Chapter

Physical Vulnerabilities from Wildfires: Flames, Floods, and Debris Flows

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Abstract

Humans live in or adjacent to wildland ecosystems that burn periodically and are part of nearly all ecosystems that are in the pyrosphere. There are many hazards posed by wildfire and certain consequences of living in these ecosystems. Most are associated with wildfire, but the increased use of prescribed fire is an issue because of associated risks with human attempts to manage ecological goals. The hazards posed by wildfire involve cultural and economic loss, social disruption, infrastructure damage, human injury and mortality, damage to natural resources, and deterioration in air quality. The economic and human health and safety costs are on the rise due to increasing wildland-urban interface problems and extreme wildfire behavior brought on by climate change. In the past, urban fires have been the greatest threat to human health and safety killing over 100,000 people. World ecosystems have been modified extensively by fire. We live on a "fire planet." With larger human populations and a changing, drying climate, the impact of fire on humans and the hazards faced by our natural and developed world will continue to increase. The increase in wildfire hazards in the twenty-first century will require higher levels of training, increased investments in wildfire personnel and infrastructure, greater wildfire awareness, and improved planning to reduce fire impacts.

Keywords: wildfires, floods, debris flows, hydrologic impacts

1. Introduction

Fire is a dynamic process, predictable but uncertain, that varies over time and landscape space. It has shaped plant communities for as long as vegetation and lightning have existed on earth [1, 2]. Wildland fire covers a spectrum from low-severity, localized prescribed fires, to landscape-level high-severity wildfires. Earth is a fire planet whose terrestrial ecosystems have been modified and impacted by fire since the Carboniferous Period, some 300–350 million years before the present time. In the Holocene Epoch of the past 10,000 years, humans have played a major role in fire spread across the planet. In the present Anthropocene Epoch (11,700 years before the present to the current date) of the twenty-first century, climate change, as well as the burgeoning human population, is now poised to increase the ecosystem hazards of wildland, rangeland, and cropland fire [3, 4].

Fire plays an important function in ecosystem processes [5]. Recycling of carbon (C) and nutrients depends on biological decomposition and fire.

Figure 1.
High-severity wildfire, Mt. Carmel Fire, Haifa, Israel, 2017 (photo courtesy of Naama Tessler, University of Haifa).

In regions where decay is constrained either by dry or cold climates or by saturated soil conditions, fire has a dominant role in recycling organic matter and maintaining some vegetation types [3]. In warmer, moist climates, decay plays the dominant role in organic matter recycling [6], except in soils that are predominantly water saturated such as hydric soils. Periodic wildfire has an important function in wildland ecosystems. However, the wildfire trend in the past several decades has raised the risk of short- and long-term damage to natural resources, infrastructure, and human health and safety.

The worldwide threat to humans and natural resources from catastrophic wildfire is greater now than at any other time in human history (**Figure 1**). Changes brought on by global warming, land management, and population expansion have resulted in much larger, more destructive wildfire events [7]. This has given rise to greater loss of life and property as well as the occurrence of postfire hazards including flooding, erosion, desertification, and environmental degradation [5, 8]. This chapter will look at the physical hazards and effects of wildfire both during and after conflagrations in wildland ecosystems.

2. Wildfire hazards

The hazards produced by wildfires affect both the biotic and abiotic components of ecosystems. They occur during active fire as well as afterwards. While the destruction produced by combustion is spectacular, the effects after burning has ceased can be subtle or dramatic and often long lasting [3, 5]. Hazards and deleterious effects produced by wildfires during the active combustion phase include vegetation combustion, loss of human and animal life, air quality deterioration, human health deterioration, destruction of personal property, loss of commercial property, and infrastructure damage and destruction. After a wildfire is extinguished, hazards and risks arise from potential flooding, erosion, debris flows, and infrastructure damage. Water supplies and infrastructure, if not damaged during the active fire period, can be at risk during subsequent postfire flood events. Economic losses accrue from declines in tourism, loss of timber and wood fiber resources, and declines in property values. Ecological impacts not assessed by traditional economic valuations include vegetation type conversion, aquatic species loss, decreased water quality, increased stream temperatures, and reduced soil quality. All of these changes are hazards in that they reduce the values and services of ecosystems or threaten human health and safety.

3. Hazards during active fire

3.1 Fire trends

The trend of a growing occurrence of fire around the world brings with it many of the consequences both direct and indirect [9]. This analysis indicated that the future for potential wildfire increases significantly in fire-prone regions of North America, South America, central Asia, southern Europe, southern Africa, and Australia [9]. Fire potential is projected to increase in these regions, from currently low to future moderate potential or from moderate to high potential. The increased fire risk is driven by climate warming in North and South America and Australia, and by the combination of temperature increases and desertification in the other regions. The analysis in Ref. [9] indicates that future increases in wildfire trends will require substantial investment of financial resources and management actions for wildfire disaster prevention and recovery.

In a discussion to the contrary [10], the argument is made that there is evidence of reduced fire worldwide today than centuries ago. Regarding fire severity, limited data are available. They indicate evidence of little change in the western USA and declines in the area of high-severity fire compared to eighteenth and nineteenth century conditions. The authors argue that direct fatalities from fire and economic losses also show no clear trends over the past 30 years [10]. Trends in indirect impacts are insufficiently quantified to be examined in any significant degree.

On the other hand, an analysis of large wildfire trends in the western USA reported a significant increase in fire numbers and area burned [11]. This was particularly true in southern mountain regions with drought. The reported increase of wildland fires in these areas has amounted to 355 km^2 $yr.^{-1}$. An analysis of wildfire in Russia demonstrated an acceleration of wildfire in the twenty-first century as a result of climate change [12]. Trends in wildfire on US Forest Service lands from 1970 to 2002 were examined in a 2005 paper in the Journal of Forestry [13]. Authors reported that the number of large fires has more than doubled over this period and the area burned has increased fourfold. The number of fires and area burned by wildfires in eastern Spain from 1941 to 1994 documented increasing fire activity in southern Europe [14]. They reported that even during this time period the areas and numbers of fires were increasing significantly and were associated with high fire hazard indices.

Wildfire appears to be on the increase globally but not uniformly. Drought and elevated temperatures are major factors contributing to wildfires and the hazards they pose to natural ecosystems and humans. Wildfire sizes and severity thus have the potential to present significant hazards to human health and safety and infrastructure in the twenty-first century [5].

3.2 Vegetation impacts

3.2.1 Hazard

The immediate and most obvious hazard of wildfire is the effect on vegetation. Impacts of wildfire on vegetation vary greatly, not only by vegetation type but also by the severity of the fire. Grassland vegetation in general is thought to be fire resilient, burning often and regrowing quickly after a fire event [15]. Some mixed conifer stands on the other hand have historically burned very infrequently and can take centuries to return to a climax state after a severe wildfire event [3]. The overall trend however is that areas that have been prone to burn in the past are now burning more frequently and at higher severity due to climate change [16]. Areas thought to rarely burn such as tropical systems or be incapable of burning such as permafrost are now undergoing changes that result in more frequent occurrences of fire [17, 18].

3.2.2 Fire regime

The general character of fire that occurs within a particular vegetation type or ecosystem across long successional time frames, typically centuries, is defined as the characteristic fire regime [3]. The fire regime describes the typical fire severity that occurs and the hazard it presents to humans and wildlife. But it is recognized that, on occasion, fires of greater or lesser severity also occur within a vegetation type. For example, a stand-replacing crown fire is usually seen in long fire-return-interval forests (**Figure 2**). The fire regime concept is useful for comparing the relative role of fire between ecosystems, describing the degree of departure from historical conditions, and assessing the relative hazards of wildfires [19]. The development of fire regime classifications has been based on fire characteristics, effects, and combinations of factors including fire frequency, periodicity, intensity, size, pattern, season, depth of burn, and severity [15, 20]. There are four main fire regimes: understory, stand replacement, mixed, and nonfire. The understory and nonfire regimes are normally not important for understanding fire hazard.

The stand replacement regime fires are lethal to most of the dominant aboveground vegetation. Approximately 80% or more of the aboveground dominant vegetation is either consumed or dies as a result of fire, substantially changing the aboveground vegetative structure and creating substantial hazards. This regime applies to fire-susceptible forests and woodlands, shrublands, and grasslands.

The mixed regime severity of fires varies between nonlethal understory and lethal stand replacement fires with the variation occurring in space or time. First, spatial variability occurs when fire severity varies, producing a spectrum from understory burning to stand replacement within an individual fire. This results from small-scale changes in the fire environment (fuels, terrain, or weather) and random changes in plume dynamics. Within a single fire, stand replacement can occur with the peak intensity at the head of the fire, while a nonlethal fire occurs on the flanks. These changes create gaps in the canopy and small- to medium-sized

Figure 2.
Stand replacement wildfire, 2002 Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, USA (photo courtesy of Dr. Peter Ffolliott, University of Arizona).

openings. The result is a fine pattern of young, older, and multiple-aged vegetation patches. This type of fire regime commonly occurs in some ecosystems because of fluctuations in the fire environment [3, 21]. For example, complex terrain favors mixed-severity fires because fuel moisture and wind vary on small spatial scales. Secondly, temporal variation in fire severity occurs when individual fires alternate over time between low-intensity surface fires and high-severity stand replacement fires, resulting in a variable fire regime [15, 21]. Temporal variability also occurs when periodic cool-moist climate cycles are followed by warm-dry periods leading to cyclic (in other words, multiple decade-level) changes in the role of fire in ecosystem dynamics and human hazards. For example, in an upland forest, reduced fire occurrence during the cool-moist cycle leads to increased stand density and fuel buildup. Fires that occur during the transition between cool-moist and warm-dry periods can be expected to be more severe and have long-lasting effects on vegetation dynamics [22].

3.2.3 Fire severity

The commonly accepted term for describing the ecological, hydrological, and geological effects of a specific fire is fire severity. This term describes the magnitude of the disturbance and, therefore, reflects the degree of change in ecosystem components. Fire affects both the aboveground and belowground components of ecosystems due to energy pulses aboveground and heat pulse transferred downward into the soil. It reflects the amount of energy (heat) that is released by a fire that ultimately affects natural resources and their functions, and human infrastructure. It reflects the amount of energy (heat) that is released by a fire that ultimately affects resource responses. Fire severity is largely dependent upon the nature of the fuels available for burning, and the characteristics of combustion that occur when these fuels are burned [3, 7].

3.2.4 Fire intensity versus fire severity

Although the literature historically contains confusion between the terms fire intensity and fire severity, a fairly consistent distinction between the two terms has been emerging in recent years. Fire managers trained in fire behavior prediction systems use the term fire intensity in a strict thermodynamic sense to describe the rate of energy released [23]. Fire intensity is concerned mainly with the rate of aboveground fuel consumption and, therefore, the energy release rate [24]. The faster a given quantity of fuel burns, the greater the intensity, the higher the severity, the greater the energy release, and the shorter the duration [25]. Fire intensity is not necessarily related to the total amount of energy produced during the burning process. Most energy released by flaming combustion of aboveground fuels is not transmitted downward. For example, Ref. [26] found that only about 5% of the heat released by a surface fire was transmitted into the ground during Australian bushfires. Therefore, fire intensity is not necessarily a good measure of the amount of energy transmitted downward into the soil, or the associated changes that occur in physical, chemical, and biological properties of the soil. For example, it is possible that a high-intensity and fast-moving crown fire will consume little of the surface litter because only a small amount of the energy released during the combustion of fuels is transferred downward to the litter surface [27]. In this case, the surface litter is blackened (charred) but not consumed. In the extreme, examples have been reported in Australia, Alaska, and North Carolina where fast-spreading crown fires did not even scorch all of the surface fuels [7]. However, if the fire also consumes substantial surface and ground fuels, the residence time on a site is greater, and more energy is transmitted into the soil. In such cases, a "white ash" or "red ash" layer is often the only postfire material left on the soil surface [27] (**Figure 3**). Because one can rarely measure the actual energy release of a fire, the term fire intensity can have limited practical application when evaluating ecosystem responses to fire. Increasingly, the term fire severity is used to describe the effects of fire on the different ecosystem components and human resources [3].

3.3 Loss of life

Fires have been major hazards for humans for many centuries. With the development of large cities, fire became a significant risk to infrastructure and human life. The lack of organized and trained fire-fighting resources was a big factor in some of the more notorious urban fires. Rome burned in A.D. 64 during windy conditions from a fire that escaped from the Circus Maximus [28]. Of the city's 14 districts, only 4 escaped fire damage. Deaths numbered in the thousands. An urban fire in Tokyo in 1657 destroyed 70% of the city and killed 100,000 inhabitants. Moscow burned during the French invasion in 1812 killing 55,000.

Wildfire in forests became a hazard factor in urban fires in the nineteenth century. The Miramichi Fire in Canada in 1825 burned 2 million ha of land and resulted in the death of 160–300 people. It was fueled by drought and spread at a rate of 1.6 km min^{-1}. The real toll was unknown and could be much higher (3000) due to inaccurate accounts of persons in the rural area [29]. Seven towns were severely damaged or destroyed. The Peshtigo Fire of 1871 burned over 250,000 ha of Wisconsin and Michigan [28]. Sixteen communities were destroyed with a loss of 1150 lives.

Although human mortality rates associated with wildfires have declined in the twentieth century, wildfires continue to exact a toll on human lives because of the increase in area burned and the numbers of large fires [13]. Wildfire fatalities from 1910 to 2017 resulted in a cumulative toll of 1128 deaths for the USA [30]. Most fire years had human losses of less than 10 per year (**Table 1**). Of the yearly fatalities over 20 per year, 67% have occurred since 1990. Most wildfire-related deaths are caused by vehicle accidents, airplane crashes, and medical incidents. The exceptions involved fatalities in fire crews (1910, 1933, 1994, 2003, and 2013). Risks and incidents from wildfires that have spread into urban areas have been on the increase in

Figure 3.
Red and white ash deposits on high-severity burn areas after the 2006 Brins Fire, Coconino National Forest, Arizona (photo by Daniel G. Neary, Rocky Mountain Research Station, USDA Forest Service).

Fatality grouping	Number per grouping	Percentage
0	3	1.3
1–4	13	16.7
5–9	18	23.1
10–14	20	25.7
15–19	11	14.1
20–24	7	11.5
>25	6	7.6

Table 1.
USA wildfire-related fatalities per year 1929–2017 by grouping (National Interagency Fire Center 2019).

the twenty-first century due to population expansion into wildland-urban interface areas, increased wildfire area coverage, greater numbers and size of wildfires, and higher fire severity [5]. Consequently, urban fatalities from wildfire incursions into urban areas have increased since 2017.

Australia suffered high human fatalities from the Black Saturday Kilmore East Fire in Victoria in 2009 [31]. Over 450,000 ha of forest and native bush burned in February of 2009 due to drought conditions and gale force winds. Speeds of 46–68 km $hr.^{-1}$ with gusts to 91 km $hr.^{-1}$ from hot air originating in the deserts of central Australia drove fire spreads of 68–153 m min^{-1}. Spot fires developed 5–33 km ahead of the main fire front. The 173 human fatalities occurred mainly among the local rural population due to the rapid fire spread and insufficient time to evacuate the wildfire-threatened areas. At one point, the fires consumed 100,000 ha in <12 hours. Wildfires of this size and severity are extremely hazardous and almost impossible to comprehend.

In 2017, Portugal experienced its most deadly fire season on record losing at least 66 people to catastrophic summer wildfires. The following year, wildfires in Greece damaged over 2000 homes and killed at least 100 people. Although nationally deaths due to wildfires are on the decline, record-breaking wildfires in northern California in 2017–2018 produced substantial increases in deaths, mostly civilians [32]. A total of 8527 fires burned an area of 766,439 ha and resulted in 102 firefighter and civilian deaths.

3.4 Economic losses

In the summer of 2018, the Camp Fire in Northern California burned 62,053 ha and destroyed 18,804 structures including the entire town of Paradise, California. In total, the fire caused $16.5 billion in damages with over a quarter of those damages uninsured [33]. It was the costliest single natural disaster in the world to that point and caused the bankruptcy of a major utility provider, the Pacific Gas and Electric Company, which was held responsible for starting the fire due to faulty equipment.

Unfortunately, it is part of a trend in California, driven mostly by climate change, of increasing destruction and cost of seasonal wildfires. Just the previous year (2017), in December, the Thomas Fire destroyed at least 1063 structures at a cost of $2.2 billion in damages [34] and was preceded by only a couple of months by a complex of fires in the northern part of the state, which destroyed at least 8900 structures and cost in excess of $14.5 billion in damages [35].

Similar trends are being seen around the world. In 2017, Portugal experienced its most deadly and expensive fire season on record due to catastrophic summer wildfires. The 2018 wildfires in Greece suffered through what was considered to be one of the worst fire events in Europe in over a century. Canada set successive records in area burned with 1,216,053 ha 2017 and 1,298,450 ha 2018, losing at least 305 and 50 structures in those respective years [36].

Common factors in these events include months of below-average precipitation followed by untimely ignitions, both natural and anthropogenic and wind events that caused fires to spread in a dramatic fashion. The speed and ferocity with which these fires burned were commonly described as "unheard of" in the past and in many cases completely uncontrollable. The only choice of fire managers at the time was to stand-down and wait for conditions to improve. Unfortunately, this predicament appears to be a hazard becoming more common worldwide.

Fire events, particularly in California, USA, where dense population areas border highly fire-prone wildland areas have seen staggering losses as described above. A study conducted by the U.S. Department of the Interior in 2016 estimated that total "costs," which includes preparedness, mitigation, and suppression, as well as "losses," which includes both direct (e.g., deaths, structure loss, timber loss, etc.) and indirect (e.g., property devaluation, supply chain disruption, evacuation costs, etc.) of wildfire within the USA range from $71.1 to $347.8 billion annually [32]. Estimates like these continue the long debate of who should pay for natural disaster losses in an era of global warming as they become more expensive and what should the future costs be to insure assets in fire-prone areas? These are difficult and complex questions to answer and are made even more urgent in an era where losses seem to be compounded every year.

3.5 Air quality

Another immediate effect of fire is the release of gases and particulate pollutants by the combustion of biomass and soil organic matter. Air quality in large-scale airsheds can be degraded during and following fires [37]. Among the pollutants emitted, the release of fine particulate matter and ozone (O_3) can have particularly deleterious effects on human health, which can be exacerbated when smoke from wildfires affect large population centers. Unfortunately, our understanding of the hazard that large-scale wildfires have on air quality is lacking and current estimates of emissions and impacts may be significantly underestimated [38].

Wildfires can cause both short- and long-term air quality impacts that are usually viewed as negative effects on environmental quality (**Figure 4**). Scientific information about air pollution from wildfires is motivated by government policies to restore the role of fire in ecosystems, to improve air quality, to protect human health, and to minimize emissions of greenhouse gases that are driving climate change [37]. Managing both fire and air quality to the standards set by national and regional governments requires sophisticated scientific knowledge of fire-related air pollution, a delicate management balancing act, and comprehensive educational outreach to both the public and government officials. The three main components of wildland fire and air quality are air resource, scale of impact, and fire management. Air resource includes such factors as smoke source, ambient air quality, and effects on receptors. Scales at which air quality is affected by wildland fires range from site and event to regional and global. Since wildland fire is a pervasive global, regional, and local phenomenon (**Figure 5**), air quality issues and interactions are inter-regional, transnational, and global. Fire management factors that are involved in air quality include planning, operations, and monitoring [39].

National and international air quality standards are set by legislative acts or agency regulations to protect the human population of negative health effects of fire-derived air pollutants [40, 41]. For most of the twentieth century, smoke emissions from prescribed fires were treated as human-caused, while wildfires

Figure 4.
Smoke plume from the Schultz fire, June 2002, Coconino National Forest, Arizona (photo courtesy of USDA Forest Service, Peaks Ranger District, Coconino National Forest).

Figure 5.
Regional air quality impacts from smoke generated by the Wallow Fire, 2011, Arizona, USA (image courtesy of MODIS web, U.S. National Aeronautics and Space Administration).

were considered to be natural [37]. Policy debates have blurred the distinct separation between the two types of fires since some lightening starts are managed as prescribed natural fires for ecosystem restoration and fuel reduction purposes, and some wildfires have human ignition sources and burn in fuel loads made unnaturally high by human activity or the lack of management.

Some of the key pollutants targeted in air quality regulations include PM10 (particulate matter <10 μm in diameter), PM2.5 (particulate matter <2.5 μm in diameter) total suspended particulates, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and lead and other heavy metals. The amounts and types of pollutants released by fires are affected by area burned, fuel characteristics prior to combustions, fire behavior, combustion stages, level of fuel consumption, and source strength [37]. Wildfires occur as episodic events that can threaten public health, cause smoke damage to buildings, and disrupt public activities [42]. Particulate concentrations rarely affect large city's air quality, but they can rise to harmful levels (e.g., 600 $\mu g\ m^{-3}$) in smaller communities located in forested regions. In some regions, wildfire smoke is the main cause of visibility reductions.

Although the public can be exposed to and become affected by wildland smoke and its constituents, the main concern is for firefighters and fire managers. Anyone who has been involved in wildfire suppression or prescribed fire management understands this. Unlike structural firefighters who utilize PBAs (personal breathing apparatus), wildland fire fighters at best have dust masks that reduce exposure to dust and large particulates but not small particulates and gases. Many data gaps exist in the understanding of human health hazards of wildland fire suppression and management [43].

The individuals whose health is most at risk include those with cardiopulmonary diseases and the elderly. However, normally healthy individuals, such as firefighters, are at increased risk of developing cardiopulmonary disease over the long term. Effects of PM10 and PM2.5 particulates, dust-borne silica, aldehydes, carbon monoxide, polyaromatic hydrocarbons, ozone, and heavy metals are poorly understood. The temporary nature of wildland fire personnel assignments make compilation of long-term health data difficult or impossible to achieve. Permanent fire personnel can be adequately assessed and monitored, but the bulk of wildland fire personnel cannot be properly evaluated.

4. Postfire hazards

4.1 Flooding and debris flows

In many cases, the greatest hazard posed by wildfires occurs in the postfire period when flooding events, made worse by the loss of vegetation, create debris flows (**Figure 6**). These catastrophic events often result in property and infrastructure destruction and in some cases loss of life [3, 7]. Debris flows typically occur in areas with steep topography after being subjected to wetting rains, which mobilize soil, rock, and other debris into a concrete-like torrent that moves downslope toward low-lying areas. These flows tend to have immense force due to the speed in which they move and can cause total destruction of objects in their path and contribute to human mortality. For example, it has been estimated based on insurance claims following the Thomas Fire southern California in 2017 that postfire damage assessments were mostly related to massive debris flows that originated in the burned area. The economic cost of these debris flows exceeded $1.8 billion [34].

While these events can be highly destructive and very costly, they can also be somewhat mitigated through prefire planning and zoning regulations as well as adequate infrastructure. The problem is that often the size of flooding events

Figure 6.
Flood flows in an urbanized area below the 2010 Schultz Fire in Arizona, USA (photo by Daniel G. Neary, Rocky Mountain Research Station, USDA Forest Service).

following wildfire can fall into a once in a century or even a millennia event making the cost justification for accommodating such an event beforehand challenging. However, as these events begin to become more common and costs begin to escalate, the argument for increased preparation must be considered.

Take for example the Schultz Fire, which occurred just outside of Flagstaff, Arizona, USA, in 2010. The fire burned on steep slopes within the Coconino National Forest immediately adjacent to subdivisions located in the valley below. Summer rainfall events following the fire initiated massive flooding and debris flows into the area. Fortunately, there was only one flood-related mortality. While estimates of the costs related directly to the fire suppression were around $9,460,909, the cost of the response to the flood was nearly twice that at $16,470,682. However, both these costs were outdone by the nearly $33,172,803 that was invested in infrastructure over the following 4 years needed to mitigate future flood risk. The financial analysis published on this event [44] in 2013 also pointed out that the cost estimates were only for official expenditures by government agencies and local utilities. The loss in property devaluation, infrastructure damage, increased insurance premiums, and other associated costs totaled more than $60 million in additional losses, making the argument for increased spending on hazard mitigation valid. The economic hazards of the fire were 10 times the funds expended to suppress the Schultz Fire. And this accounting did not include the value of lost or damaged natural resources.

4.2 Water quality

Landscape scale fire events can have profound influence on elements of water quality including increasing turbidity, temperature, and contaminants sometimes for many years following the fire [45–49]. One study near Denver, Colorado, found that average spring and summer water temperatures increased by 5–6°C and that nitrate concentrations increased over 100 times greater than typical stream concentrations following the Hayman Fire in 2002. In addition, summer storms continued to mobilize sediment and create surface runoff corresponding to spikes in nutrient concentration and turbidity for years following the fire event [50].

Ecologically, flooding events following a wildfire can be catastrophic on aquatic communities. This is due primarily to the depletion of oxygen and the increase in turbidity in ash-laden debris flows (**Figure 7**). The two biggest factors affecting long-term recovery and health of aquatic habitats impacted by fire are physical channel stability and water temperature [51]. Loss of streamside vegetation due to fire and instability or changes in physical habitat due to flooding can diminish aquatic habitats for decades. The timing and severity of flooding events are directly related to preceding fire incident. Typically, low order or headwater streams are more susceptible to vegetation changes and flooding than higher order streams; however, depending on the magnitude of input, even larger rivers and reservoirs can be subjected to diminished water quality and loss of aquatic species due to ash-laden flow inputs.

4.3 Ecological changes

The increase in scope and scale of wildfire worldwide tends to have a more intrinsic effect on ecosystem function, affecting qualities that are not always measureable in economic terms. Degradation of soil [8] and water resources [3, 5] along with landscape scale changes in vegetation [51] has the ability to shape ecosystems for decades if not centuries [52]. These cascading effects are becoming selective for plant and animal species, which are pioneer species at first and later are disturbance oriented as these

Figure 7.
Post-fire runoff with high concentrations of sediment, ash, and charcoal, Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, Arizona, 2002 (photo by Daniel G. Neary, Rocky Mountain Research Station, USDA Forest Service).

systems begin the slow process of recovery, often punctuated by reoccurring disturbance events such as flooding or even subsequent fire events. At relatively small scales, the input of fire, even high-severity fire, can introduce heterogeneity into a landscape that can be beneficial to the ecosystem as a whole, creating niches and freeing up resources for new species to establish in an area. However, there is a size threshold that once crossed starts to become an impediment to recovery and results in long-term loss of habitat suitability for specific species. For example, the loss of seed sources both in the soil bank and from mature plants for obligate seed species can have a limiting effect on the recolonization and distribution of many long-lived conifer species [53]. Similarly, the impact from flooding events on fragmented streams due to anthropogenic or natural barriers may make the recolonization of some aquatic species impossible and result in permanent extirpation [54]. In these cases, wildfire begins to act on a genetic level to influence the long-term stability and ecosystem function of an area. This poses a serious environmental hazard due to the permanent loss of important species in an ecosystem and increasing the risk of desertification [8].

5. Summary and conclusions

Humans live in or adjacent to wildland ecosystems that burn periodically and are part of nearly all ecosystems that are in the pyrosphere. There are many hazards posed by wildfire and certain consequences of living in these ecosystems. Most are associated with wildfire but the increased use of prescribed fire is an issue because of associated risks with human attempts to manage ecological goals. The economic and social consequences of wildfire have been discussed by a number of authors [3, 5, 7, 42]. These consequences involve cultural and economic loss, social disruption, infrastructure damage, human injury and mortality, damage to natural resources, and deterioration in air quality. The economic and human health and safety costs are on the rise due to increasing wildland-urban interface problems and extreme wildfire behavior brought on by climate change. In the past, urban fires have been the greatest threat to human health and safety killing over 100,000 people.

With modern fire control organizations in cities, the greatest hazard has shifted to wildlands. The Miramichi Fire in Canada's eastern woodlands in 1825 may have killed 3000. In the USA, the most devastating wildland wildfire known was the

Peshtigo Fire of 1871 that killed over 1150 people. Recent wildfires in Australia in 2009 and California in 2017 and 2018 claimed up to 270 lives in a single fire event in each country. The increasing development of the wildland-urban interface in the USA and other countries is raising the risks that a similar fatal event could occur in the future. Large fatalities due to wildfire hazards may be a thing of the past, but frequent deaths such as those in Australia in 2009 may tally up to greater numbers. In addition, the economic hazards of wildfires are growing. The large amounts of funds needed to suppress large wildfires are a small fraction of the total economic damage. Nationally, in the USA, fire suppression, collateral infrastructure damage, urban destruction, and other wildfire mitigation efforts exceed the total management budgets of the state and federal agencies.

World ecosystems have been modified extensively by fire. We live on a "fire planet" [1, 2, 42]. With larger human populations and a changing, drying climate, the impact of fire on humans and the hazards faced by our natural and developed world will continue to increase. The increase in wildfire hazards in the twenty-first century will require higher levels of training, increased investments in wildfire personnel and infrastructure, greater wildfire awareness, and improved planning to reduce fire impacts.

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