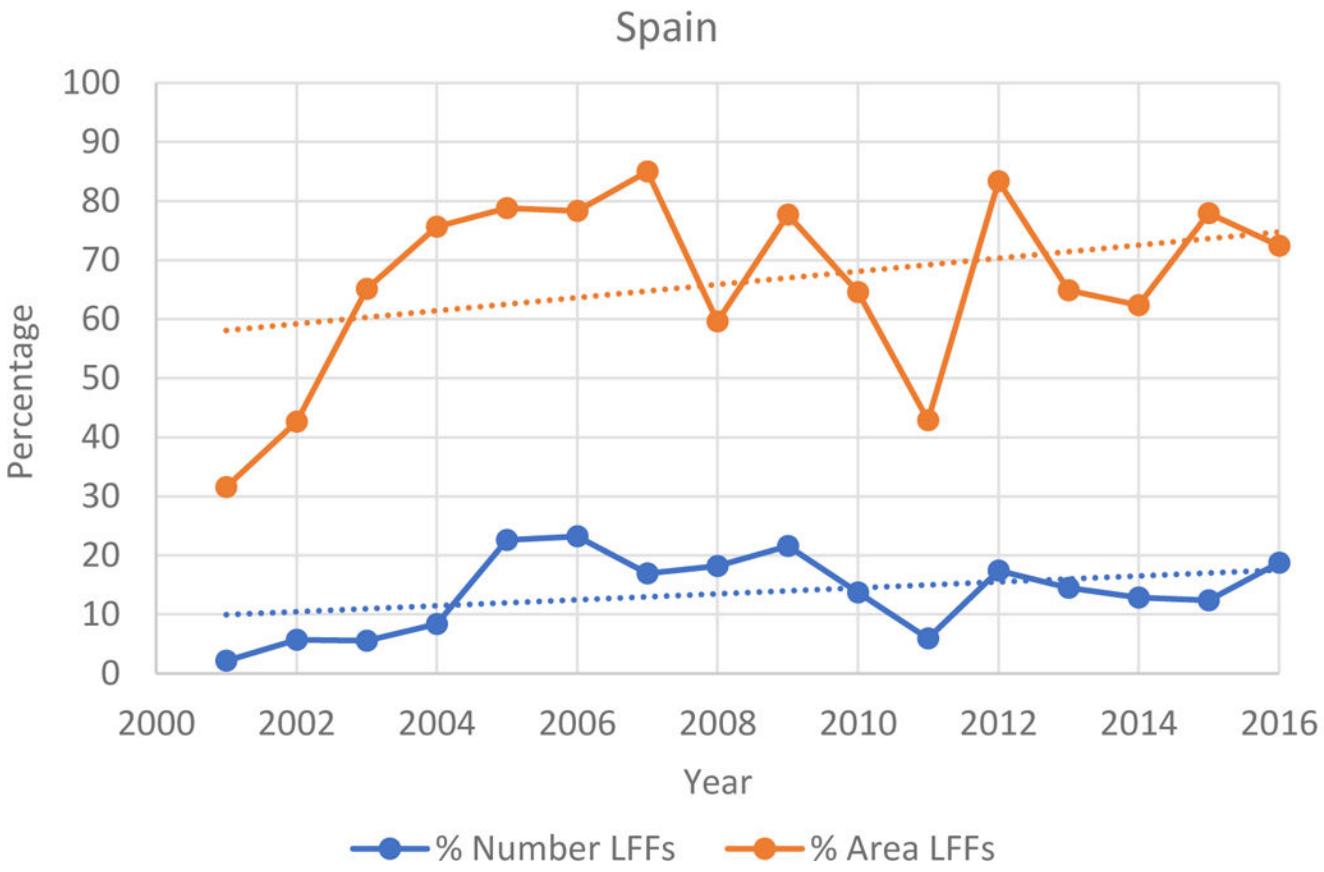

Figure 6.

Tendency in the percentage of large forest fires (LFF) occurrence and area burnt in Spain over the period 2001–2016 (taken from, http://effis.jrc.ec.europa.eu).

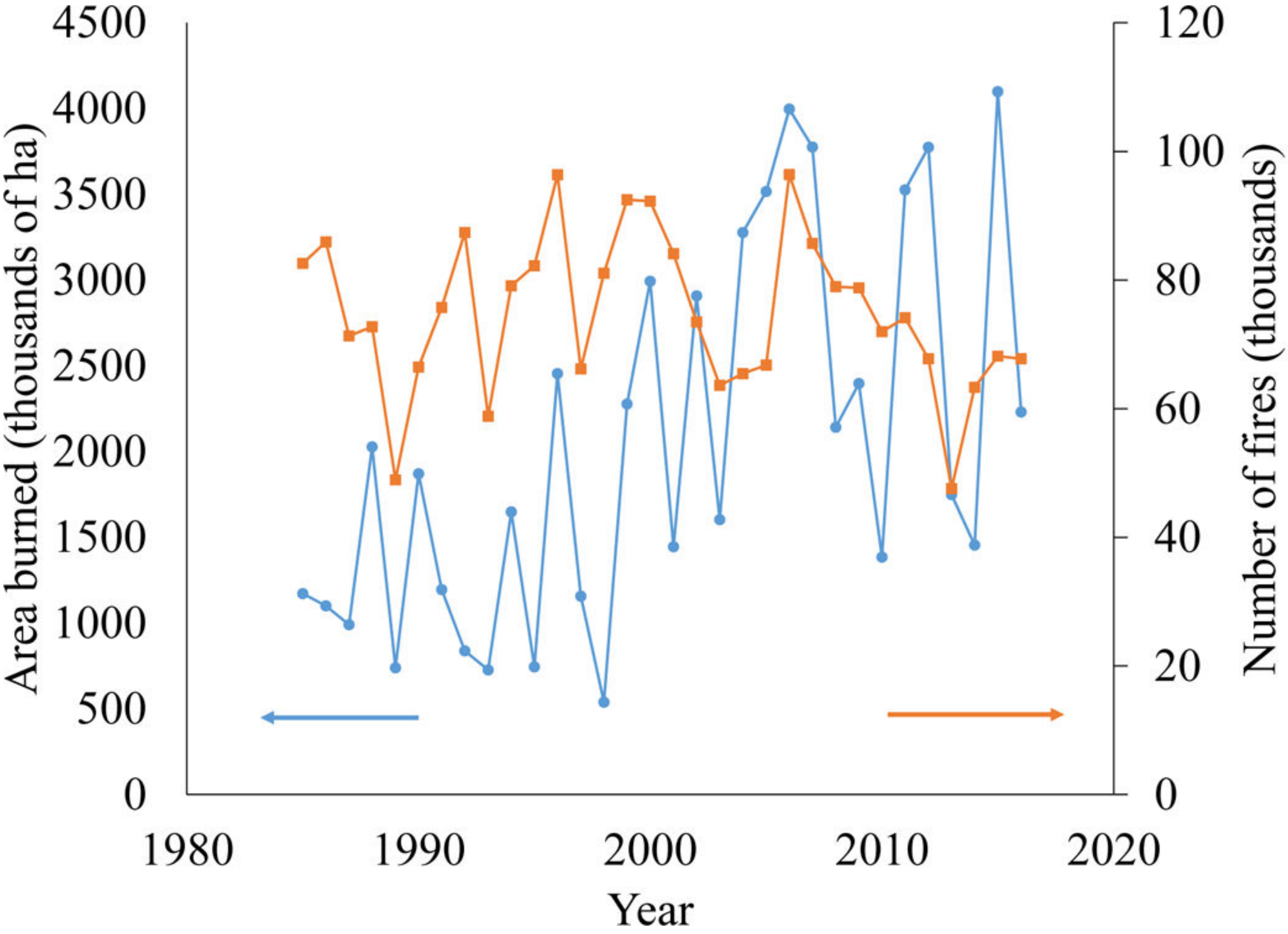

Figure 7-

Number of fires and area burned in the United States from 1985–2016 (data from [1]).

Proposed Subleader	Topic
Elsa Pastor (Spain)	Ignition Resistant Communities
Enrico Ronchi (Sweden)	Emergency Management and Evacuation
Raphaele Blanchi (Australia)	Large Outdoor Firefighting

Table 1

Demographic and economic figures for different continents.

	Population ($\times 10^6$ inhab.)	Land area ($\times 10^6$ km^2)	Pop. density (inhab./km^2)	GDP ($\times 10^{12}$ USD)
Africa	1,225	30.4	36.4	3.3
Asia	4,164	44.5	87.0	18.5
Europe	742	10.1	72.9	19.7
N. America	565	24.7	22.9	21.2
Oceania	41	8.5	4.19	1.5
S. America	410	17.8	21.4	3.8

Table 2

Some recent WUI fires in Chile and Argentina.

Location	Country	Year	Casualties	Losses
Quillón	Chile	2012	2 dead	224 houses, 1 paper pulp plant (> USD 160 million)
chubut	Argentina	2012	-	7 houses
Valparaíso	Chile	2013	-	280 houses
Valparaíso	Chile	2014	-	20 houses
Valparaíso	Chile	2014	15 dead 500 injured	2900 houses (> USD 110 million)
Valparaíso	Chile	2015	33 injured	2 houses
Chubut	Argentina	2015	-	5 houses
Valparaíso	Chile	2017	19 injured	140 houses
Central Chile	Chile	2016–2017	11 dead	1020 houses 550,000 Ha burnt
Viña del Mar	Chile	2017	-	16 houses

Table 3

Bushfires (unplanned fires) burnt area in Australia and New Zealand (Ha).

	AUSTRALIA							NEW ZEALAND[5]
	NSW[1]	NT[1]	QLD[1]	SA[1]	TAS[2]	VIC[3]	WA[4]	
2006–2007	352,000	3,899,000	3,480,000	353,000	125,000	1,207,899	1,945,633	4,099
2007–2008	51,000	2,583,000	2,125,000	500,000	31,600	28,396	1,425,806	9,082
2008–2009	23,000	2,031,000	2,013,000	33,000	5,890	446,244	1,740,000	2,363
2009–2010	160,000	2,712,000	5,149,000	15,000	15,800	24,166	2,602,767	5,254
2010–2011	2,000	1,245,000	450,000	137,000	1,479	13,524	645,505	2,920
2011–2012	no data	no data	no data	no data	9,350	3,976	4,991,503	1,495
2012–2013	no data	no data	no data	no data	69,017	200,455	5,477,394	4,362
2013–2014	no data	no data	no data	no data	7,512	415,107	2,209,619	2,051
2014–2015	no data	no data	no data	no data	6,848	53,875	2,569,695	4,651
2015–2016	no data	no data	no data	no data	143,500	25,345	1,887,954	3,508

[1] Data sources: SOE,

[2] Data source: Tasmanian forest service,

[3] Data source: Country Fire Authority,

[4] Data source: Department of Biodiversity, Conservation and Attractions,

[5] Data source: National Rural Fire Authority New Zealand Fire Service

Table 4

Annual mean values of the number of fires and burnt area (Ha) for the period 1991–2015 by decades in the European Mediterranean Countries (http://effis.jrc.ec.europa.eu/reports-and-publications/annual-fire-reports/).

Period	**Portugal**	**Spain**	**France***	**Italy**	**Greece**
Annual mean number of fires for the period (ha)					
1991–2000 (Fires per 10,000 ha of forest surface)	25,203 (81.84)	19,272 (6.92)	2,549 (8.75)	10,968 (13.59)	4,833 (5.32)
2001–2010 (Fires per 10,000 ha of forest surface)	25,250 (87.75)	17,127 (6.32)	2,511 (11,04)	6,887 (8.50)	1,871 (2.66)
2011–2015 (Fires per10,000 ha of forest surface)	17,721 (59.87)	12,851 (4.73)	3,609 (12.22)	5,614 (6.93)	1,019 (1.47)
Annual mean burnt area for the period (ha)					
1991–2000 (% of the total forest surface)	104,438 (3.32)	159,878 (0.58)	12,207 (0.39)	99,594 (1.23)	60,016 (0.69)
2001–2010 (% of the total forest surface)	148,707 (5.03)	113,725 (0.42)	17,781 (1.35)	77,065 (0.95)	36,870 (0.53)
2011–2015 (% of the total forest surface)	85,234 (2.88)	100,650 (0.37)	(1.35) (0.27)	61,906 (0.76)	33,737 (0.49)