PNAS Nexus, 2024, **3**, pgae151
https://doi.org/10.1093/pnasnexus/pgae151
Advance access publication 7 May 2024
Perspective

Wildfire risk management in the era of climate change

Costas Emmanuel Synolakis [a,*] and Georgios Marios Karagiannis [b]

[a]Viterbi School of Engineering, University of Southern California, 3620 South Vermont Ave., Los Angeles, CA 90089, USA
[b]Resilience First, 16 Great Queen Street, Covent Garden, London WC2B 5AH, UK
*To whom correspondence should be addressed: Email: costas@usc.edu
Edited By: Cristina Amon

Abstract

The August 8, 2023 Lahaina fire refocused attention on wildfires, public alerts, and emergency management. Wildfire risk is on the rise, precipitated through a combination of climate change, increased development in the wildland–urban interface (WUI), decades of unmitigated biomass accumulation in forests, and a long history of emphasis on fire suppression over hazard mitigation. Stemming the tide of wildfire death and destruction will involve bringing together diverse scientific disciplines into policy. Renewed emphasis is needed on emergency alerts and community evacuations. Land management strategies need to account for the impact of climate change and hazard mitigation on forest ecosystems. Here, we propose a long-term strategy consisting of integrating wildfire risk management in wider-scope forest land management policies and strategies, and we discuss new technologies and possible scientific breakthroughs.

Keywords: wildland fire risk, emergency management, climate adaptation, evacuation modeling, satellite fire observations

Significance Statement

Here, we draw from research on wildland–urban interface (WUI) fires from forestry and climate science to emergency management and economics, and we summarize the complexity and offer recommendations for policy making. Its significance stems from the analysis of emergency response in recent deadly fires, and our integrated approach which brings together multiple, diverse disciplines to explore policy-related, strategic, and operational approaches for addressing wildland fire risk in the era of climate change.

Introduction

Wildland fires have existed since the beginning of history, with Paleontological evidence suggesting that early forest fires started to spread about 383 million years ago (1). As humanity evolved, forest fires were allowed to burn, depending on the objectives of human settlers (2). For example, even with the advent of fire suppression capabilities in the late 19th century, fire control efforts in the United States focused around settlements, and those beyond were left to burn unabated (3).

Despite impressive advances in forestry, fire science and firefighting technologies, and the leaps in wildland firefighting capabilities compared to 200 years ago, wildfire deaths are on the rise. The early February 2024 wildfires in Valparaiso, Chile killed over 130 persons and were the deadliest natural disaster in the country since the 2010 Mw~8.8 earthquake and tsunami (4) and occurred in what has been called a "megadrought" (5). The August 8, 2023 Maui fires resulted in the highest death toll in the United States since the 1918 Cloquet and Moose Lake fires, and they amount to the fifth deadliest incident on record nationwide (6). It has been argued that at least some of these casualties might have been prevented had there been evacuation orders or emergency alerts (7, 8). Less than two months after this catastrophe in Hawaii, the nationwide test of the Integrated Public Alert and Warning System established by the Federal Emergency Management Agency (FEMA), a state-of-the-art capability which has served as a model for countries around the world, came as a stark reminder of the complexity of wildfire risk.

The National Academies of Sciences, Engineering, and Medicine (9) point out that wildfire smoke can be transported over fairly long distances downwind and contaminate indoor and outdoor air, indoor surfaces, soil, and surface and even drinking water. Air pollution by plume transport is an insidious yet potent source of morbidity and mortality. In Europe alone, Kollanus et al. (10) estimated 1,080 premature deaths in 2008 from wildfire-originated fine particles in the atmosphere, with southern and eastern Europe disproportionately affected. The 2018 Camp Fire (Butte County, CA) resulted in $PM_{2.5}$ concentrations in downtown San Francisco, 240 miles away, peaking about six times higher than, and about double the US benchmark, for two weeks after the event (11). Chen et al. (12) found that fine particulate matter from wildfires was significantly associated with increased

Competing Interest: The authors declare no competing interest.
Received: November 21, 2023. **Accepted:** March 29, 2024

cardiovascular and respiratory mortality at a global level, and estimated the associated death toll at 33,000, or approximately 0.6% of all deaths in 749 cities in 43 countries and regions, in 2000–2016.

The devastation caused by many wildfires does not come without nontrivial societal and political ramifications. Communities affected by wildfires face the trauma of death, injury, loss of livelihoods, damage to homes, and psychological effects. Notwithstanding the provision of relief aid, more often than not, decision-makers face the outrage of their constituents for everything they didn't do, for example, issuing alerts and evacuation orders. Electorates tend to punish incumbents for wildfire deaths and damage, so there is scapegoating and denial of responsibility by officials, which makes forensic analysis exceptionally difficult.

Wildfire risk lies in the confluence of climate change and development in the WUI. According to the NASEM (9) report, the WUI in the United States has expanded by 50% in the past 50 years, the fastest growing land use type, and another 10% increase is projected by 2030. Stemming the tide of wildfire death and destruction will involve bringing together diverse scientific disciplines into policy. Here, we will first review three fires to elucidate challenges posed, then we discuss how climate change is projected to increase fire activity, that is the frequency and intensity of fires. We will explore how governments are responding, and we argue that improvements in fire suppression capabilities, although required in the short term, may be financially unsustainable in the long run.

Three catastrophic fires in the past five years

Lahaina, Maui, HI

On August 8, 2023, fires broke out in different parts of Maui, Hawaii. One of the fires destroyed the historic town of Lahaina and claimed 98 lives, becoming the deadliest US wildfire in more than a century.

Maui is no stranger to vegetation fires. However, on August 8, dry vegetation and strong descending winds climbed up to about 125 kilometers per hour and caused the fire to quickly spread out of control. Firefighting resources were stretched thin, responding to multiple incidents on the island. Lahaina was ravaged, and the majority of its about 1,800 buildings were completely burned. Some people sought refuge at sea, whereas others burned in their cars while trying to evacuate (7, 8).

As fires broke out, broadcast emergency messages and social media posts from the County of Maui provided updates, alerts, and evacuation calls for some areas but apparently not Lahaina, a densely populated area with limited escape routes. Confusing messaging and delayed evacuation alerts (if they even took place) did not help.

Looking at milestones in the timeline, around 3:30 PM, a major road was closed just north of Lahaina because of what appeared then as just a flare-up of an earlier fire. Maui County's social media page didn't announce the closure until 4:46 PM Evacuation orders for the entire area appear not to have been issued when the road was closed, or even soon thereafter. Maui officials claimed that text alerts were sent out, but that power and cellular disruptions prevented residents from receiving them. Some survivors have reported receiving no warning messages before the fire reached them, whereas at least one visitor reported receiving an emergency alert on their cellphone at 4:17 PM, 47 minutes after the road closure. Many local residents reported that they didn't know the flames were approaching until the fire was nearby, and some said that they were informed by neighbors to evacuate. By 5:19 PM the fire had reached the waterfront in Lahaina, and by 5:33 PM people were seeking shelter in the water.

All this is quite surprising. Not only was there a fire in Maui in 2018 with similar problematic issues, but Hawaii has one of the most sophisticated tsunami warning systems in the world, fine-tuned since 1946, when a 17-meter tsunami hit the islands in the aftermath of the 1946 Aleutian tsunami (13), claiming 159 lives. Sirens are an integral part of the islands' warning capabilities, yet local authorities defended their decision not to activate them in this fire. Mechanical sirens, as in Hawaii's All-Hazard Statewide Outdoor Warning Siren System produce a single tone, alerting people of an impending hazard, but provide no information about the nature of the hazard, its severity and, most importantly, protective action guidance. Note that the siren system is referred to as all-hazard, including wildfires, and claimed as the largest in the world.

To be effective, sirens need to be associated with a single clear protective action (14). In fact, Maui County had advised people that "[w]hen a siren tone is heard other than a scheduled test, tune into local Radio/TV/Cable stations for emergency information and instructions by official authorities. If you are in a low-lying area near the coastline; evacuate to high grounds, inland, or vertically to the 4th floor and higher of a concrete building". In other words, Maui residents were given incomplete information—the reference to evacuating to high ground is likely for tsunami emergencies, yet there is no reference in the instructions to tsunamis. This confusing messaging is exactly what emergency managers are taught to avoid yet, in the aftermath, local authorities claimed they couldn't have done anything differently.

A High Wind Watch issued on August 6 spoke of gale-force winds from the northeast on Maui until the night of August 8, as Hurricane Dora passed south of the Hawaiian Islands. It was upgraded to a High Wind Warning for Maui on August 7, with forecasts of gale-force winds from the east. Fire danger in Hawaii is weather-dominated, as vegetation grows rapidly with subtropical rainfall extremes, and dries rapidly during drought periods (15). On August 8, dry conditions on the island, strong easterly winds, and densely populated areas on the west coast of the island combined to create a dangerous situation. With hindsight, this combination may have fulfilled the criteria for issuing a warning of potential extreme fire behavior.

The Maui disaster triggered political backlash and legal battles. State and national levels came under scrutiny over their handling of the situation. The Maui County Emergency Management Administrator resigned in the weeks following the disaster. Three months following the fire, the Governor announced the creation of a $150 million recovery fund to help those who were injured in the fires or lost family members if they waive their right to file associated legal claims. The fund is initially paid for by the State of Hawaii, Maui County, Hawaiian Electric, and Kamehameha Schools, all of which have been named in legal actions over the wildfires.

Mati, Greece

Emergency and civil defense managers in Hawaii should have known better. Five years earlier, almost to the day, on July 23, 2018, a fairly small brush fire claimed 104 lives in Mati, Greece. Mati is a seaside community of about 5,000, approximately 30 km west of Athens, and a popular summer destination. On July 23, very strong winds descending from Mount Penteli at about 95 km/h (gusting to over 110 km/h) pushed the fire rapidly over dry vegetation, causing it to spread quickly, covering one-half mile in about half an hour from the nearest highway east of the town to the sea. In total, the fire took two hours to spread from where it started to the nearest beach—there is security camera video that captured the ignition. About 1,200 buildings were destroyed by the fire.

People were burned in their cars as they attempted to flee, while hundreds of people escaped to nearby seaside cliffs, hiked down to the beach, and were evacuated hours later from the water. A large number of firefighting resources had already been committed to a major incident about 80 km to the east, leaving limited resources available for the Mati fire.

In Mati, there was no warning, and people self-evacuated when flames were hundreds of feet away or did so at the encouragement of neighbors. Some police officers and firefighters reportedly went door-to-door to urge people to evacuate, but the lack of evacuation planning led to a series of traffic management failures, including, in one case, leading evacuees back toward the fire. The government and civil defense denied responsibility and claimed they couldn't have done anything differently, even with hindsight (16). Despite the rapid spread of the fire, our calculations using agent-based evacuation models showed that, with a proper evacuation plan and public warning, the area could have been evacuated in time.

Unlike Maui, the legal and political fallout of the Mati disaster had historic proportions. At first, there were ad hominem attacks against scientists who spoke out about the lack of evacuation orders as contributing to the high death toll. This is also what happened in several countries in the first months of the COVID pandemic—governments were shooting the messengers. Eventually, however, the Alternate Minister for Citizen Protection, the Secretary General for Civil Protection, the Chief of the Hellenic Fire Service and the Chief of the Hellenic Police resigned. A series of negligence lawsuits were filed against the government by those who had lost loved ones and/or their homes. In addition, a four-year criminal investigation culminated with a trial which began on October 31, 2022, with twentyone senior elected and appointed officials facing felony charges. On April 29, 2024, six of the twentyone defendants were found guilty of negligent homicide. Some have argued that the handling of the aftermath of this fire led to the government losing national elections a year later.

The new government that took over rolled out the 112 Emergency Communications Service, following our relentless advocacy, editorials in major newspapers, and actual implementation work. The new service integrates a unified, multi-agency public safety answering capability, based on the European emergency number 1-1-2 with a nationwide, integrated public alert and warning system. This system is now used by the General Secretariat for Civil Protection (i.e. the country's national emergency management agency) to deliver effective life-saving information to the public. Alert messages are delivered primarily through cell phone SMS and additional communications pathways. In addition, new legislation voted in 2020 established an all-hazards planning approach, and municipalities are required to prepare a single emergency operations plan with hazard-specific and function-based annexes, as required. An evacuation annex is now mandatory.

The Maui and Mati fires bear eerie similarities. Dry vegetation and high winds, which pushed the fires downslope to densely populated areas with poor evacuation routes, and insufficient firefighting resources combined to cause both fires to quickly spread out of control. Preparedness failures, poor warning capabilities, and an apparent deficiency in evacuation planning led to the high death tolls. In both locales, people were burned in their cars, in Mati some because of a lack of evacuation planning that resulted in drivers being redirected back to the inferno, while in Lahaina possibly because of delays in evacuation and confusion with closed roads. In both cases, officials claimed that call centers were overwhelmed. Both events had political repercussions, and in both cases officials abdicated responsibility, claiming they wouldn't have done anything differently even with hindsight.

WUI fires need not be so ghastly.

Rhodes, Greece

On July 18, 2023, a fire broke out on the Greek island of Rhodes. The fire was initially confined to the island's mountainous center, but spread to the south on the fourth day, fanned by strong, northerly seasonal winds. By July 23, the fire had reached the southern coast of the island, scorching more than 16,000 ha. With multiple fires burning simultaneously throughout the country, resources were stretched thin, despite the reinforcements sent by EU countries and the United States. The island is one of the most popular tourist destinations in the Mediterranean, exceeding 2 million visitors every year, and roughly the same size as Maui.

When it comes to evacuations, visitors are a vexing challenge, not least because of their limited proficiency in the host country's language, and their lack of familiarity with the area they are visiting. Yet, Greek authorities were able to evacuate over 20,000 local residents and tourists from the affected areas in Rhodes, within half a day, making it Greece's largest ever wildfire evacuation (17, 18). The country's public alert and warning system was used to send multiple evacuation messages, as the fire approached residential areas. The slower overall rate of spread of the Rhodes fire may have allowed for the timely evacuation. However, the scale of the evacuation was considerable for Greece, and much more so for an island like Rhodes, and we that without a public warning system and a tried emergency management program, such as 112, the outcome would have been quite different. Ultimately, the fire devastated homes, hotels, and other businesses, yet the only casualty was the tragic loss of a volunteer firefighter. The efficacious crisis management in the aftermath bears noting, as most evacuees were sheltered in hotels or hosted by locals from night one. While at first tourist arrivals drastically fell, and hundreds of incoming flights were canceled, normalcy was restored within three weeks.

Wildland–urban interface risk and climate change

The wildland–urban interface challenge

More people living in WUI areas enhance ignition opportunities. Moritz et al. (19) identified several socioecological linkages and have focused on the impact to ecosystems by and their interdependencies with humans. While fires in remote areas are usually triggered by lightning storms, most wildfires appear to be human-caused (20). It is therefore hardly surprising that hot spots of fire activity have been identified in the WUI in the United States (21), and 95% of wildfires in Europe are reportedly caused by human negligence or arson (22). Radeloff et al. (23) state that the number of houses within wildfire perimentes has doubled since the 1990s, due to both increased number of houses and larger burned areas. The number of wildfire-related deaths worldwide in the last four decades, based on the global EM-DAT database (24) shows that 10% of the fires appear responsible for 78% of the deaths (Figure 1). Furthermore, the single deadliest fire each year was responsible for 65% of all the deaths in that year, on average. In other words, a small number of fires produce the vast majority of deaths, while eight out of the ten deadliest fires occurred in the WUI.

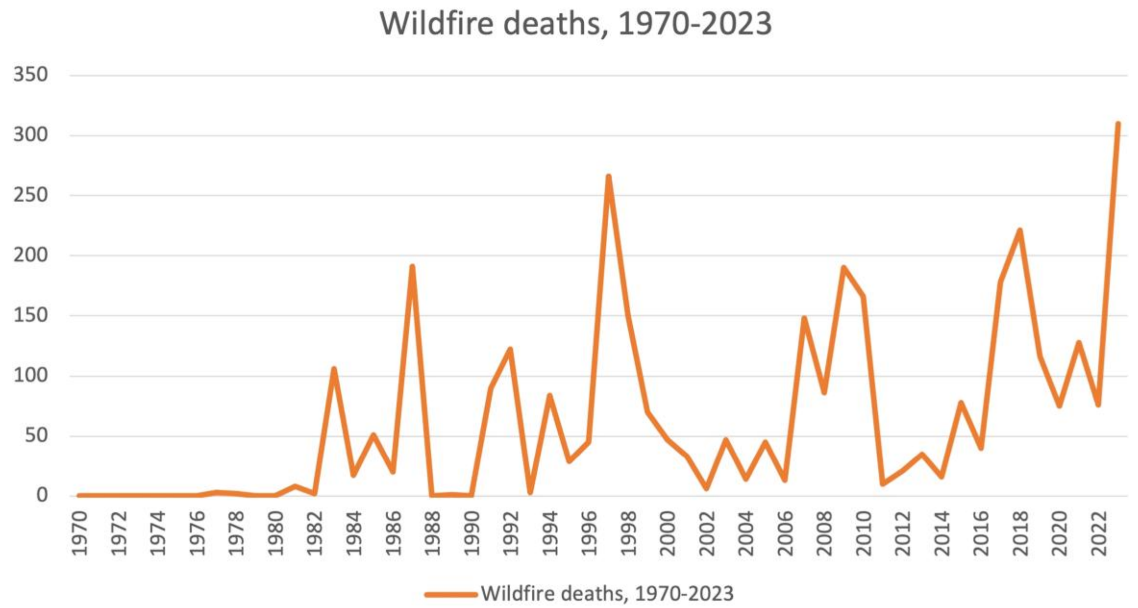

Figure 1. Wildfire deaths per year, 1970–2023 (24).

Fires in the WUI pose unique challenges to fire suppression and emergency response. First, whereas urban and wildland firefighting tactics are fundamentally different, WUI fire suppression inherently involves both in close proximity, and tactical incompatibilities may appear. Urban fires will typically have multiple exposures with a fixed source, and direct fire attack using water or foam is the norm. On the other hand, wildland firefighting techniques very often involve indirect attack (25, 26). For example, a fireline may be used to interrupt fuel continuity or a backfire may be employed to deprive the fire of oxygen. In the WUI, exposure usually involves a long flame front and multiple sources of ignition. In WUI fires, structural firefighters operate in close proximity with their wildland counterparts, which often creates challenges in communications and coordination, especially when they come from different organizations and jurisdictions.

Different firefighting tactics also mean different equipment. Wildland firefighting personal protective equipment is lighter because structural and atmospheric hazards are more limited in the open, and mobility is essential (26). Wildland firefighting engines are typically smaller and carry less equipment to remain mobile. This essential mobility in the wilderness may become a limiting factor, and possibly a source of danger, to firefighters in the WUI.

In addition, delayed fire reporting or increased response times increase fire risk to isolated homes and other structures (27). Fireline access can be challenging, as small backcountry roads and covered bridges might constrain anything but the smallest fire engines, and mutual aid resources could find navigating poorly charted rural roads a hindrance. Also, water supply may be scarce because of a lack of fire hydrants or failures during a power outage (28). This was the case in Lahaina, in both 2018 and 2023 and in the 2024 Viña del Mar fires in Chile, which took place while this paper was under review.

Second, evacuations are often required in WUI fires but are substantially different than organized evacuations implemented before river floods, landslides, and other natural hazards, or following accidents involving hazardous materials. Wildfire evacuations usually are decided and implemented on very short notice, notably because of difficulties in forecasting weather and predicting fire behavior. In Australia, in particular, there was debate about "stay and defend or go", but the discussion seems to have settled in favor of "go" (29). Emergency planning helps alleviate some of that uncertainty. A small number of evacuation courses of action may be analyzed and included in emergency plans, offering options depending on the relative position of residential areas and the fire perimeter, as well as the current and projected weather, topography, and fuels. In Portugal, for example, predesigned evacuation routes and shelter locations are communicated to the public before disaster strikes, thus reducing clearance times when evacuations are warranted (30).

Regardless, many WUI areas have poor evacuee egress options, not only because of narrow, winding roads, but also traffic congestion (31). For instance, 23 people, including three seasonal firefighters, were trapped and perished while evacuating the village of Artemida, Greece during the 2007 fire south of ancient Olympia (32), over a narrow backcountry road that was the only option (33). In the 2018 Camp Fire in Northern California, staff evacuated patients from the local hospital in their own vehicles. On one occasion, the drive to safety out of the heavily wooded area allegedly took about three hours. This was a very difficult terrain for timely evacuations, nonetheless over 40,000 managed to evacuate. Alerts were reportedly not received by at least 50% of the residents, but completely without them the death toll would likely have been much higher than the 84 who perished. In another example, serious traffic congestion ensued when residents in West Kelowna, British Columbia were asked to evacuate during the 2015 Munt Law wildfire (34).

With this inadvertently rapid operational tempo, reducing the time between decision-making and the actual evacuation by providing people advanced notice is paramount. Mati and Maui and, to a lesser extent, Paradise—all three incidents were haunted by the lack or failure of public alert and warning systems (35).

Third, wildfires can rapidly spread out of control and increase in complexity. Large fires are among the most complex incidents, not least because of the geographic area involved, the large number of resources involved, organizational complexity, jurisdictional boundaries, weather, and difficulty in predicting fire spread (36–39). WUI fires add more layers of complexity, due to the threat to life, property and critical infrastructures, as well as political sensitivities. For example, it has been reported that, during the Mati fires, politicians were calling the fire department asking for prioritization of resources to favor friends and relatives. Climate change is one of the factors increasing the potential for extreme fire behavior, therefore making firefighting less routine while making fires themselves more routine.

Fourth, wildland fires are intricately related to critical infrastructure and form complex feedback loops which lead to compound events (40, 41). The risk to energy production and generation assets and the power grid increases with wildfire incidence. Power lines can ignite wildfires through a variety of mechanisms, and fires can damage power utility assets, causing widespread power outages (42). California's largest utility, Pacific Gas and Electric, pleaded guilty to manslaughter charges and filed for bankruptcy in early 2019, accepting responsibility for its downed power lines that triggered the 2018 Camp Fire, allegedly the costliest natural disaster in that year worldwide. Hawaiian Electric is currently facing lawsuits for alleged negligence in the Maui fires. On the other end, in Mati, the country's national electricity corporation steadfastly refused to entertain even the suggestion that one of its power lines near the point of ignition may have triggered the fire, and thus far has gotten away with it.

The cascading effects of wildland fires increase agent-generated demands and complicate response-generated demands (40, 43). Almost any critical infrastructure asset may be affected by wildland fires, even water treatment plants. Fires can melt underground water pipes, thus affecting firefighting, and they can destroy communication towers and power substations. Operators then need to find workarounds or make temporary repairs to restore service to priority customers, typically other critical infrastructure systems. At the same time, governments need to work with operators and affected critical customers to provide backup solutions. A vicious circle ensues, as infrastructure damage delays response and short-term recovery efforts, which in turn slow down restoration and repair (44).

Climate change and wildfire risk

Wildland fires have an intricate relationship with climate change. Bowman et al. (45) estimated that wildland fires are responsible for 19% of the anthropogenic radiative forcing. Climate change does yield higher temperatures and drier conditions that prime the landscape for fires to catch and spread more easily. Flannigan et al. (46) estimate that fire seasons will last 20 days per year longer in the northern high latitudes by the end of the century. The IPCC Sixth Assessment Report (47) notes that fire weather is expected to increase in many parts of the world and, a 2-degree global warming scenario is projected to increase burned area globally by 35%. These estimates are corroborated by regional studies, which point to an increase in the number of human-induced wildfires, burned area, and wildfire risk (21, 48–56).

These scenarios are hardly fictitious, as climate change is already increasing wildfire risk around the world. Fire-prone areas are extending poleward to areas previously unaffected. Jolly et al. (2015) found that, by 2013, fire seasons had lengthened in about one-quarter of the Earth's vegetated surface, resulting in an increase of the global average fire season length by 18.7%, compared to 1979. They also estimated that, between 1979 and 2013, the burnable area affected by longer fire weather seasons had doubled. Furthermore, the frequency of long fire-weather seasons increased across more than half of the global vegetated area between 1996 and 2013, compared with 1979–1996. Regional studies corroborate these global findings by showing an increase in the number of fires and the burned area during fire seasons, as well as in the size, extent, and frequency of large fires (49, 56–61). Consensus is emerging that the conventional suppression-centered wildfire and forest management strategies applied so far no longer efficiently address megafires, variously defined, but usually as fires that burn over 40,000 hectares.

Furthermore, overnight burning events (OBE), defined as fires that burn through the night, have recently been changing what used to be a familiar diurnal fire cycle. Luo et al. (62) found that 20% of the 1084 fires burning over 1000 hectares in the period 2017–2020 were OBEs, peaked in the summer, and were primarily associated with droughts. Balch et al. (50) claimed that, worldwide over the past 30 years, flammable nights have increased by seven, across all burnable lands, and found that night fires are about 7% more intense, while the vapor pressure deficit has increased by 25%. For the western United States, they estimated an 11-day increase over the same period. There is little doubt that there has been an acceleration of OBEs.

Figure 2 depicts megafires between 2012 and 2022 in Europe, Canada, and the United States, compiled out of three different datasets. The European Forest Fire Information System is operated by the European Commission Joint Research Center. Burned areas are estimated from satellite imagery, and information was available until 2023. Natural Resources Canada maintains the Canadian Wildland Fire Information System, based on a compilation of information provided by Canadian fire management agencies including provinces, territories, and Parks Canada. At the time of this writing, data was available only until 2021. In the United States, the National Interagency Fire Center Open Data Site provides a wealth of wildfire-related geospatial information. This dataset includes wildland fires reported to the Integrated Reporting of Wildland Fire Information incident service until 2023.

One conclusion from the map in Figure 2 is the lack of a unified system for reporting wildfires around the world. Wildfire data collection around the world is a highly localized endeavor. Data collection techniques vary widely, from the compilation of reports from fire services to highly sophisticated uses of satellite imagery. Although most G20 countries publish quasi-regularly annual wildfire statistics in their official languages, data on individual fires is generally scarce. To make matters worse, there is hardly any consistency in either content or the granularity of the information reported across countries.

Finally, although the short- and long-term effects of wildfires on forests vary with the ability of tree species to regenerate after fires, both the size and costs of wildland fire suppression operations are growing. The increase in cost is partially driven by the high cost of protecting property in the WUI, and urbanization will drive costs even higher. Wildfire suppression costs in the United States have increased fourfold from 1985 to 2016 (21).

Discussion and recommendations: Improving wildfire risk reduction efforts

Wading into uncharted waters, governments have mobilized funding for improving suppression capabilities, with aerial firefighting absorbing the lion's share. Improvements in preparedness tend to follow particularly destructive fires or very active fire seasons. For example, following an increase in wildfire incidence across EU countries, the European Commission established "rescEU", for procuring fixed and rotary wing firefighting aircraft, to create a last-resort capability buffer. Thus, rescEU's aerial

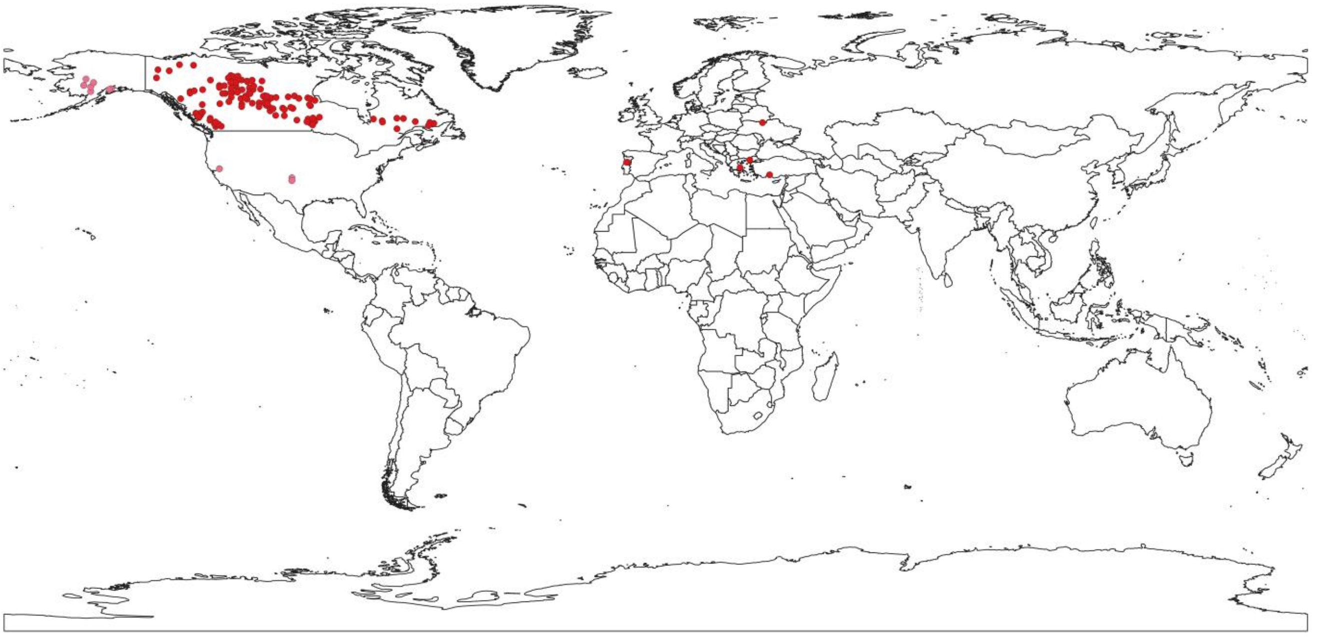

Figure 2. Megafires in Europe (63), Canada (64) and the United States (65) between 2012 and 2022.

firefighting fleet was doubled in 2023, reaching 28 aircraft in 2023, with 12 additional aircraft on order (66, 67).

Greece has relied on a combined aerial firefighting fleet of nationally owned and leased aircraft. The country found itself in a double predicament, facing increasingly devastating fire seasons, just as it was getting out of a deep financial crisis, which had essentially prevented the acquisition of expensive assets. It has been progressively leasing more firefighting helicopters and airplanes. Following a series of devastating fire seasons, in 2020, the government announced “Aegis”, a behemoth two-billion-euro program, a third of which will serve to essentially double the country’s aerial fighting fleet. In 2022, the Hellenic Fire Service also instituted helitack crews, that is, teams of firefighters transported by helicopter to poorly accessible wildfire flare ups.

France faced a particularly active season in 2022. The total burnt area was 72,000 hectares, or almost five times that of 2021 and about three times that of 2017. Preparing for 2023, it added nine additional fixed and rotary wing aircraft to its 38. It also increased the number of wildland fire-engine strike teams from 44 in 2022 to 51 in 2023 (68). According to the US Congressional Budget Office (69), the federal government spent $17.5 billion on wildfire suppression and disaster assistance between 2016 and 2020. In California, following expanding fire seasons and a series of devastating fires, the Department of Forestry and Fire Protection recently acquired 12 new firefighting helicopters and is planning to add seven air tankers to its fleet (70).

On the other hand, wildfire mitigation and prevention have traditionally received less attention and funding. For instance, the Greek Forest Service had been understaffed, and activities poorly coordinated and underfunded, for decades (71). Feo et al. (72) noted a “long history of underinvestment in prevention and mitigation” in California. These are examples of how voters often reward politicians for delivering disaster relief, but not for investing in preparedness, and even less so for mitigation and adaptation, hence governments underinvest (73).

Moritz et al. (19) have argued that “cultural and institutional systems affect public response to wildfire, as do psychological and social dynamics”. While true overall, the death toll in recent WUI fires suggests the public is inching towards favoring evacuation. Recent research suggests that public education can motivate voter support in favor of mitigation and preparedness (74). Anecdotal wildfire policy examples suggest that climate change education in the last few years may have helped to sway public opinion in favor of wildfire mitigation. For instance, in preparation for the 2022 fire season, the Greek government spent 72 million euros, equivalent to the cost of two medium-sized firefighting airplanes, in two nationwide wildfire hazard mitigation programs, involving (i) fuel reduction and clearing and (ii) forest thinning; such an investment was unthinkable five years earlier. It also reorganized the Forest Service to improve coordination and funding. In 2020 and 2021, the State of California appropriated $2.7 billion over a four-year period to wildfire prevention and mitigation, a number which dwarfs the Federal Government’s $4 billion through the Infrastructure Investment and Jobs Act and the Inflation Reduction Act (75).

With rising fire activity brought on by climate change and human development, and increased exposure of people and property in WUI areas, it is unlikely that today’s suppression-focused paradigm will remain sustainable, possibly not even in the near future. Here, we present a new paradigm in wildfire risk management that goes beyond suppression and even mitigation, by integrating science-based land management.

First, in light of the projected increase in fire activity and decades of unmitigated biomass accumulation in forests around the world, maintaining adequate fire suppression capabilities, even through mutual aid agreements, may no longer be a fiscally responsible option. On the other hand, the cost-to-benefit ratios of wildfire hazard mitigation measures, including retrofitting buildings to meet or exceed building code standards, range from ¼ to ½ (76). Communities should consider mitigation strategies that have worked for other hazards, such as insurance and drastically limiting development in the WUI. Fuel treatment strategies, such as prescribed burning, fuel reduction and clearing, and forest thinning, have all shown potential in mitigating wildland fire risk (2, 77). In addition, retrofitting properties in the WUI to resist fire hazards has paid off time and again (78). For instance, a photograph of a 100-year-old wooden house in Lahaina became viral in the aftermath of the August 8 fire, as it was left unscathed while surrounded by piles of charred debris (Figure 3). It was later revealed that the owners had retrofitted the home to mitigate wildfire risk. Furthermore, learning from indigenous fire stewardship practices can help mitigate wildfires and increase biodiversity (79).

Nevertheless, even with increased investment, implementing hazard mitigation strategies and developing additional capabilities will take time. Therefore, improving wildfire response is still needed. Given resource constraints, communities will likely have to prioritize the development of both suppression and mitigation capabilities by accounting for the effects of climate change on forest ecosystems. Multi-year, integrated wildfire risk management plans extending beyond electoral cycles can help reduce the sensitivity of risk management to shifting political short-term priorities and ensure sustainable strategies. Governments need to avoid the established pitfalls of short-sighted, political decision-making and policy choices shaped by what just happened instead of planning for future expectations (80).

Second, the growing number of megafires indicates that land management strategies need to account for the impact of climate change on forest ecosystems, as well as local effects, such as the rate at which biomass re-accumulates. Governments need to work closer with the forest products industry to integrate land management and wildfire risk management policies. Heterogeneity in vegetation type, age, and structure can help ecosystem resilience to climate change and reduction of biodiversity loss. Fire hazard mitigation measures can be adapted to deliver the needed heterogeneity, for example, by diversifying the conditions of prescribed burns (19). Moreover, novel uses of wood products and creating markets for excess biomass and smallwood removal and utilization can create local economic development opportunities, while increasing the ecosystem's resilience to wildfires. Several funding mechanisms are now being considered to support appropriate public/private partnerships. Examples include green bonds and more complex schemes, such as partial subsidization of economic opportunities, contingent on the implementation of wildfire mitigation or post-wildfire restoration measures, including landslide and flood mitigation.

Third, in terms of crisis management, a fundamental shift is needed from a mindset of fire suppression to one of emergency response. The increased exposure of people reinforces the need for community-based evacuation planning. Evacuation plans identify transportation routes and ways to increase evacuation throughput (such as contraflow), transportation modes, including mass transit, and shelter locations, so that emergency managers know how little time they have to issue evacuation orders. It is thus clear that public alert and warning systems are becoming an increasingly critical link in the process. These systems provide emergency information to the public, and save lives when disasters are about to strike. Early disaster research (81, 82) highlighted that to be effective warning messages need to be received from multiple communication pathways and issued from credible sources. Modern public alert and warning systems enable emergency management agencies to disseminate information through multiple pathways, including mobile and landline phones, radio, television, highway variable-message signs and others. The combination of evacuation plans, public education before disaster strikes, and public alert and warning systems can create a powerful defense against wildland fires and can reduce the loss of life.

Because of the inherent complexity in combining all those technologies, these systems should be tested to the limit of their abilities at regular intervals. In addition to the obvious maintenance benefit, these tests are opportunities for informing the public about the capabilities of alert and warning systems, as well teaching individual and family self-protection in disasters. In the United States, nationwide tests of the Emergency Alert System (which is based on radio and television, cable systems, and satellite radio and television) and the Wireless Emergency Alert (WEA) system, (which delivers alerts from cellular towers to mobile devices using a one-to-many technology called Cell Broadcast (CB)), they have been required no less than every three years since 2015. Nonetheless, the third nationwide test on October 4, 2023 (Figure 4, left), which came after the Maui catastrophe (83), was treated by the major news media everywhere as if it was the first ever. In one way it was, because people paid attention to it and could not have opted out, as was the case with the second test message. For the record, the first test was conducted on October 3, 2018, using the Presidential Alert classification and the second on August 11, 2021, using the State/Local WEA Test classification, which requires users to opt in to receive the test alert.

As of December 2018, and likely following the realization that lives could have been saved in the Mati fires earlier that year had there been warnings, European Union countries have been legally required to put in place public alert and warning systems using location-based SMS, or similar technologies, no later than June 2022. However, there are no testing requirements. Although such systems were already used in several European countries before that deadline, Greece was one of the first countries to use Cell Broadcast for wildfire evacuations. Tests are not legally required in Greece as in the United States, but its first nationwide alert was sent on March 11, 2020 (Figure 4, right), in response to mounting cases of COVID-19, and served as a demonstration of the capability.

Warning and evacuation processes also need to account for populations with access and functional needs. Effective systems can alert populations with disabilities or other special needs, include those with limited proficiency in the main language(s) used in alert and warning messages and, ultimately, anyone who may have difficulties obtaining alert and warning SMS and information.

A combination of forward and reverse planning is required to prepare such plans (84, 85). Forward planning builds the evacuation process by describing potential decisions and actions sequentially. Plans should address both agent-generated demands (for example, transportation and shelter) and response-generated demands (for example, information management and logistics). Then, reverse planning determines the time required to complete each task, given the resources that can realistically be made available. Working backwards and using time estimates and task dependencies, emergency managers can identify the times required to complete evacuations once the decision is made. The combination of forward and reverse planning informs the development of time or land-benchmark triggers for evacuation decision-making. For example, there will be evacuations regardless of conditions, if a fire reaches a particular critical location, or if there is less than x minutes for the fire to spread from its point of ignition to the nearest shoreline.

Fundamentally, hard as it may be in practice, evacuations need to be completed before the flame front spreads close enough to populated areas. Fire smoke may cause serious injury to sensitive individuals; this needs to be accounted for as well. Evacuation modeling is necessary to inform evacuation planning and decision-making. It can provide estimates of the time needed to evacuate areas threatened by wildfires, as well as pedestrian

Figure 3. Red-roofed Lahaina home left unscathed by the August 8 fire (Source: Getty Images).

and vehicle traffic flow rates, in different scenarios and allows analysis of different courses of action (86, 87). As was done post-facto in Mati (88, 89), combined with wildfire spread simulation, evacuation modeling can be a powerful tool in setting triggers for evacuation decision-making (90). Stefanakis et al. (91) used an AI statistical model of a tsunami "experiment" constantly updated as new results arrived, then future query points were selected according to the objectives, until achieved. In this manner, they identified worst-case scenarios that were previously only obvious with 100% hindsight. Such active experimental design and machine learning algorithms can reduce the exceptionally large number of numerical simulations needed to identify time-optimal escape routes in advance, particularly in the presence of projectiles (embers), which change the spread dynamics. Evacuation modeling is also a powerful tool in public outreach, as people at risk can expect how much time they really have. Coupled with avatars, people can visualize themselves evacuating, at different speeds, temperatures, and visibilities. Such an approach could become the gold standard for planning evacuations and educating people.

Fourth, science and technology can be leveraged to improve strategic, operational, and tactical emergency planning. Evaluating variables, such as meteorological conditions, fire danger, fire location, time of day, and fire size at the time of dispatch are now increasingly used in setting dispatch levels and resource estimates, along with lessons learned from previous fires and institutional memory. Machine learning, again, can streamline these processes. For example, Lam et al. (92) show how it can best medium-range numerical weather predictions (NWP) forecasts very quickly. Introducing AI fire prediction operationally remains vexing, given the varied locations, diverse data, and one-of-a-kind fires, even in a single locale.

Even when such timely predictions materialize, resource management should become more dynamic and anticipatory through the employment of other tools. For instance, mutual aid agreements can be activated preemptively based on risk estimates. In 2023, Greece activated the EU Civil Protection Mechanism (the European equivalent to the Emergency Management Assistance Compact in the United States) to preposition fire engines and hand crews from other countries in high-risk areas, during the hottest and driest summer months. The Hellenic Fire Service hires seasonal firefighters every year, aiming to increase its force by 10% during the "hot" season (8). These actions are particularly useful in islands, which present additional tactical challenges, not the least of which is related to their insularity and limited options for evacuation. Emergency management worldwide needs to consider the option of evacuating to beaches, which has made fires on Greek islands far less deadly than the mainland.

Earlier, we discussed how advances in forestry and biology can support integrated management of wildfire risk, how cutting-edge communications systems enable alert and warning messages to reach millions of people in seconds, and how evacuation modeling can support emergency planning and rapid decision-making.

Satellite images are a staple in many crisis management centers. Landsat has been around for decades, but the time windows between images do not allow for effective proactive modeling. Algorithms convert observations of the Earth's surface in the visible and infrared domains from meteorological and other satellites into measurements of fire hot spots and assessments of wildfire impacts in near real-time (93–95). Recently, advances in

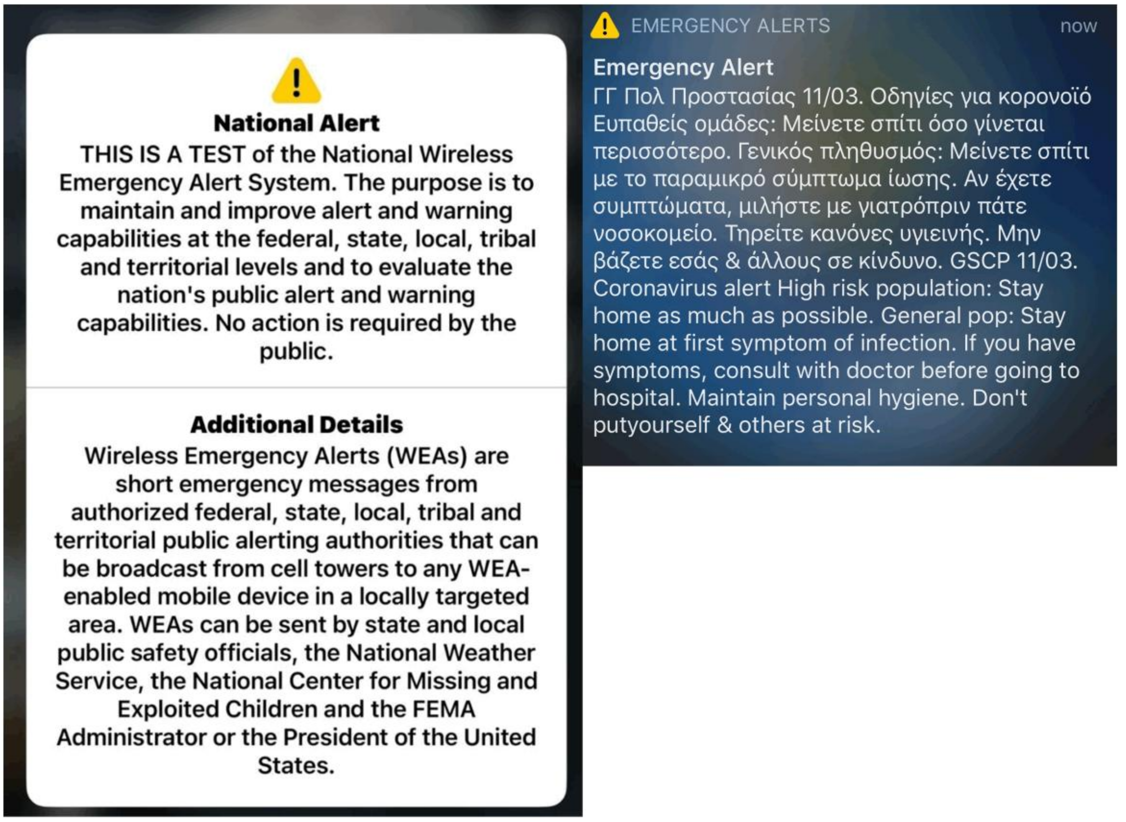

Figure 4. Screenshots of the 2023 nationwide WEA test in the United States (left) and the first nationwide Cell Broadcast message ever in Greece, in 2020 (right). An estimated 300 national messages have followed since then this 11 March 2020 first CB message.

earth observation have allowed scientists, at least in Europe and North America, to track wildfires and even calculate fire spread, every twelve hours, based on satellite imagery (96). NASA's Fire Events Data Suite is claimed to provide more frequent monitoring of fire activity, growth, and behavior than has ever been available (59). In a significant breakthrough, private operating satellite constellations now claim they are able to provide end users with predictions of the spread of wildfires and floods, informed through data assimilation, as images become available from successive satellite passes. In one example, a satellite constellation of Portugal and Spain, possibly to be augmented by Greek satellites, beginning (it's been claimed) in 2024, will provide high resolution synthetic aperture radar (SAR) images about every four hours. The consortium will also provide estimates of the projected evolution of the fire perimeter, until the next set of images becomes available. When augmented by thermal imaging and comprehensive vegetation spatial distributions, the evolution predictions can improve further and can become game changers in megafire suppression. Once such analyses become standard, AI fire modeling could become routine, given that there will be uniform image datasets associated with specific weather parameters to mine from.

Moreover, artificial intelligence is already in use to streamline real-time or near real-time detection of wildfires in poorly accessible areas (97, 98). State-of-the-art robots provide situational awareness, and autonomous systems operating closer to the fireline are under development for improving information management (99). The integration of satellite imagery with feeds from other sources, such as thermal, surveillance and traffic cameras and weather stations, they can vastly accelerate information management in the Emergency Operations Centers of the next decade.

Conclusion

Climate change, increased development in the WUI, and a long history of emphasis on fire suppression over hazard mitigation has increased wildfire risk worldwide. Governments are exploring the issue, but spending is mostly geared toward fire suppression. Here, we propose a long-term approach, incorporating wildfire risk management in wider-scope forest land management policies and strategies. The latter need to account for the impact of climate change and hazard mitigation on forest ecosystems. Improving suppression capabilities is like performing CPR on a cardiac arrest patient: it buys needed time until a more sustainable strategy takes effect, but will not, in and by itself, suffice for longevity. A renewed focus and increased spending on hazard mitigation and fire prevention is also required to stem the impact of megafires threatening human settlements and ecosystems in the WUI. Furthermore, a fundamental shift is needed from a mindset of fire suppression to one of emergency response. Evacuation planning supported by public alert and warning capabilities always saves lives, and more so with prior planning. Last, we urge the wildland fire community to invest in the uptake of scientific breakthroughs and new technologies, including machine learning and earth observation, to help improve decision-making and, ultimately, save more lives. Until then, in at-risk WUI areas, everyone needs to understand that a threatening wildfire could happen anytime from spring to fall and that they may need to leave immediately.

Funding

The authors declare no funding.

Author Contributions

Both authors designed and performed research, analyzed the data, and wrote the paper.

Data Availability Statement

The following data were used in the preparation of this manuscript:

1. [dataset] CRED/UCLouvain, n.d., "EM-DAT". Brussels, Belgium: University of Louvain. www.emdat.be.
2. [dataset] European Forest Fire Information System (EFFIS), n.d., "Burnt Areas database". European Commission. [accessed 2023 Nov 12]. https://forest-fire.emergency.copernicus.eu/apps/effis.statistics/estimates.
3. [dataset] Natural Resources Canada (NRC), n.d., "National Fire Database fire point data". [accessed 2023 Nov 12]. https://cwfis.cfs.nrcan.gc.ca/datamart/download/nfdbpnt.
4. [dataset] National Interagency Fire Center (NIFC), n.d., "Wildland Fire Incident Locations". [accessed 2023 Nov 12]. https://data-nifc.opendata.arcgis.com/datasets/nifc::wildland-fire-incident-locations/explore.

All of the data listed above are publicly available to download at no charge by the respective organizations.

References

1 Lu M, Ikejiri T, Lu Y-H. 2021. A synthesis of the Devonian wildfire record: implications for paleogeography, fossil flora, and paleoclimate. *Palaeogeo Palaeoclimat Palaeoeco* 571(1):110321. https://doi.org/10.1016/j.palaeo.2021.110321

2 Bowman DMJS, *et al.* 2011. The human dimension of fire regimes on earth. *J Biogeogr*. 38:2223–2236.

3 van Wagtendonk JW. 2007. The history and evolution of wildland fire use. *Fire Ecol*. 3:3–17.

4 Associated Press. 2024. The death toll from Chile's wildfires reaches 131, and more than 300 people are missing. [accessed 2024 Feb]. https://apnews.com/article/chile-deadly-wildfires-valparaiso-d40a40ed31d14d7901080f0d700d2afa.

5 Akbarzai S, Paddison L. 2024. Wildfires that are turning neighborhoods to ash are likely Chile's deadliest on record, UN agency says. CNN. [accessed 2024 Feb]. https://edition.cnn.com/2024/02/06/climate/chile-wildfires-deadliest-climate-intl/index.html.

6 National Fire Protection Association (NFPA). 2023. Wildland Fires in US History with Ten or More Fatalities. Available at: https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/WUI/Wildland-Fires-in-the-US-history-with-10-or-more-deaths.ashx (August 2023).

7 Synolakis CE. 2023. The Fire in Maui and the Lesson of Greece. Wall Street Journal. Available at: https://www.wsj.com/articles/lahaina-and-the-fires-in-greece-firefighters-natural-disaster-evacuations-maui-emergency-hawaii-fa99f1c0 (August 13, 2023).

8 Synolakis CE, Karagiannis GM. 2023. Why Didn't Hawaii Evacuate Sooner During the Fires?. The New York Times. Available at: https://www.nytimes.com/2023/08/19/opinion/maui-wildfires-hawaii-sirens.html (August 19, 2023).

9 National Academies of Sciences, Engineering, and Medicine (NASEM). 2022. *The chemistry of fires at the wildland-urban interface*. Washington (DC): The National Academies Press.

10 Kollanus V, *et al.* 2017. Mortality due to vegetation fire-originated $PM_{2.5}$ exposure in Europe—assessment for the years 2005 and 2008. *Environ Health Perspect*. 125(1):30–37.

11 Rooney B, *et al.* 2020. Air quality impact of the Northern California camp fire of November 2018. *Atm Chem Phys*. 20(23):14597–14616. https://doi.org/10.5194/acp-20-14597-2020

12 Chen G, *et al.* 2021. Mortality risk attributable to wildfire-related $PM_{2.5}$ pollution: a global time series study in 749 locations. *Lancet Plan Health*. 5(9):E579–E587.

13 Okal EA, Plafker G, Synolakis CE, Borrero JC. 2003. Near-field survey of the 1946 Aleutian tsunami on Unimak and Sanak Islands. *Seism Soc Am Bul*. 93:1226–1234.

14 McEntire DA. 2022. *Disaster response and recovery: strategies and tactics for resilience*. Third Edition. Hoboken (NJ): Wiley.

15 Burgan RE, Fujioka FM, Hirata GH. 1974. A fire danger rating system for Hawaii. *Fire Technol*. 10:275–281.

16 Kantouris C, Gatopoulos D. 2018. Greek fire damages over 2,000 homes, 500 of them gutted. Associated Press. Available at: https://apnews.com/article/fires-forensics-greece-wildfires-international-news-d364517576614fc78022d1993a491aed (July 27, 2018).

17 BBC. 2023. Greece fires in maps and satellite images show extent of damage. Available at: https://www.bbc.com/news/world-europe-66295972 (July 27, 2023).

18 Nellas D. 2023. 2,000 people including tourists evacuated as a wildfire rages on the Greek island of Rhodes. Associated Press. Available at: https://apnews.com/article/fire-rhodes-greece-evacuations-heat-wave-1a9fb0d687ce22c9087bf83ac7973cf1 (July 22, 2023).

19 Moritz MA, *et al.* 2014. Learning to coexist with wildfire. *Nature*. 515:58–66.

20 Krawchuck MA, Moritz MA. 2011. Constraints on global fire activity vary across a resource gradient. *Ecology*. 92(1):121–132.

21 USGCRP. 2018. [Reidmiller DR, *et al.* (eds.)], *Impacts, risks, and adaptation in the United States: fourth national climate assessment*, Volume II. Washington, DC, USA: US Global Change Research Program.

22 Ganteaume A, *et al.* 2013. A review of the main driving factors of forest fire ignition over Europe. *Environ Manage*. 51(3):651–662.

23 Radeloff VC, *et al.* 2023. Rising wildfire risk to houses in the United States especially in grasslands and scrublands. *Science*. 382:702–707.

24 CRED/UCLouvain. 2023. [dataset] n.d., *EM-DAT*. Brussels, Belgium: University of Louvain.

25 Gorte RW, Bracmort K. 2012. *Wildfire protection in the wildland urban interface*. Washington (DC): Congressional Research Service.

26 National Wildfire Coordinating Group (NWCG). 2014. Wildland fire incident management field guide. https://gacc.nifc.gov/swcc/dc/nmadc/dispatch_logistics/dispatch/documents/2014%20Wildland%20Fire%20Incident%20Management%20Field%20Guide.pdf.

27 Lampin-Maillet C, *et al.* 2010. 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(3):732–741.

28 United States Fire Administration (USFA). 2002. Fires in the wildland/urban interface. *US Fire Admin Top Fire Res Ser*. 2(16). https://apps.usfa.fema.gov/downloads/pdf/statistics/v2i16-508.pdf.

29 McLennan J, Ryan B, Bearman C, Toh K. 2019. Should we leave now? Behavioral factors in evacuation under wildfire threat. *Fire Technol*. 55:487–516.

30 Benali A, Aparicio BA, Goncalves A, Oliveira S. 2023. Defining priorities for wildfire mitigation actions at the local scale: insights from a novel risk analysis method applied in Portugal. *Front For Glob Change*. 6:1270210. https://doi.org/10.3389/ffgc.2023.1270210

31 United States Fire Administration (USFA). 2022. Wildland Urban Interface: A Look at Issues and Resolutions. US Fire Administration. [accessed 2024 Apr 27]. https://www.usfa.fema.gov/downloads/pdf/publications/wui-issues-resolutions-report.pdf.
32 Synolakis CE. 2007. Olympic Torching. Wall Street Journal. Available at: https://www.wsj.com/articles/SB118816586120409172 (August 27, 2007).
33 Xanthopoulos G, Viegas DX, Caballero D. 2009. The fatal fire entrapment accident of August 24, 2007, near the village of Artemida, Ilia, Greece. Abstracts from the 10th Wildland Fire Summit, Phoenix, Arizona. [accessed 2024 May 6]. https://www.researchgate.net/profile/Gavriil-Xanthopoulos-2/publication/285541773_The_fatal_fire_entrapment_of_Artemida_Greece_2007/links/56653a2f08ae15e746330760/The-fatal-fire-entrapment-of-Artemida-Greece-2007.pdf.
34 Szeto W. 2022. Bracing for wildfire season, residents of this West Kelowna neighbourhood are asking for more exit routes. CBC. Available at: https://www.cbc.ca/news/canada/british-columbia/west-kelowna-wildfire-glenrosa-road-traffic-congestion-1.6412905 (April 2022).
35 Synolakis C. 2018. Lessons from the Paradise Fire. The Wall Street Journal. Available at: https://www.wsj.com/articles/lessons-from-the-paradise-fire-1542577702 (November 18, 2018).
36 McLennan J, Holgate AM, Omodei MM, Wearing AJ. 2006. Decision making effectiveness in wildfire incident management teams. *J Conting Crisis Manag*. 14(1):27–37.
37 Hand M, Katuwal H, Calkin DE, Thompson MP. 2017. The influence of incident management teams on the deployment of wildfire suppression resources. *Int J Wild Fire*. 26(7):615–629.
38 Thompson MP. 2013. Modeling wildfire incident complexity dynamics. *PLoS One*. 8(5):e63297. https://doi.org/10.1371/journal.pone.0063297
39 Thomspon MP. 2014. Social, institutional, and psychological factors affecting wildfire incident decision making. *Soc Nat Resourc*. 27(6):636–644.
40 Pescaroli G, Alexander D. 2018. Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. *Risk Anal*. 38(11):2245–2257.
41 Pescaroli G, *et al.* 2023. Managing systemic risk in emergency management, organizational resilience and climate change adaptation. *Disast Prev Manag*. 32(1):234–251.
42 Mitchell JW. 2013. Power line failures and catastrophic wildfires under extreme weather conditions. *Eng Fail Anal*. 35:726–735.
43 Alexander D. 2000. *Confronting catastrophe: new perspectives on natural disasters*. Hertfordshire, UK: Terra Publishing.
44 Kern H, Krausmann E. 2020. *Wildfires triggering natech events*. Luxembourg: Publications Office of the European Union.
45 Bowman DMJS, *et al.* 2009. Fire in the earth system. *Science*. 324(5926):481–484.
46 Flannigan M, *et al.* 2013. Global wildland fire season severity in the 21st century. *For Ecol Manag*. 294:54–61. https://doi.org/10.1016/j.foreco.2012.10.022
47 Intergovernmental Panel on Climate Change (IPCC). 2022. *Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge, UK and New York, NY, USA: Cambridge University Press.
48 Zhuang Y, Fu R, Santer BD, Dickinson RE, Hall A. 2021. Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States. *Proc Natl Acad Sci U S A*. 118(45):e2111875118. https://doi.org/10.1073/pnas.2111875118
49 Barbero R, Abatzoglou JT, Larkin NK, Kolden CA, Stocks B. 2015. Climate change presents increased potential for very large fires in the contiguous United States. *Int J Wild Fire*. 24:892–899.
50 Balch JK, *et al.* 2022. Warming weakens the night-time barrier to global fire. *Nature*. 602:442–448. https://doi.org/10.1038/s41586-021-04325-1
51 Yue X, Mickley LJ, Logan JA. 2014. Projection of wildfire activity in southern California in the mid-twenty-first century. *Clim Dyn*. 43:1973–1991.
52 Litschert SE, Brown TC, Theobald DM. 2012. Historic and future extent of wildfires in the Southern Rockies Ecoregion, USA. *For Ecol & Man*. 269:124–133.
53 Prestemon JP, *et al.* 2016. Projecting wildfire area burned in the south-eastern United States, 2011–60. *Int J Wild Fire*. 25:715–729.
54 San Miguel J, *et al.* 2017. Climatological risk: wildfires. In: Poljanšek K, Marín Ferrer M, De Groeve T, Clark I, editors. *Science for disaster risk management 2017: knowing better and losing less*. Luxembourg: Publications Office of the European Union.
55 Dowdy AJ, *et al.* 2019. Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Sci Rep*. 9:10073.
56 Costa H, de Rigo D, Libertà G, Houston Durrant T, San-Miguel-Ayanz J. 2020. *European Wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions*. Luxembourg: Publications Office of the European Union.
57 Belcher CM, *et al.* 2021. *UK Wildfires and their climate challenges*. Exeter, UK: University of Exeter Global Systems Institute.
58 Horton H. 2022. Summer wildfires increased fourfold in England in 2022. The Guardian. Available at: https://www.theguardian.com/world/2022/dec/30/summer-wildfires-increased-fourfold-in-england-in-2022 (December 30, 2022).
59 National Aeronautical and Space Agency (NASA). 2023. Tracking Canada's Extreme 2023 Fire Season. Available at: https://earthobservatory.nasa.gov/images/151985/tracking-canadas-extreme-2023-fire-season (July 23, 2023).
60 Abatzoglou JT, Cohen CA. 2013. Relationships between climate and macroscale area burned in the western United States. *Int J Wild Fire*. 22:1003–1020.
61 Donovan VM, Wonkka CL, Twidwell D. 2017. Surging wildfire activity in a grassland biome. *Geoph Res Let*. 44:5986–5993.
62 Luo K, Wang X, de Jong M, Flannigan M. 2024. Drought triggers and sustains overnight fires in North America. *Nature*. 627:321–327. https://doi.org/10.1038/s41586-024-07028-5
63 [dataset] European Forest Fire Information System (EFFIS). n.d., Burnt Areas database. European Commission. [accessed 2023 Nov 12]. https://forest-fire.emergency.copernicus.eu/apps/effis.statistics/estimates.
64 [dataset] Natural Resources Canada (NRC), n.d. National Fire Database fire point data. Available at https://cwfis.cfs.nrcan.gc.ca/datamart/download/nfdbpnt (accessed November 12, 2023).
65 [dataset] National Interagency Fire Center (NIFC), n.d. Wildland Fire Incident Locations. Available at: https://data-nifc.opendata.arcgis.com/datasets/nifc::wildland-fire-incident-locations/explore (accessed November 12, 2023).
66 Abnett K. 2023. EU plans to buy new firefighting planes as climate crises worsen, Reuters. Available at: https://www.reuters.com/world/europe/eu-plans-buy-new-firefighting-planes-climate-crises-worsen-2023-07-26/ (July 26, 2023).
67 Tennant C. 2023. Will the EU's €720 million gamble on firefighting planes pay off?, Euronews. Available at: https://www.

euronews.com/my-europe/2023/09/17/will-the-eus-720-million-gamble-on-firefighting-planes-pay-off (September 17, 2023).

68 Ministère de l'Intérieur et des Outre-mer (MIOM), Ministère de la Transition écologique et de la Cohésion des territoires, Ministère de l'Agriculture et de la Souveraineté alimentaire, "Lutte contre les feux de forêt: protéger les populations, les biens et l'environnement—Dossier de presse 2023". Available at: https://agriculture.gouv.fr/telecharger/136293 (April 11, 2023).

69 US Congressional Budget Office (CBO). 2022. Wildfires. [accessed 2022 Jun]. https://www.cbo.gov/system/files/2022-06/57970-Wildfires.pdf.

70 California Department of Forestry and Fire Protection (CALFIRE), Aviation Program. Available at: https://www.fire.ca.gov/what-we-do/fire-protection/aviation-program (Accessed October 2023).

71 Pandey P, *et al.* 2023. A global outlook on increasing wildfire risk: current policy situation and future pathways. *Tr For Peo*. 14:100431.

72 Feo TJ, Mace AJ, Brady SE, Lindsey B. 2020. *The costs of wildfire in California—an independent review of scientific and technical information*. Sacramento (CA): California Council on Science and Technology.

73 Healy A, Malhotra N. 2009. Myopic voters and natural disaster policy. *Am Pol Sci Rev*. 103(3):387–406.

74 Anderson SE, DeLeo R, Taylor K. 2023. Legislators do not harness voter support for disaster preparedness. *Risk Haz Cris in Pub Pol*. 14(1):68–88.

75 Foard C, *et al.* 2022. Wildfires: Burning Through State Budgets. The Pew Charitable Trusts. Available at: https://www.pewtrusts.org/-/media/assets/2022/11/wildfires-burning-through-state-budgets.pdf (November 2022).

76 Porter K, *et al.* 2019. *Natural hazard mitigation saves: 2019 report*. Washington (DC): National Institute of Building Sciences.

77 United States Forest Service (USFS). Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests. Available at: https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Confronting-the-Wildfire-Crisis.pdf (January 2022).

78 Penman TD, *et al.* 2017. Retrofitting for wildfire resilience: what is the cost? *Int J Dis Risk Red*. 21:1–10.

79 Hoffman KM, *et al.* 2021. Conservation of Earth's biodiversity is embedded in indigenous fire stewardship. *Proc Natl Acad Sci U S A*. 118(32):e2105073118. https://doi.org/10.1073/pnas.2105073118

80 Mulligan TD, Taylor K, DeLeo RA. 2019. Politics and policies for managing natural hazards. *Oxf Res Enc on Nat Haz Sci*. https://doi.org/10.1093/acrefore/9780199389407.013.314

81 Mileti DS, Sorensen J. 1990. *Communication of emergency public warning: A social science perspective and state-of-the-art assessment*. Oak Ridge (TN): Oak Ridge National Laboratory.

82 Quarantelli EL. 1990. *The warning process and evacuation behavior: the research evidence*. Newark (DE): Disaster Research Center, University of Delaware.

83 Carballo R. 2023. Nationwide Alert Reaches Cellphones, TVs and Radios. The New York Times. Available at: https://www.nytimes.com/2023/08/30/us/test-alert-us-october.html (October 4, 2023).

84 Karagiannis GM, Synolakis CE. 2017. Twenty challenges in incident planning. *J Hom Sec Emer Man*. 14(2):20160061. https://doi.org/10.1515/jhsem-2016-0061

85 Federal Emergency Management Agency (FEMA). 2010. *Developing and maintaining emergency operations plans—comprehensive preparedness guide (CPG) 101—version 2.0*. Washington (DC): US Department of Homeland Security.

86 Zhao B, Wong SD. 2021. Developing transportation response strategies for wildfire evacuations via an empirically supported traffic simulation of Berkeley, California. *Trans Res Rec*. 2675(12):557–582.

87 Pishahang M, Ruiz-Tagle A, Lopez Droguett E, Ramos M, Mosleh A. 2024. WISE: A Probabilistic Wildfire Safe Egress Planning Framework and Software Platform. Probabilistic Safety Assessment and Management PSAM 16, Honolulu, HI. Available at: https://www.iapsam.org/PSAM16/papers/ALL-PSAM16-PAPERS.zip (April 3, 2024).

88 Synolakis C. 2018. The deadly fire of July 23rd at Mati: Fire and evacuation modeling [Greek]. Available at: https://www.youtube.com/watch?v=CTPUEyNh7-0 (September 2018).

89 Synolakis C, Karagiannis G. 2023. Heatwaves and wildfires: How Greece is handling the double whammy. eKathimerini. Available at: https://www.ekathimerini.com/opinion/1216624/heatwaves-and-wildfires-how-greece-is-handling-the-double-whammy/ (July 30, 2023).

90 Li D, Cova TJ, Dennison PE. 2018. Setting wildfire evacuation triggers by coupling fire and traffic simulation models: a spatio-temporal GIS approach. *Fire Tech*. 55:617–642 https://doi.org/10.1007/s10694-018-0771-6

91 Stefanakis TS, Contal E, Vayatis N, Dias F, Synolakis CE. 2014. Can small islands protect nearby coasts from tsunamis? An active experimental design approach. *Proc R Soc A*. 470:20140575. https://doi.org/10.1098/rspa.2014.0575

92 Lam R, *et al.* 2023. Learning skillful medium-range global weather forecasting. *Science*. 382:1416–1421 https://doi.org/10.1126/science.adi2336

93 Jiao L, Bo Y. 2022. Near real-time mapping of burned area by synergizing multiple satellites remote-sensing data. *GISci Rem Sens*. 59(1):1956–1977. https://doi.org/10.1080/15481603.2022.2143690

94 Thangavel K, Spiller D, Sabatini R, Marzocca P, Esposito M. 2023. Near real-time wildfire management using distributed satellite system. *IEEE Geosci Rem Sens Lett*. 20:5500705. https://doi.org/10.1109/LGRS.2022.3229173

95 Andela N, *et al.* 2022. Tracking and classifying Amazon fire events in near real time. *Sci Adv*. 8(30):eabd2713. https://doi.org/10.1126/sciadv.abd2713

96 Chen Y, *et al.* 2022. California wildfire spread derived using VIIRS satellite observations and an object-based tracking system. *Sci Rep*. 9:249.

97 Fuller T. 2023. Can AI detect wildfires faster than humans? California is trying to find out. The New York Times. Available at: https://www.nytimes.com/2023/08/24/us/wildfires-ai-detection-california.html (August 24, 2023).

98 Ban Y, Zhang P, Nascetti A, Bevington AR, Wulder MA. 2020. Near real-time wildfire progression monitoring with sentinel-1 SAR time series and deep learning. *Sci Rep*. 10:1322. https://doi.org/10.1038/s41598-019-56967-x

99 Colajanni G, Daniele P, Nagurney A, Nagurney L, Sciacca D. 2023. A three-stage stochastic optimization model integrating 5G technology and UAVs for disaster management. *J Glob Optimiz*. 86:741–780. doi: 0.1007/s10898-023-01274-z