Chapter

Recent Megafires Provide a Tipping Point for Desertification of Conifer Ecosystems

Daniel G. Neary

Abstract

Recent megafires and gigafires are contributing to the desertification of conifer forest ecosystems due to their size and severity. Megafires have been increasing in their frequency in the past two decades of the 21st century. They are classed as such because of being 40,469 to 404,694 ha in size, having high complexity, resisting suppression, and producing desertification due to erosion and vegetation type conversion. Increasingly, gigafires (>404,694 ha) are impacting coniferous forest ecosystems. These were once thought of as only pre-20th century phenomena when fire suppression was in its infancy. Climate change is an insidious inciting factor in large wildfire occurrences. Fire seasons are longer, drier, hotter, and windier due to changes in basic meteorology. Conifer forests have accumulated high fuel loads in the 20th and 21st centuries. Ignition sources in conifer forests have increased as well due to human activities, economic development, and population demographics. Natural ignitions from lightning are increasing as a result of greater severe thunderstorm activity. Drought has predisposed these forests to easy fire ignition and spread. Wildfires are more likely to produce vegetation shifts from conifers to scrublands or grasslands, especially when wildfires occur with higher frequency and severity. Severe erosion after megafires has the collateral damage of reducing conifer resilience and sustainability.

Keywords: wildfire, megafires, gigafires, desertification, type conversion, drought

1. Introduction

Wildfires are now the most common disturbance in forest ecosystems other than tree harvesting [1]. Warmer, dryer, and windier weather conditions that are characterizing climate change-related drought in the western USA and elsewhere are driving wildfire occurrence and severity [2]. Future wildfire conditions are most likely to be aggravated in coniferous and boreal biomes, but grasslands are also at risk of serious disturbance [3]. Wildfire size and terrain features have also contributed to a destructive nexus of conditions that have resulted in unprecedented fire disturbances to wildland and urban landscapes. Forested catchments are particularly susceptible to this disturbance [4, 5].

Fire is not new to the planet. It has been a major disturbance force affecting terrestrial ecosystems since vegetation developed as an abundant fuel 450 million years during the Paleozoic Ordovician Period [6]. The sedimentary record indicates that wildfires have been occurring since the Paleozoic, but they increased substantially with the development of plant fuels in a lightning-filled atmosphere of the Carboniferous Period (307 to 359 million years before the present). Fire was one of the environmental and evolutionary pressures that created forest and grassland ecosystems. Humans then used fire as an ecological agent to further sculpt vegetation to suit their needs [6]. What was once a relatively stable and predictable tool for use in forest and grassland ecosystems, is now, under the pressure of changes in the climate and human activity, an unpredictable ecological stressor. Wildfires are now burning in meteorological environments that are hotter, windier, and drier than in previous decades [2]. The result has been on fires increasing numbers, size, severity, and complexity. Forest management has been forced to change to adapt to these conditions by placing more resources into fire suppression and management.

One example can be easily viewed in decadal areas burned by wildfire in the southwestern United States (**Figure 1**). Accurate wildfire records began tallying areas burned at the turn of the 20th century (1910). For the next eight decades, the cumulative area burned in each decade was steady with less than 20,235 ha (<50,000 ac) burned by wildfires that were small in areal extent. An ecological tipping point occurred in the 1990 to 1999 decade when the burned area doubled due to increasing numbers and size [7]. The next decade (2000 to 2009) saw a 69.3-fold increase. The following decade was characterized by an even larger 110.6-fold increase over the average of the 1910 to 1990 decades. In the first year of the 2020–2029 decade so far, wildfires burned over the record sizes of wildland landscapes.

A second example comes from Australia which suffered another devastating, record-smashing bushfire season in 2019–2021. Australia is no stranger to bushfires but climate change is wreaking havoc on the continent [8]. The 2019–2020 season proved to be unprecedented in many ways [9]. The first major bushfires began even before the official arrival of spring in June. Then, new out-of-control fires ignited at the beginning of Sept. 2019. This was followed by even worse fires at the beginning of November 2019 due to a lengthy drought and increasing temperatures. High temperatures, drought, and high winds in the late summer aggravated the bushfire escalated the crisis again over the first weekend in February. The fires in this outbreak were either extinguished or contained in early March after 9 months of

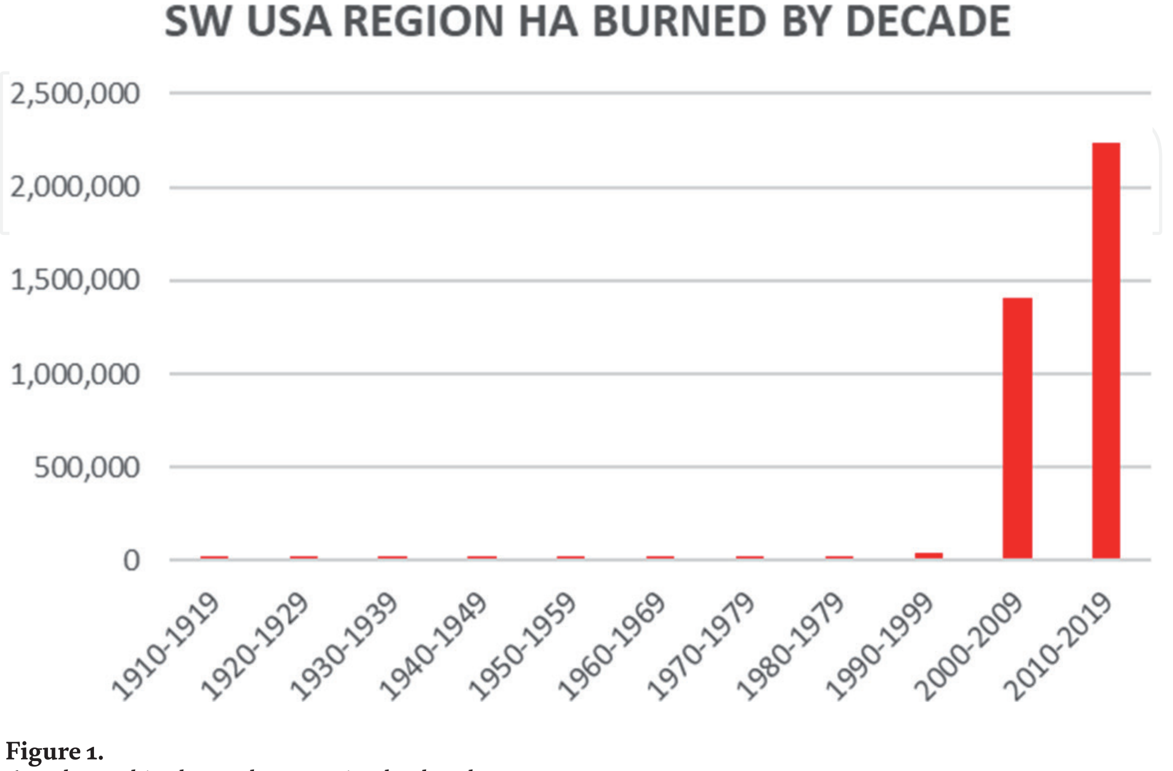

Figure 1.
Area burned in the southwest region by decade.

raging around the Australian continent. The infrastructure, ecosystem, and human impacts were staggering.

The bushfires burned more than 18.6 million ha, an area the same as the entire State of Washington in the USA, 70% of New Zealand, or 55% of Finland. At least 3500 houses and 5852 other buildings were burned to some degree. A total of 34 people died as a direct consequence of the bushfires between September 2019 and March 2020, but another 445 died due to other fire-related medical co-morbidities. This was much more than the 170 people estimate that died in the 2009 bushfires. Economic losses were initially estimated at the USA$1.3 billion in insured claims. But it may not be possible to completely determine the real economic loss from the bushfires because of: 1) the difficulties in evaluating intangible losses, 2) the confluence of the bushfires and COVID-19 impacts, 3) mortality of a billion native animals [10], and 4) the impacts on Australian fishing and tourism. The real economic effects probably surpass the infamous Black Saturday fires of 2009 that resulted in losses of the USA$2.9 billion to the Australian economy.

On the other side of the Pacific Ocean, the California wildfire season was record-setting with 9639 fires burning 1,779,730 ha [11]. Direct deaths were about the same as in Australia but there were ten times as many fatalities due to indirect air pollution impacts. The economic cost was much higher at over >$USA 12.1 billion. The number of buildings destroyed was 10,488 which contributed to the high cost. One gigafire, the August Complex, set the California record for size (417,907 ha) [7]. The 2021 fire season is underway and has the potential to eclipse 2020, which was a record year.

2. Wildfire, climate change, and drought

The trends in global wildfire potential under climate change was investigated by Liu et al. [12] using drought indices and general circulation models. It is shown that future wildfire potential increases significantly in the United States, South America, Central Asia, southern Europe, southern Africa, and Australia. Expected changes in drought and fire potential are expected to be the largest and smallest in southern Europe and Australia, respectively. The increased fire potential is mainly caused by warming in the U.S., South America, and Australia and by the combination of warming and drying in the other regions. The results of the Liu et al. suggest dramatic increases in wildfire potential that will require increased future investments in human resources, fire suppression infrastructure, and management activities to prevent fire disasters and recover from fire catastrophes. Stephens et al. [13] examined the role of drought-induced tree mortality in fueling wildfires. Their analysis points out that the scale of the western USA tree mortality creates a risk for even greater landscape-scale wildfires in the coming decades.

3. Wildfire characteristics

3.1 Ignition sources

The types of wildfire ignition are related to natural sources such as lightning, but more importantly human activities (e.g. agriculture, vehicle operations, and forestry activities), infrastructures (e.g. power lines, railways, etc.), or human behavior (e.g. recreation, delinquency, etc.). The main sources of human-caused ignitions vary by country but also at a regional scale [14, 15]. However, despite its importance in the improvement of fire prevention, knowledge of human-induced fire ignitions is still very limited in most parts of the world [16]. Ignitions by lightning are considerably enhanced by long-term drought plaguing forest regions of the world.

3.2 Frequency

Wildfire frequency is a key factor in describing a fire regime. It is a useful concept for comparing the relative role of fire between ecosystems and for describing the degree of departure from historical conditions [17, 18]. Brown [19] contains a discussion of the development of fire regime classifications based on fire characteristics and effects, combinations of factors including fire frequency, periodicity, intensity, size, pattern, season, and depth of burn, severity, and fire periodicity, season, and effects [20]. Several investigators have used modal severity and frequency to map fire regimes in the Western United States (**Table 1**) [21].

However, a number of the wildfire factors that affect this classification system have changed substantially in the past three decades. Wildfires are occurring over a longer period (season) and the fire climate is hotter, drier, and windier. This trend has been true for the past three decades and is accelerating. An example of the change in frequency and size of wildfires can be seen in the data from the southwestern USA.

Wildfire burned area tracking started in 1910. For the next eight decades, the total burned area remained under 20,000 ha **Figure 1**. Starting in 1990, fires began to occur at a higher frequency, size, and severity as the regional climate shifted into a mega-drought. Fires in 2020 and 2021, the current decade, are occurring at a record-setting pace.

3.3 Severity

3.3.1 Severity definition

At finer spatial and temporal scales the effects of a specific fire can be described at the stand and community level [2, 22]. The fire term is used to describe the ecological effects of fire severity. It describes both the degree of ecosystem disturbance and the amount of change in ecosystem components. Thus, severity integrates the damaging effect of both the heat pulse above ground and the energy transferred into the soil. In essence, it describes the amount of heat that is released by a fire that ultimately affects ecosystem functions. Fire severity is a good descriptive term that categorizes multiple ecosystem impacts [23]. The most important factors which determine the degree of fire severity are the fuel characteristics and the type of combustion. The amounts of flaming versus smoldering combustion that occur when wildland fuels are burned determine the degree of severity.

Wildfire literature is rife with confusion between the terms fire intensity and fire severity. A consistent distinction between the two terms has emerged in

Fire regime	Fire frequency (Years)	Fire type
I	0–35	Understory Fire
II	0–35	Stand Replacement
III	35–100	Mixed
IV	35 * 100	Stand Replacement
V	>200	Stand Replacement

Table 1.
Fire regime classifications according to Hardy [21].

the past three decades as fire science has improved and evolved. Fire managers trained in the science of fire behavior prediction systems now use the term fire intensity in a strict thermodynamic sense to describe the rate of energy released [24]. Fire intensity describes the rate of above-ground fuel consumption and, therefore the energy release rate [25]. It can be measured in thermodynamic terms of heat transfer per unit length of the fireline (kW m^{-1}) [2, 26]. The faster a mass of fuel combusts, the greater the fire intensity and the shorter the time that the soil is subjected to heat impact. Fast-moving wildfires typically do not produce complete litter combustion, whereas slower fires can completely combust the litter layer of soils. The rate at which energy can be transmitted through soils is restricted by the thermal properties of the mineral medium. As mentioned earlier, the duration of burning is critically important to the ultimate effect on soils [27].

Fire intensity is often related to the total amount of energy produced during the combustion process, but it is a measure of both small-scale prescribed fires as well as large-scale wildfires. Most energy released by the flaming combustion of above-ground fuels is transmitted upwards, not downward into the soil [28]. For example, Packham and Pompe [29] determined that only about 5 percent of the heat released by a surface fire occurs as heat pulses are transmitted into the ground. Therefore, fire intensity alone is not a good measure of the amount of fire-derived heat transmitted downward into the soil. Changes that occur in the physical, chemical, and biological properties of the soil are better indicators of heat transfer to the ground. For example, a high-intensity, and fast-moving crown fire will consume little of the surface litter because only a small amount of the heat energy released during the combustion of fuels is transferred downward to the litter surface [22]. In this case, the surface litter is identified as severe and presents as blackened, charred litter, but not completely consumed ash. Fire intensity can be quantitatively measured but fire severity can only be described (low, moderate, or high).

In wildfires in Alaska and North Carolina, fast-spreading crown fires were observed to completely consume the forest canopy but did not even scorch all of the surface fuels. However, if the fire also consumes substantial surface and ground fuels as a result of a longer residence time on a site, more energy is transmitted into the soil. Then, damage to the soil system is much greater. In such cases, a white or white-orange ash layer is often the only postfire material left on the soil surface [2, 30, 31].

Because the actual energy release of fire cannot be easily measured across a burned piece of land, the term fire intensity has limited practical application when evaluating ecosystem responses to fire. Increasingly, the term fire severity is used to indicate the ecosystem effects of fire on the landscape and its components [2, 31]. Fire severity was commonly used to describe the magnitude of negative fire impacts on natural ecosystems in the past. Wider usage of the term to include all fire effects is proposed. In this context, severity does not necessarily imply that there are negative consequences. Thus, a low severity fire may be discontinuous in nature, restoring and maintaining a variety of ecological attributes that are generally viewed as positive. For example, in fire-adapted longleaf pine (*Pinus palustris*) or ponderosa pine (*P. ponderosa*) ecosystems, fire is viewed as a necessary disturbance for maintaining the ecological characteristics of these forest types. In contrast, a high severity fire may be a dominant, albeit infrequent, disturbance in a non-fire adapted ecosystem. For example, in spruce (*Picea* spp.) forests fire is often a destructive disturbance. Frequent low severity fire is normal in a fire-adapted ecosystem. While all high severity fires may have some significant negative social and ecological impacts, only in the case of non-fire adapted ecosystems is the long-term functioning of the ecosystem significantly altered.

3.3.2 Fire severity classification

Judging fire severity solely on ground-based processes ignores the aboveground dimension of severity implied in the ecological definition of the severity of a disturbance. This is especially important because soil heating is commonly shallow even when surface fires are intense [22, 28]. Fire intensity classes were combined with the depth of burn (char) classes by Ryan and Noste [32] to develop a two-dimensional matrix approach to defining fire severity. Their system is based on two components:

1. An above-ground radiation and convection heat pulse associated with flaming combustion, and

2. A below-ground heat pulse due to conduction from smoldering combustion where duff is present, or radiation from flaming combustion where duff is absent on bare mineral soil.

Fire-intensity classes qualify the relative peak energy release rate (kW m^{-1}), whereas depth-of-burn classes qualify the relative duration of fuel combustion [2]. The concept of severity focuses on the ecological impacts of fire both above-ground and below-ground. Ryan [22] revised the Ryan and Noste [32] surface fire characteristic classes and depth of burn classes. By this nomenclature change, two burned areas would be contrasted as having had, for example, an active spreading-light depth of burn fire versus an intense-moderate depth of burn fire, common in high severity wildfires (**Figure 2**).

3.4 Wildfire size: Megafires and Gigafires

Wildfires burn on a number of scales between and within wildfires. Most do not go beyond the Zone of Prescribed Fire (4 to 400 ha) or the low end of Small Wildfires (400 to 4040 ha) (**Table 2**). All large fires will have components of smaller-scale fires embedded within them. A change that has occurred in the past

Figure 2.
High severity wildfire impacts on a young Pinus ponderosa stand, after the 2000 rodeo-Chediski fire, apache-Sitgreaves National Forest, Arizona.

Fire size class	**Fire burned area range**	**Fire name**	**State prov.**	**Actual fire size**
	ha			**ha**
Micro	10^{-4}	“A Burning Stump”		
Zone of Prescribed Fires...				
A	<0.1			
B, C, D, E	121 to 404			
Zone of Small Wildfires...				
F G	404 to 2023 2023 to 4049			
H	4049 to 20,234	Schultz Fire 2010 Cerro Grande Fire 2000	AZ NM	6100 19,425
I	20,234 to 40,469	Okanagon Park 2003	BC	25,600
Zone of Megafires...				
J	40,469 to 202,347	Rim Fire 2013 Chelaslie River 2014 Rodeo-Chediski 2002	CA BC AZ	104,135 133,098 189,655
K	202,347 to 404,694	Wallow Fire 2012 Biscuit Fire 2002 Dixie Fire 2021	AZ CA CA	217,741 229,057 384,150
Zone of Gigafires...				
L	>404,694	August Complex 2020	CA	417,907
		Taylor Complex 2004	AK	428,500
		Yellowstone Fire 1988	MT/ID	607,042
		Peshtigo Fire 1871	WI/MI	1,214,083
		Great Fire 1910	ID/MT	1,600,000

Fire size class	Fire burned area range	Fire name	State prov.	Actual fire size
	ha			ha
		Miramichi Fire 1825	NB	1,700,000
		Chinchaga Fire 1950	BC/AL	2,000,000
		Victoria Black Fri. 1939	AUST	3,000,000

Table 2.
Modified wildfire size classes and individual fire examples (from [33, 34]).

three decades is the increasing number of wildfires and the scale of those fires. Mega Fires (4060 to 40,469 ha) are now more common and there is a resurgence of Giga Fires (>404,604 ha) [33, 34].

The largest Giga Fires known in the historical record are from the 19th and 20th Centuries when fire suppression knowledge, technology, and resources were limited or non-existent. Land managers and owners relied on weather changes to dampen fire activity. Both Giga and Megafires (classes J, K, and L) are more prevalent in the first two decades of the 21st Century due to fuel loadings and climate change. Wildfires are burning in hotter, drier, and windier weather conditions than was experienced in much of the 20th century. The sizes and severities of current wildfires are proving to be much more resistant to suppression activities. Consequently, the infrastructure, ecological, and economic costs continue to escalate.

4. Erosion

4.1 Types of fire induced erosion

Erosion involves three separate processes that are a function of sediment size, transport medium (water, wind, or air), and velocity. These are (1) detachment, (2) transport, and (3) deposition. Erosion occurs when sediments are affected by water, wind, or air and velocities that are sufficient to detach and transport sediments. Erosion is a natural process occurring on landscapes at different rates and scales depending on geology, topography, vegetation, and climate. Natural rates of erosion vary from <0.01 to 15.00 Mg ha^{-1} [2, 31]. These rates increase as annual precipitation increases, peaking in semiarid ecoregions on the transition desert to wet forest [35]. This occurs because there is sufficient rainfall to produce erosion from the sparser desert and semiarid grassland covers. As precipitation increases, the landscapes start supporting dry and eventually wet forests, which produce increasingly dense plant and litter covers that decrease natural erosion. However, if landscapes are denuded by disturbances (e.g. fire, grazing, timber harvesting, mining, and so forth), then erosion continues to increase with greater precipitation. Surface physical conditions, topography, and soil hydrological status after wildfires and prescribed fires are important for determining post-fire water flows and the magnitude of erosion (**Table 3**).

Apart from the consumption of vegetation, erosion is certainly the most visible and dramatic impact of fire. Wildfire suppression, prescribed fire, and post-fire watershed rehabilitation also affect erosion processes in wildland ecosystems. Fire management activities such as fireline construction, temporary roads, and new and unpaved roads receiving heavy vehicle traffic will increase erosion. Stormflows after wildfires will also accelerate erosion rates. Burned Area Emergency Response (BAER) activities on watersheds have the potential to decrease some post-fire erosion

Soil surface condition	Infiltration	Runoff	Erosion
Litter Charred	High	Low	Low
Littter Consumed	Medium	Medium	Medium
Bare Soil	Low	High	High
Water Repellent	Very Low	Very High	Severe

Table 3.
Soil surface conditions that affect infiltration, runoff, and erosion after wildfires and prescribed fires (from [31]).

to varying degrees depending on the timing, amount, and intensity of rainfall, slope, degree of litter combustion, and the presence of water repellent soils [36].

4.2 Sheet, rill, and gully erosion

In sheet erosion, slope surfaces erode somewhat uniformly. This type proceeds to rill erosion in which small, linear, rectangular channels cut into the surface of a slope. Further redevelopment of rills leads to the formation of deep, large, rectangular to v-shaped gully [35]. Another type of slope erosion called dry ravel is initiated by a variety of disturbances, including fire. Dry ravel may best be described as a type of dry grain flow. Fires greatly alter the physical characteristics of hillslopes, stripping them of their protective cover of vegetation and organic litter, and removing log barriers that were naturally trapping sediment. Consequently, during and immediately following fires, large quantities of surface material are released and transit downslope as dry ravel even before rainfall events occur [37]. Dry ravel can equal or exceed rainfall-induced hillslope erosion after a fire in semi-arid ecosystems [38]. In the Oregon Coast Range of the United States, prescribed fires in heavy slash after clearcutting produced non-cohesive soils that were less resistant to the force of gravity [39]. Sixty-four percent of post-fire erosion occurred as dry ravel, not water erosion, happening within the first 24 hours after the end of active fire behavior.

4.3 Mass failure erosion

Mass failure erosion includes slope creep, falls, topples, rotational and translational slides, lateral spreads, debris flows, and complex movements. The largest, most dramatic, and main form of mass wasting that delivers sediment to streams are debris flows [40]. Most fire-associated debris flows are associated with the development of water repellent conditions in soils [2]. These mass failures are a large source of localized sediment delivered to stream channels. They can account for 50% of the total post-fire sediment yield in some ecoregions). Wells [41] reported that wildfire in chaparral vegetation in coastal southern California can increase average sediment delivery in large watersheds from 7 to 1910 $m^3 km^{-2} yr^{-1}$. However, individual storm events in smaller basins can produce much greater sediment yields. Single storms have delivered sediment yields as high as 65,238 $m^3 km^2$ in unstable terrain.

4.4 Channel destabilization erosion

Fire-related sediment yields depend on fire frequency, climate, vegetation, and geomorphic factors such as topography, geology, and soils [41, 42]. In some regions, more than 60% of the total landscape sediment production over the long term is fire-related. Much of the sediment production can occur the first year after a wildfire [2, 43]. However, a risk of increased sediment in streamflow can persist for 10 or more years after a wildfire. Sediment transported from wildfire scars as a result of increased stream peak flows can adversely affect aquatic habitat, recreation areas, roads, buildings, bridges, and culverts. Management of newly deposited sediments is a problem in both the terrestrial and aquatic environment since fire-derived material can block roads, block culverts, alter drainage patterns, and fill in channels, lakes, and reservoirs [44, 45] (Reid 1993, Rinne 1996).

4.5 Effect of water repellent soils on post-fire erosion

Fire affects rainwater infiltration in two ways. First, the combustion of soil organic horizons leaves mineral soil unprotected from raindrop impact. The force of rainfall loosens and disperses fine soil and ash particles, causing the soil surface to seal [46]. Second, soil heating during a fire frequently produces a water-repellent layer at or near the soil surface. This process further impedes water infiltration into the soil. The severity of this water repellency in the surface mineral soil layer, however, decreases over time as it is exposed to moisture, freeze–thaw cycles, and animal and insect burrowing. In many cases, water repellency does not substantially affect infiltration beyond the first year. However, fire-induced repellency can persist for several years. Water repellency has a particularly important effect on two post-fire erosion processes, raindrop splash, and rill formation.

The sequence of rill formation as a result of fire-induced water repellency has been documented to follow several well-defined stages [2]. First, the wettable soil surface layer, if present, is saturated during initial infiltration. Water moves rapidly into the wettable surface ash layer until it encounters a water-repellent layer. This process occurs uniformly or discontinuously over the burned landscape so that when the wetting front reaches the water-repellent layer, it can neither drain downward nor laterally. If the water repellent soil layer is right at the soil surface, runoff starts immediately after rain droplets reach the soil surface. As rainfall continues, water fills all available pores until the wettable soil layer becomes saturated. Because of the underlying water-repellent layer, the saturated pores cannot drain, which creates a positive pore pressure above the water-repellent layer. The shear strength of the soil mass declines and it results in a failure zone located where pore pressures are greatest, at the boundary between the wettable and water-repellent layers. As the water flows down this initial failure zone, turbulent flow develops, which accelerates erosion and entrains particles from both the wettable ash layer and the water-repellent layer. The downward erosion of the water-repellent rill continues until the water-repellent layer is eroded away and water begins infiltrating into the underlying wettable soil. Flow then diminishes, turbulence is reduced, and down-cutting temporarily ceases. The result is a rill that has stabilized immediately below the water-repellent layer. Additional rainfall over time will cause these rills to deepen and widen into a gully network. On a watershed basis, these individual rills and gullies develop into a well-defined drainage network that can extend throughout portions of small and large watersheds. The net result is a dramatic increase in the volume of hydrologic response and a decrease in the timing of runoff from the catchment area.

4.6 Post-fire sediment yields

Natural erosion rates for undisturbed forests range from <0.01 to 7 Mg ha^{-1} yr^{-1} [2, 47], but do not approach the average upper limit of geologic erosion in highly erodible or mismanaged soils (560 Mg ha^{-1} yr^{-1} [48]. These differences are due to natural site factors such as soil and geologic erosivity, rates of geologic uplift, tectonic activity, slope, rainfall amount and intensity, vegetation density, and percent cover. Normal landscape-disturbing activities such as agriculture (560 Mg ha^{-1} yr^{-1} [49], mechanical site preparation (15 Mg ha^{-1} yr^{-1} [50], and road construction (140 Mg ha^{-1} yr^{-1}) produce a range of sediment losses.

Sediment yields from fires vary considerably, depending on fire frequency, climate, vegetation, and geomorphic factors such as topography, geology, and soils [2, 51]. In some regions, over 60% of the total landscape sediment production over the long term is fire-related. Much of that sediment loss can occur the first year after a wildfire but may extend to 10 years or more [2, 38, 43]. Sediment yields 1 year after prescribed burns and wildfires range from very low, in flat terrain and in the absence of major rainfall events, to extreme, in steep terrain affected by high-intensity thunderstorms. Erosion on burned areas typically declines in subsequent years as the site stabilizes, but the rate of recovery varies depending on fire severity, vegetation recovery, climate, and depth of soil loss.

Soil erosion following fires has been measured to range from under 0.1 Mg ha^{-1} yr^{-1} to 15 Mg ha^{-1} yr^{-1} in prescribed burns, and from <0.1 Mg ha^{-1} yr^{-1} in low severity wildfire, to more than 369 Mg ha^{-1} yr^{-1} in high-severity wildfires on steep slopes [2, 43, 50]. More recent analyses have estimated sediment losses after wildfires in steep terrain of upwards of 1500 Mg ha^{-1} yr^{-1} from a combination of steep slopes and high-intensity rainfall. Nearly all fires increase sediment yield, but wildfires in steep terrain produce the greatest amounts, >1500 Mg ha^{-1} yr^{-1} [52]. Sediment yields usually are usually the highest during the first year after a fire and then decline in subsequent years. However, if precipitation is below normal, the peak sediment delivery year might be delayed. In semiarid areas, postfire sediment transport is episodic in nature, and the delay may be longer. All fires increase sediment yield, but it is the combination of steep slopes, high severity fire, and intense rainfall that is the most problematic.

There is increasing evidence that short-duration, high-intensity rainfall (>50 mm h^{-1} in 10–15 minute bursts) over areas of about 1 km^2 often produces flood flows that result in large amounts of sediment transport [31]. *A* thunderstorm after the 2010 Schultz Fire in Arizona had a peak rainfall of 24 mm in 10 minutes and resulted in debris flows and floods that had a return period of >1000 years [52]. High severity fire (>70% coverage), steep slopes (>100%), and intense rainfall contributed to the unusual erosion. Best Management Practices certainly have value in reducing sediment losses from prescribed fires. However, mitigative techniques for reducing sediment losses after wildfires often that are often used as part of burned area emergency watershed response (BAER), have their limitations and cannot really cope with large erosion events.

After wildfires, streamflow turbidity usually increases due to the suspension of ash and silt-to-clay-sized soil particles [53]. Turbidity is an important water quality parameter because high turbidity reduces municipal water quality and can adversely affect fish and other aquatic organisms. It is often the most easily visible water quality effect of fires [2]. Less is known about turbidity than sedimentation in general because it is difficult to measure, highly transient, and extremely variable. Extra coarse sediments (sand, gravel, boulders) transported off of burned areas as a consequence of increased storm peak flows can adversely affect aquatic habitat, recreation areas, and reservoirs. Deposition of fine sediments as well as the previously mentioned coarse sediments destroys aquatic and riparian habitat, reduces the storage capacity of lakes and reservoirs, negatively affects stream and lake biota, degrades water quality, and imperils infrastructure [2, 45].

5. Desertification

Desertification was introduced into the fire-related lexicon in the 1940s by [54] before the modern outbreak of large fires. Although there is no general agreement on the definition of the term it is not necessarily associated with a classical desert. It is a landscape deterioration process that involves reductions of plant and soil ecosystem services. Desertification occurs on a continuum and is usually associated with human activities, especially erosion. The loss of key plant species and diversity, and erosion perturbation of soil physical properties and functions are key factors in the progression of desertification. The environmental hazards that result are most notably losses of soil fiber and food production capability, declines in water supply capability of watersheds [55], accelerated erosion of key soil horizons, and vegetation type conversions.

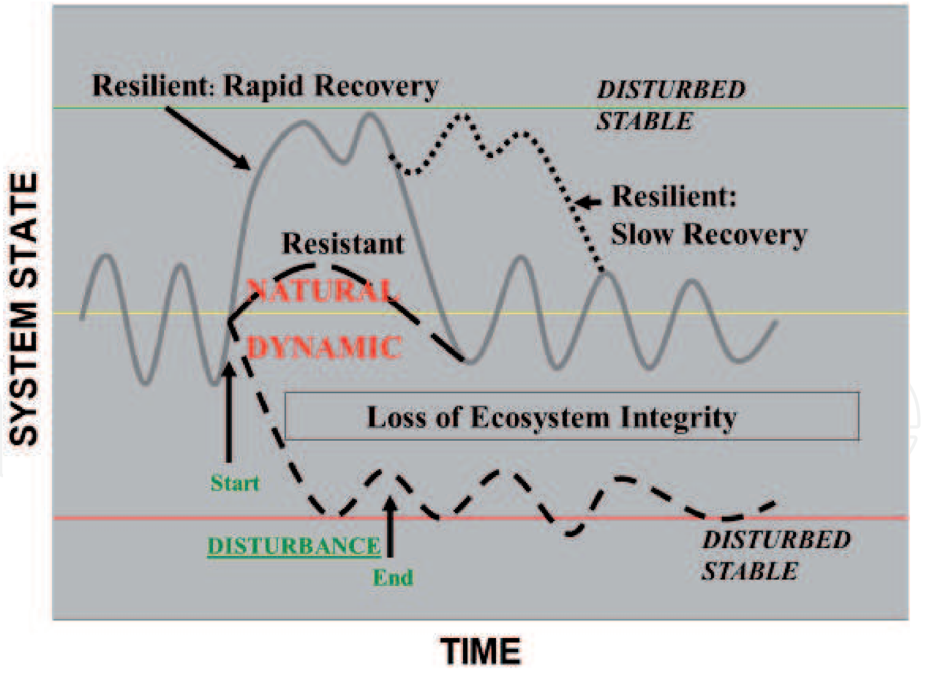

Figure 3.
Ecosystem responses to disturbance: Resistant, resilient, loss of ecosystem integrity.

The desertification process involves a shift in the normal ecosystem dynamic to a lower disturbed, but stable state (**Figure 3**). Fire-resistant forest ecosystems are characterized by a natural variability that stays within a normal range of disturbance and recovery. Fire resilient forests are disturbed from their normal range of variability but they recover rapidly or slowly. Excessive wildfire disturbance that results in the loss of ecosystem integrity pushes a forest to a lower system state that may never recover or take excessively long periods of time to do so [56].

6. Type conversion

Type conversions of ponderosa pine to chaparral scrublands is an example of loss of ecosystem integrity. Vegetation conversion from stable conifer forests to fire-prone scrublands usually produces an increase in fire frequency and severity which prolongs ecosystem persistence at a lower, desertified system state (**Figure 3**). Under these conditions, desertification magnifies the impact of the fire scale and the persistence of disturbance plant species [57, 58]. These investigators clearly point out the role of fire severity in driving plant community-type conversions. Keeley [58]. The greatest threat to the persistence of native California vegetation types is type conversion to herbaceous species more resilient to and more conducive to frequent fires. These fires are more likely to impact conifer species and prevent the re-colonization of severely burned sites [59]. Since 1996, high-severity crown fires in Southwestern ponderosa pine forests have produced large treeless areas, which are unprecedented in the regional historic record [60]. Other dry conifer forests, similar to ponderosa pine, are also experiencing extensive levels of high severity fire and type conversions to grasses and fire-prone scrub species.

7. Conclusion

It is clear now at the beginning of the 21st Century that changes in the climate have accentuated fire weather. Fires are now burning in hotter, drier, and windier conditions than they were 30 years ago. Wildfires are also burning into higher elevations, due to a warming climate. This climate condition has led to larger and higher severity wildfires since fires are more difficult to suppress and contain safely in steep terrain. In addition, fire seasons are now 4 months longer. In some areas, such as California, the fires season is 12 months long. This fire situation has provided an ecological tipping point leading to accelerated desertification of conifer ecosystems. This condition limits the success of management interventions to reverse desertification.

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Conflict of interest

The authors declare that there are no conflicts of interest related to the subject of this paper.

Author details

Daniel G. Neary
USDA Forest Service, Rocky Mountain Research Station, Flagstaff, Arizona, USA

*Address all correspondence to: danneary46@yahoo.com

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