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Chapter 8

WILDFIRE CONTRIBUTION TO DESERTIFICATION AT LOCAL, REGIONAL, AND GLOBAL SCALES

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ABSTRACT

Wildfire is a natural phenomenon that began with the development of terrestrial vegetation in a lightning-filled atmosphere of the Carboniferous Period (307-359 million years before the present). Sediment deposits from that era contain evidence of charcoal from post-fire ash slurry flows. As human populations developed in the Pleistocene and Holocene epochs, mankind transformed fire into one of its oldest tools. Human and naturally ignited fires from lightning altered and steered the trajectories of ecosystem development in most parts of the world. Humans are now the primary source of forest and grass fire ignitions throughout the world. As human populations have increased and industrialized in the past two centuries, fire ignitions and burned areas have increased due to both sheer numbers of people and anthropogenic changes in the global climate. Recent scientific findings have bolstered the hypothesis that climate change is resulting in fire seasons starting earlier, lasting longer, burning greater areas, and being more severe. Computer models point to the Western U.S., Mediterranean nations and Brazil as "hot spots" that will get temperature extremes at their worst. The climatic change to drier and warmer conditions has the potential to aggravate wildfire conditions, resulting in longer fire seasons, larger areas of vegetation consumed, and higher fire severities. Wildfire is now driving desertification in some of the forest lands in the western United States. The areas of wildfire in the Southwest USA have increased dramatically in the past two decades from <10,000 ha yr^{-1} in the early 20th Century to over 230,000 ha yr^{-1} in the first decade of the 21st Century. Individual wildfires are now larger and produce higher severity burns than in the past. A combination of natural drought, climate change, excessive fuel loads, and increased ignition sources have produced the perfect conditions for fire-induced desertification. Desertification is about the loss of the land's proper hydrologic function, biological productivity, and other ecosystem services as a result of human activities and climate change. It now affects 75% of the earth's land surface and over a billion people. In the past, desertification was considered a problem of only arid, semi-arid, and dry sub-humid areas. However, humid zones can undergo desertification with the wrong combination of human impacts. The Amazon region is an example of where forest harvesting, shifting cut and burn agriculture, and large-scale grazing are producing desertification of a tropical rain forest on a large scale. Some of the environmental consequences of wildfires are vegetation destruction, plant species and type shifts, exotic plant invasions, wildlife habitat destruction, soil erosion, floods, watershed function decline, water supply disruption, and air pollution. All of these are immediate impacts. Some impacts will persist beyond the careers and lifetimes of individuals. Small, isolated areas of fire produce noticeable localized desertification. But, the cumulative effect of multiple, large area, and adjacent fires can lead to landscape-level desertification.

Keywords: wildfire, desertification, erosion, sediment, type conversion, BAER

1. INTRODUCTION

Earth has been called the “Fire Planet” because of the long period, extent of, and impact of fire on ecosystems and their biota (Pyne 1997, Scott et al. 2013). Fire has been an integral part of many of the world’s ecosystems ever since vegetation developed as a fuel on the planet (Belcher et al. 2013). The sedimentary record indicates that wildfires have been occurring over the past 450 million years since the Paleozoic’s Ordovician Period, but really ramped up with the development of terrestrial vegetation in a lightning-filled atmosphere of the Carboniferous Period (307-359 million years before the present) (Scott 2000, Glasspool and Scott 2013). Fire was one of the environmental and evolutionary pressures that led to the diversity of plant and animal life on Earth. Humans are unique among the species on the planet in that they are a fire-making species, affecting natural fire regimes (David et al. 2011). Past climate changes have influenced the spread, severity, and biological effects of natural fire. Human activities such as forest clearing, agriculture development, grazing expansion, exotic plant dispersal and cultivation, fire ignition pattern changes, and fire suppression have strongly influenced the effects of fire on the atmosphere, terrestrial ecosystems, and human populations.

Changes in climate hydrological and drought cycles driven by increased greenhouse gas emissions associated with human activities is having a negative effect on wildfire timing, size, and severity thereby leading to significant feedback effects on ecosystems (David et al. 2011). Although lightning continues to be a major factor in wildfire ignition, the primary source of forest and grass fire starts throughout the world now is human activity, (Pyne 1997, Scott et al. 2013). As human populations have increased and industrialized over the past two centuries, fire ignitions and burned areas have increased due to sheer numbers of people and anthropogenic changes in the global climate. An example of the extent of fire across the globe can be seen in a MODIS satellite generated image of global fires during the period of 01 June to 31 August 2005 (Figure 8.1; Davies et al. 2004). This is the “Fire Planet”.

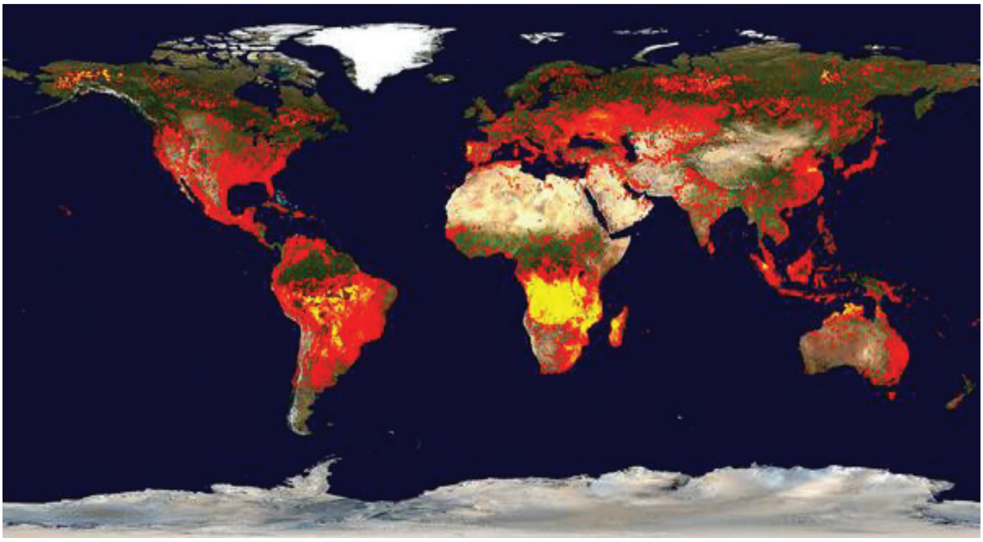


Figure 8.1. Global fires from MODIS satellite imagery 01 June 2005 through 31 August 2005. Red indicates fires recorded during the MODIS monitoring period. Yellow indicates regions of high fire frequency. Green is unburned vegetation. Light brown and brown areas are deserts. Ice shows up as white. (NASA 2018). http://rapidfire.sci.gsfc.nasa.gov/firemaps/from 2000 to 2010.

Recent scientific findings have bolstered the hypothesis that climate change is resulting in fire seasons starting earlier, lasting longer, burning greater areas, and being more severe (Tebaldi et al. 2006, Westerling et al. 2006). Computer models developed by a number of researchers (Tebaldi et al.2006; Werth et al. 2011) point to the USA, Mediterranean nations, and Brazil as hot spots that will commonly experience extreme fire behavior. The climatic change to drier and warmer conditions is already aggravating wildland fire conditions in the USA, the Mediterranean, and Australia. For instance, the wildfire season in the western USA is now 105 days more than two decades ago. It starts earlier and lasts longer. California's wildfire season is now 12 months long. These conditions are expected to continue well into the 21st century. Wildland fire can have positive, neutral, or negative impacts on ecosystems and their components. A wildfire negative impact of prime concern in the 21st century is desertification.

2. DESERTIFICATION

2.1. Description

Desertification is a human-induced or natural process which negatively affects ecosystem function and which results in disturbance to the ability of an ecosystem to accept, store, recycle water, nutrients and energy (Glantz and Orlovsky 1983, Lane 2918). It is not the immediate creation of classical deserts such as the Sahara, Gobi, Sonoran, or

Atacama deserts (Dregne 1986, Walker 1997). These types of landscapes are more one type of "end point" of other geologic, geomorphic and climatic processes. Although desertification is commonly thought of as land degradation that is a problem of arid, semi-arid, and dry sub-humid regions of the world, humid regions such as Brazil and Indonesia are now experiencing severe land degradation because of wide-scale deforestation and fire use (Figure 8 2).

Three salient features of desertification are soil erosion, reduced biodiversity, and the loss of productive capacity, such as the transition from grassland dominated by perennial grasses to one dominated by perennial shrubs (Aubreville 1949). For example, in the southwestern United States, semiarid grassland ecosystems dominated by the perennial bunchgrasses such as *Andropogon cirratus, Bouteloua curtipendula*, and *Trachypogon secundus* were replaced by shrublands dominated by creosotebush (*Larrea tridentata*)and mesquite (*Prosopis* spp.) as a result of overgrazing since the late 1800's (Brown 1982). This change in vegetation has resulted in desertification in this region.

It is a common misunderstanding that droughts cause desertification since dry periods are common in arid and semiarid lands and are part of the ebb and flow of climate in these regions (Walker 1997). Well-managed lands can recover from the dry segments of climate cycles when the rainfall increases. However, continued land abuse from agriculture, grazing, forest harvesting, wildfire, and mining during droughts certainly increases the potential for permanent land degradation (MacDonald 2000). Desertification results in the loss of the land's proper hydrologic function, biological productivity, and other ecosystem services as a result of human activities and climate change (Black 1997, Walker 1997, Millennium Ecosystem Assessment 2005a,b). It affects one third of the earth's surface and over a billion people. In the past, desertification was considered a problem of only arid, semi-arid, and dry sub-humid areas. However, humid zones can also undergo desertification-like degradation with the cumulative effects of human impacts (Figure 8.2; MacDonald 2000). The Amazon region is an example of where forest harvesting, shifting cut and burn agriculture, and large-scale grazing are producing serious land degradation (desertification?) of a tropical rain forest on a large scale (Malhi et al. 2008, Schiffman 2015). Indonesia is also having problems where large areas of tropical forest have been converted to oil palm cultivation using fire as a clearing technique (Margono et al. 2014).

Desertification of formerly productive land is a complex process. It involves multiple causes, and it proceeds at varying rates in different climates. It may intensify a general climatic trend toward greater aridity, or it may initiate a change in local climate. Desertification does not occur in straight-forward, easily predictable patterns that can be rigorously mapped. Deserts advance erratically, forming patches on their borders. Areas far from natural deserts can degrade quickly to barren soil or rock through poor land management. The proximity of a nearby desert has no direct relationship to desertification. Unfortunately, areas subjected to the process of desertification are brought to professional or public attention only after the process is well underway. This is especially true in regions where little or no data are available to indicate the previous state of the ecosystem or the rate of degradation. Scientists and many land managers are beginning to recognize that is a process that is part of global climate change (Reynolds and Stafford-Smith 2002, Stringer 2006, FAO 2010, UNCCD 2009).

a b

Figure 8.2. Conceptualization of desertification: a) True natural desert, Atacama Desert, Chile, and b) Wildfire associated desertification, Schultz Fire, Coconino National Forest, Arizona (Photos by Daniel G. Neary, USDA Forest Service).

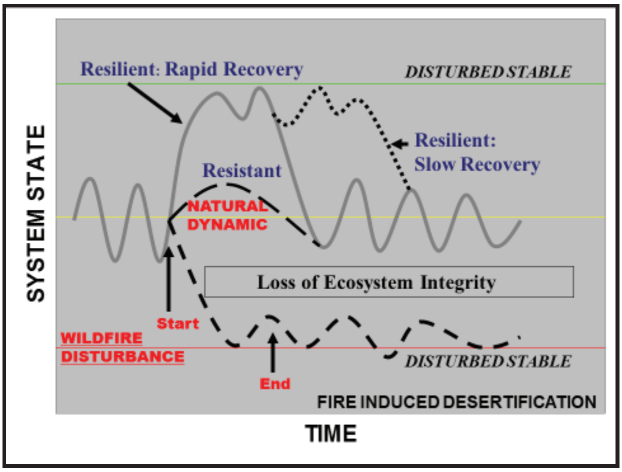


Figure 8.3. Conceptual diagram of severe wildfire induced degradation in ecosystem natural dynamics and response to disturbance.

The permanence of desertification depends on framework used to evaluate this geomorphic process. Efforts are now underway by natural resources science and management agencies to determine how desert-ification should be addressed and what are the social, environmental, and economic costs potentially facing countries in the short- and long-term (Requier-Desjardins 2006). Fire-induced desertification has many of the same consequences with the addition of substantial impacts in the short-term.

Severe wildfires produce disturbances in the natural dynamics of wildland ecosystems that cause them to lose integrity of various components and degrade to a lower system state (Figure 8.3). Instead of recovery to their original state, they decline to a new but disturbed, stable state where recovery to the original natural dynamic could take centuries (Yackinous 2015). Repeat fires aggravate the initial desertification and could prolong recovery or prevent it from ever occurring. There is growing evidence that new severe fires are burning into older fire scars and aggravating desertification by accelerating vegetation type conversion, species diversity loss, and erosion. Other environmental effects add to the degree of desertification (Geist and Lambin 2004). Some of the environmental consequences of severe wildfires are vegetation destruction, plant species and type shifts, exotic plant invasions, wildlife habitat destruction, soil erosion, floods, watershed function decline, water supply disruption, and air pollution. All of these are immediate impacts. Some will persist beyond the careers and lifetimes of individuals. Small, isolated areas do not produce noticeable desertification. But, the cumulative effect of multiple, large area, and adjacent fires can be landscape-level desertification.

Vegetation destruction encompasses the temporary loss of timber-producing roundwood and regeneration stock, as well as herbaceous flora (Brown and Smith 2000). Forests can be replanted or regenerated naturally after fires, but there will be a period of time from 30 to 200+ years where burned sites are degraded from the viewpoint of wood production. In addition, landscape-scale species type shifts can occur. For example, large areas of *Pinus ponderosa* stands (20,000+ ha) within high-severity fire portions of the Rodeo-Chediski Fire of 2002 and the Wallow Fire of 2011, Arizona, were instantly converted to a chaparral (evergreen oak and related species) type by the loss of pine regeneration and the seed reservoir in the soil. Without planting of seedlings, these areas will take centuries to return to their pre-fire productive state. Herbaceous plants often recover quite rapidly after fires, increasing plant diversity and productivity in the short-term. However, areas with high-severity wildfire may recover slowly (Neary et al. 2005). These sites are also subject to exotic plant invasions which may dramatically reduce biodiversity. These invasions are difficult and expensive to reverse. Fire affects animals mainly through changing the vegetative structure of their habitat (Smith 2000). It usually causes short-term improvements in wildlife foods that then result in wildlife population increases. Some species may be negatively affected by changes in the structure of forests after wildfire (e.g., removal of canopies).

2.2. Classification

There are four site-specific desertification categories with criteria that are directly linked to soil erosion and plant species composition (Dregne 1986, Table 8.1). The “Very Severe” category represents the situation of badly degraded land that is considered to be unusable and deteriorated beyond economically feasible restoration. In the past, drought, overgrazing, and wind erosion have been the leading factors of desertification in regions such as the southwestern USA. With the advent of large, high severity mega-fires (generally >30,000 ha) in the past two decades, wildfire has assumed an important role in desertification (Neary et al. 2005). Mega-fires are defined as wildfires that are extraordinary, in terms of their size, complexity, and resistance to control (Williams and Hamilton 2005; Heyck-Williams et al. 2017).

Table 8.1. Desertification classification system categories (After Dregne 1986)

Desertification Category	Topsoil Loss Percent	Climax Plant Species Percent
None to Slight	None to <25	100
Moderate	25 – 75	26 – 50
Severe	>95	10 – 25
Very Severe	Gullys Developed	<10

Table 8.2. Desertification wide area map classification criteria (After Dregne 1986)

Map Classification	Percent of Area in Various Desertification Categories
Slight	>50% in slight category <20% in severe category <10% in very severe category
Moderate	<50% in slight category <30% in severe and very severe category
Severe	>30% in severe category 0-30% in very severe category
Very Severe	>30% in very severe category

Classification of desertification has facilitated analysis at local, regional, national and continental scales (Table 8.2). Arid lands are much more prone to desertification as 81% fall into the slight to moderate category (Dregne 1986). A somewhat higher value was estimated for North America arid lands (90%). Area-wide desertification classifications use additional criteria within Dregne’s (1986) four-class system (Table 8.1). These criteria include plant cover, plant productivity declines, geomorphic evidence of desertification (e.g., dunes, gullies, and hummocks), soil salinity increases, undesirable forbs and shrubs, salt crusts, declines in soil permeability, soil stability, soil compaction, desertification spatial distribution, and departure from pristine conditions (Dregne 1977). The additional criteria give land managers a more in-depth understanding of the degree of desertification beyond topsoil loss and plant climax species changes.

2.3. Global Desertification Distribution

A recent report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessed land degradation and desertification using 100 experts from 45 countries (Leahy 2018). The IPBES analysis indicated that 75% of the planet's land surfaces are significantly degraded now and that the percentage could increase to 95% by 2050. Currently degraded lands have either become classical deserts, are polluted, or have been deforested and converted to agricultural or urban areas, leading to a substantial decline in biodiversity, increased erosion, reduced plant productivity, impaired ecosystem services such as water supply, and undesirable alterations in biomass quantity and quality. These are the key characteristics proposed by Aubreville (1949) in his treatise on desertification. The main drivers of this desertification trend are human population expansion, deforestation, unsustainable management of crop, forest, and grazing lands, and climate change. Wildfires are now interacting with these drivers to produce additional levels of desertification on lands previously devoid of significant degradation (Neary 2009).

3. WILDFIRES

3.1. Global Scale

Wildfire is now the prime factor next to climate change driving desertification in some of the forest lands in the western United States, the Mediterranean area, Chile, and Australia, to mention a few places. Individual wildfires are now larger and produce higher severity burns than in the past (Keeley et al. 2016). A combination of drought, climate change, fuel load build-ups, and increased ignition sources have produced the perfect conditions for fire-induced desertification (DeBano et al. 1998; Neary et al. 2005).

From 1983 to 2007, the USA had wildfires that burned a mean area of 2,587,831 ha yr^{-1} (USDA Forest Service 2018a). The mean area burned in the next ten years (2008 to 2017) increased by almost 100,000 ha yr^{-1} to 2,681,177 ha yr^{-1}. The maximum burned area increased slightly from 3,995,905 ha yr^{-1} to 4,097,648 ha yr^{-1}, but the minimum area burned each year in that 10-year period tripled from 464,751 ha to 1,385,176 ha. Clearly, wildfires and their effects are on the increase in the USA despite a decline in overall numbers (USDA Forest Service 2018a). The western USA in particular has been experiencing in a substantial drought over the past two decades (Soulé 2006; Koch et al. 2014).

Portugal has experienced a number of mega-fires in the 21st Century that it had little history of prior to 2000 (Tedim et al. 2012). The country suffered the worst and second worst wildfire seasons in a three-year period (2003 – 2005). In 2005, 338,262 ha of forest land burned (Neary 2006). This was a 77% increase over the 10-year burn average of

189,500 ha. Portugal has been experiencing one of its worst droughts ever, and the dry conditions have fed extensive wildfires (Pires and Silva 2008). Besides the lack of rainfall, temperatures were also higher than normal (European Commission 2006). Wildfires returned with a vengeance in 2016 and 2017. Dry thunderstorms ignited fires in 2017 that over a four day period burned over 45,000 ha.

Chile battled wildfires in 2017 on a scale never seen before (Watts 2017). Over 90 wildfires burned 180,000 ha of forest, farmland, and urban area in the middle of the country. Wildfire destroyed hundreds of homes, villages, and vineyards, and killed livestock, residents, and firefighters. Drought, high temperatures (40° C+), and strong winds contributed to the fire storm. Firefighters were brought in from France, Peru, Mexico, and the USA to assist local firefighting resources. Air suppression operations included helicopters, light aircraft, and a Boeing 747-400 VLAT (Very Large Air Tanker) from the USA. Chile has seen a substantial increase in wildfires from the 5,200 average for the 1990-2000 fire seasons. The main causes are climate change associated drought and large contiguous stands of introduced *Pinus* and *Eucalyptus* species (Leon, A.S. 2018. Personal Communication, University of Chile).

Australia has routinely experienced wildfires due to its hot and dry climate. For the most part it is a desert continent but substantial forests grow on the margins near the sea. Some native flora have evolved a dependence on wildfires to reproduce. Native Australians certainly were a factor in fire spread over many thousands of years. The country has experienced thirteen wildfires over one million hectares since 1851, five of these have been in the past three decades. The most notorious was the Black Saturday Bushfire in 2009 that resulted in 173 human fatalities, 4,000 structure losses, and unknown but substantial wildlife losses (Engel et al. 2012). What drove this wildfire were extreme temperatures (40° C+), winds in excess of 100 km hr^{-1}, and drought (Karoly 2009).

Other countries such as China, Greece, Indonesia, Russia, Spain, and Sweden are experiencing the same trend. Clearly this is a world-wide trend, linked to climate change, not isolated to the USA and Canada. Warmer temperatures, windier conditions, and drought across the regions shown in Figure 8.1 are fanning wildfires and increasing the rate of desertification at a global scale (DeBano et al. 1998; Lane 2018).

3.2. Regional Scale

An example of regional scale desertification due to wildfires is presented by the Southwest USA. This region is currently in a two to three decades long drought (Koch et al. 2014). Climate change projections have this area of the USA continuing in drought, decreasing streamflows, and increasing temperatures (Blanco et al. 2014, Melillo et al. 2014). The result is a prediction of reduced snowpack and streamflows, and increased wildfire size and severity. Thus the desertification trend of the past 28 years related to wildfires is likely to continue. The area burned by wildfire in this region has increased dramatically in the past two decades (Figure 4).

Wildfire area coverage in Arizona, New Mexico, and western Texas and Oklahoma started in 1910. The number of hectares burned on an annual basis was stable at less than 7,300 ha until 1990 (USDA Forest Service 2018b). The frequency and size of wildfires increased significantly with decadal wildfire area exploding over three orders of magnitude (Figure 4). The combination of climate change induced drought, fuel loads, fire weather, and ignition sources pushed the forest and grasslands of the region over the edge (DeBano et al. 1998, Neary et al. 2005).

A common comment by fire incident managers was "it is hotter, drier, and windier than normal and fire is out of the box". This comment reflected the situation that fire behavior prior to 1990 that was fairly predictable had changed significantly. Fuel loads reached an ecological tipping point and in combination with aggravated fire weather were able to produce larger and more severe wildfires that were in the realm of "Megafires" (Kodas 2017).

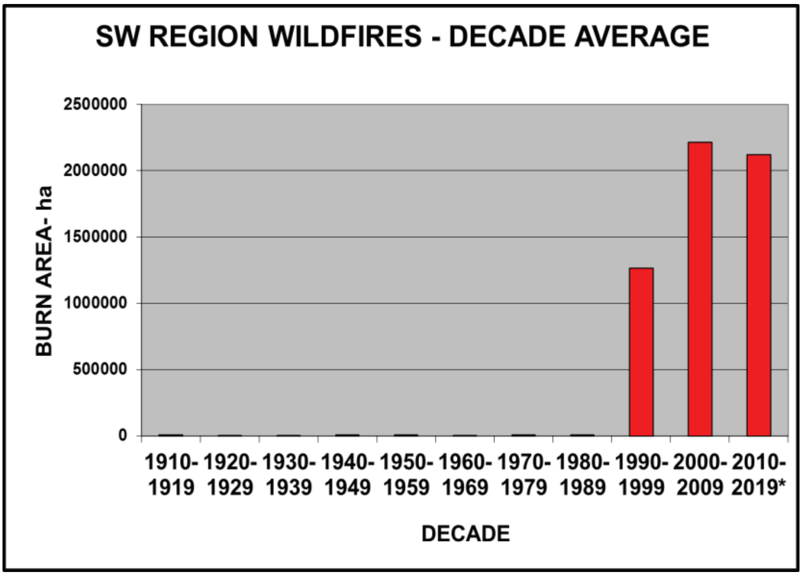


Figure 8.4. Southwest Region, USDA Forest Service, wildfires by decade, all land ownerships, 1910 to 2017, burned area in hectares. 2010 to 2019 decade does not include areas burned in 2018 and 2019 (USDA Forest Service, 2018b) https://gacc.nifc.gov/swcc/predictive/intelligence/Historical/Fire_Data/Historical_Fires_Acres.htm.

Other regions in the western USA experienced the same conditions. The fire season was suddenly widened by over 100 days, and, in the instance of California, became 12 months long. This situation has led to multiple fires within one region and multiple regions experiencing regional fires complexes. An example from the Pacific Northwest in 2017 is shown in Figure 8.5.

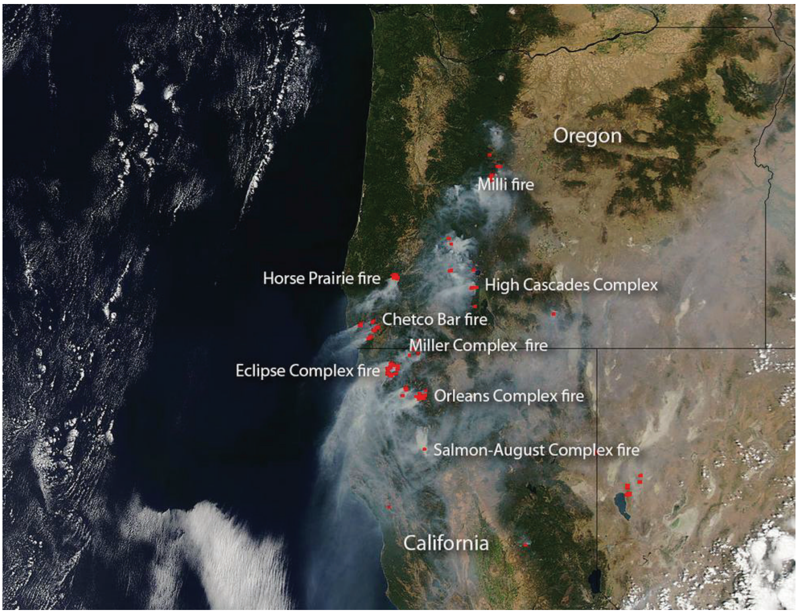
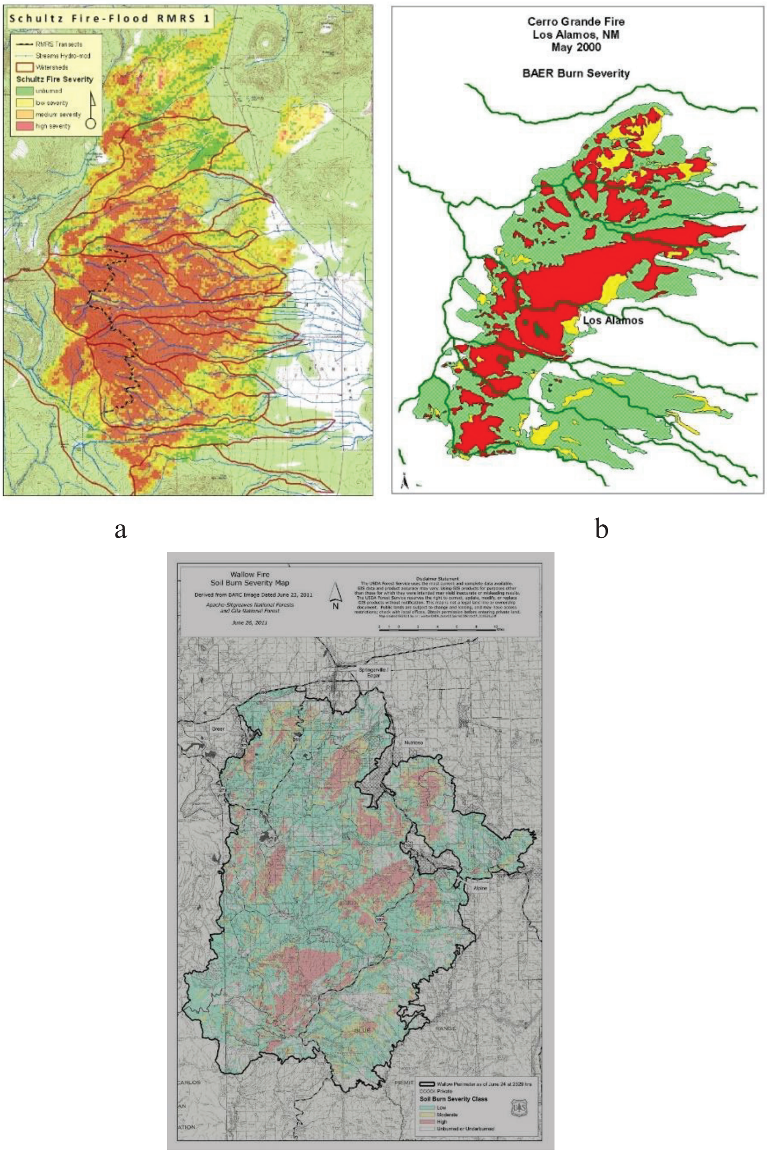


Figure 8.5. Multiple fire complexes within a region of northern California and southwestern Oregon during the summer of 2017 recorded by MODIS satellite imagery. https://www.nbclosangeles.com/news/tech/NASA-Satellite-Images-California-Wildfire-Brush-Fires-Images-Photos-433867203.html.

These fires started as single tree ignitions from lightning and then grew to larger fires because of drought conditions and wind events. The fires were declared "complexes" because of multiple fires in the same local area that often merged. Nearly 20 fires or complexes were located in the coastal region of southwest Oregon and northern California. The Chetco Bar Fire smoldered in a wilderness in mid-July until it blew up in August, burned into the 202,350 ha 2002 Biscuit Fire scar, made a run to the coast, and consumed nearly 76,900 ha before being contained in October. There is increasing evidence of new wildfires burning into older fire scars, increasing the risk of regional desertification. Wildfire should now be classified as a regional and multi-regional desertification problem in the USA.

3.3. Local Scale

At a local scale, desertification by wildfires is best examined by looking at the levels of fire severity and size produced by individual wildfires. Desertification becomes a real problem when individual fires have large areas of high severity fire, lose a substantial amount of soil, go through a vegetation type conversion, lose biodiversity, and coalesce over time to produce a significant landscape coverage (Neary et al. 2005, Keeley et al. 2016). Examination of several recent wildfires presents a good picture of the degree of local scale desertification.



a b

c

Figure 8.6. Burn severities and potential desertification on three wildfires in the Southwest USA. a) Schultz Fire, Coconino National Forest, Arizona, 6100 ha, 2010 (USDA Forest Service 2018b). b) Cerro Grande Fire, Santa Fe National Forest, New Mexico, 19400 ha, 2000 (USDA Forest Service 2018b). c) Wallow Fire, Apache-Sitgreaves National Forest, Arizona, 213700 ha, 2011 (USDA Forest Service 2018b).

Three fires from the Southwest USA are presented as examples of desertification on a local scale (Figure 8.6). They range in size from 6,100 to 213,700 ha and have different patterns of high severity fire. All three wildfire areas suffered from substantial soil erosion, vegetation type conversion, loss of biodiversity, and reduced productivity. Hence, desertification occurred on all three fires but patterns were different. Localized erosion was a function of fire severity, degree of water repellency, steep slopes >60%, and rainfall.

The Schultz Fire of 2010 burned 6,100 ha of the Coconino National Forest, on the east flanks of the San Francisco Peaks, Arizona (Neary et al. 2012; Figure 8.6a). Drought conditions led to the wildfire that originated in an unattended campfire. It accounted for 7% of the wildfire area in the region in 2000. The Schultz Fire in occurred in coniferous forest, composed mostly of ponderosa pine (*Pinus ponderosa*) with mixed conifer at the higher altitudes and aspen stands (*Populus tremuloides*). The fire was a mosaic of severities but what makes it stand out from other fires of its size was the high amount of high severity fire (61%) on steep slopes.

The Cerro Grande Fire of 2000 burned 19,400 ha in the Santa Fe National Forest north, west and south of Los Alamos, New Mexico (Nisengard et al. 2002; Figure 8.6b). This mid-sized wildfire was a typical mosaic of severities except for a large swath of high severity fire west and north of Los Alamos in moderately steep terrain. This fire accounted for 7% of the wildfires in the region during 2000.

It burned in coniferous forest, composed largely of ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii)*, white fir (*Abies concolor*), and aspen (*Populus tremuloides*). Drought set the stage for the fire and high winds caused a prescribed fire on the Bandolier National Monument to get out of control. The Wallow Fire of 2011 was the largest wildfire in modern history in the Southwest. It burned 213,700 ha on the Apache Sitgreaves National Forest, Arizona, and into a portion of Catron County, New Mexico (Figure 8.6c). The fire started in an unattended campfire and blew up due to drought, strong southwesterly winds, high fine and heavy fuel loadings and low humidity. It burned in multiple vegetation types consisting of ponderosa pine, mixed conifer, spruce-fir, oak woodland, grasslands, and riparian forest (Wadleigh 2011). The Wallow Fire accounted for 38% of the wildfire burned area in the Southwest in 2011. Some of the high severity areas shown in Figure 8.6c are the size of the Schultz Fire of 2010 presented in Figure 8.6a.

3.4. Fire Scales

Wildfire in forests, woodlands, and grasslands occurs across a range of scales from individual burning trees or stumps that occupy areas of 10^{-4} ha to mega-fires that burn over 40,000 ha. In North America, before modern fire suppression was established, fires over 100,000 ha in size were common (U.S. National Park Service 2018). The worst was a 2.0 x 10^6 ha monster, the Great Fire of 1919, that burned in Alberta and Saskatchewan. These types of fires are most likely to lead to desertification at a landscape level. But the 21st Century is not immune from these fires. Mega-fires over 10^6 ha in size have become more routine. One in the Northwest Territories of Canada exceeded 3.4 x 10^6 ha in 2014 but did not get much attention due to its remote location. Fires of this size are quite possible in populated areas of Canada and the USA even with a highly organized wildland fire suppression network. Drought produced by climate change is certainly a factor in this increase in landscape-level fires (Stringer 2005; Koch et al. 2014).

4. EROSION

4.1. Soil Loss Tolerance

In some instances, it is impossible to calculate percent loss of a soil's A horizon after wildfire due to the lack of pre-fire data. If erosion rates are measured or estimated, the Natural Resources Conservation Service (NRCS) Soil Loss Tolerance rates can be used can be used (Schmidt et al. 1982, Larson et al. 1983). The "None to Slight" category in the Desertification Classification (Table 8.3) is then replaced by "Tolerable" and "Low" categories of Soil Loss Tolerance (Table 8.4).

Table 8.3. Effect of soil conditions and erosion on desertification classification (From Garcia et al. 2005)

Soil	A Horizon Depth	Slope	Soil Loss[1]	Loss of A Horizon	Desertification Classification
	cm	%	Mg ha^{-1}	cm (%)	
Undisturbed	16	10	109	1 (6)	None - Slight
	16	66	311	3 (18)	Slight
Eroded	2	10	109	1 (50)	Moderate
	2	66	311	3 (150)	Severe

[1] Based on Rodeo-Chediski Fire of 2000, Garcia et al. 2005.


a) b)

Figure 8.7. Undisturbed Typic Hapludult soil (a), from the Jefferson National Forest, Virginia, and a burned and eroded Mollic Eutroboralf soil (b), from the Schultz Fire, Coconino National Forest, Arizona (Photos by Daniel G. Neary).

Table 8.4. NRCS soil loss tolerance rates (From McCormack et al. 1979)

Soil Loss Tolerance Rates – Natural Resources Conservation Service	
Soil Erosion Class	Soil Loss Mg $ha^{-1}yr^{-1}$
Tolerable (Very Low)	<6.7
Low	6.7 – 11.2
Moderate	11.2 – 22.4
High	22.4 – 33.6
Severe	>33.6

4.2. Degree of Desertification

The degree of desertification is very much dependent on soil type, slope, climate, and the past erosional history. The degree of and susceptibility to desertification can be assessed by the initial depth of a soil's "A" horizon and the subsequent loss of soil dues to erosion. For example, a soil that is undisturbed and has no history of fire in the previous century has a deep "A" horizon (Figure 8.7a). It can tolerate much higher erosion losses and is more resistant to desertification than one that has been previously and recently disturbed by any combination of causes (Figure 7b). The first soil, potentially losing 3 cm of depth to a high severity wildfire, rises to a slight desertification level. By contrast, the other soil falls into the severe to very severe category because of its thin "A" horizon and the loss of 3 cm (Table 8.3).

4.3. Soil Loss Due To Wildfires

Soil loss due to wildfires has been discussed by DeBano et al. (1998) and Neary et al. (2005). Fire-related sediment yields vary considerably, depending on fire frequency, climate, vegetation, and geomorphic factors such as topography, geology, and soils (Swanson 1981). In some regions, over 60 percent 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 (DeBano et al. 1998).

Sediment yields one 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 burn or fire severity and vegetation recovery. Soil erosion following fires can vary from under 0.1 to 15 Mg ha^{-1} yr^{-1} in prescribed burns, and <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 (DeBano et al. 1998; and Neary et al. 2005).

DeBano et al. (1998) reported that following a wildfire in ponderosa pine, sediment yields from a low severity fire recovered to normal levels after 3 years, but moderate and severely burned watersheds took 7 and >14 years, respectively. Nearly all fires increase sediment yield, but wildfires in steep lands suffer erosional losses that contribute to desertification. Sediment yields usually are the highest 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 until years 2 or more. In semiarid areas, post-fire sediment transport is episodic in nature, and the delay may be longer. All fires increase sediment yield, but it is wildfire that produces the largest amounts. Slope, water repellency, and rainfall intensity are major factors in determining the amount of sediment yielded during periods of rainfall following fire. There is growing evidence that short-duration, high-intensity rainfall (>50 mm hr^{-1} in 10- to-15 minute bursts) over areas of about 1 km^{2} often produce the flood flows that result in large amounts of sediment transport (Neary et al. 2005). It was estimated that soil loss on the 2010 Schultz Fire was catastrophic due to loss of the A horizon and parts of the B horizon. Soil loss totals were estimated to be in the range of 1,400 to 1,500 Mg ha^{-1} due to steep slopes (>100%), high severity fire, water repellency, and high intensity rainfall (Neary et al. 2012).

5. TYPE CONVERSION

Vegetation type conversion due to wildfires is another factor contributing to desertification (Bachelet et al. 2001). The most common scenario is a shift from coniferous forest species to chaparral-type ones. This shift is often perpetuated by recurrent fires in the fire-prone chaparral. A permanent vegetation type conversion would constitute desertification, especially where re-establishment of the original vegetation is hindered by the lack of seed source. High severity wildfires can consume any soil-based seed source and hinder regeneration. This especially true of tree species like ponderosa pine that do not sprout, and must rely on seeding from fire edges or manual planting. Fire can be a tool for restoring native shrublands affected by exotic grass invasions (Cione et al. 2002). However, fire can produce the opposite effect with exotic grasses like buffelgrass (McDonald and McPherson 2011). In some instances fire has been used to convert fire-prone vegetation types to less hazardous types (Keeley 2002). Vegetation type conversion is an important facet of desertification that is often overlooked in evaluations of severe wildfire impacts.

6. BURNED AREA EMERGENCY RESPONSE (BAER)

Burned Area Emergency Response (BAER) treatments have been used in the past and continue to be used to reduce wildfire impacts on desertification. But the question that is continually raised about BAER is this: "Is BAER really effective or just wishful thinking"? Robichaud et al. (2000) analysis found very little quantitative data to support cost/benefit analyses for most BAER treatments. Data on cost/benefit are very scarce. Efforts have been underway since 2000 to fill in data gaps (Robichaud et al. 2005). A number of BAER treatments were evaluated for two years after the 2002 Hayman Fire in Colorado (Robichaud and Elliot 2006). They reported that wood and straw mulch reduced erosion rates by 60 to 80%, contour-felled log erosion barriers 50 to 70%, hydro mulch, and grass seeding had little effect the first year when rainfall events were small and intensities low. The burned but untreated areas were classified as "High" to "Severe" desertification both years. The wheat straw kept desertification in the "None to Slight" category the first year, but in the following year it rose to "Moderate". The hydro mulch kept erosion in the "Moderate" to "Severe" range so it was not very effective in reducing post-fire desertification.

Seeding with white winter wheat (*Triticum estivum*) and additions of fertilizer after a wildfire in north-central Washington was evaluated but the treatment did not significantly reduce desertification-related erosion the first year (Robichaud et al. 2006). Soil loss varied from 31 to 16 Mg ha^{-1} yr^{-1} so it was in the "High" to "Moderate" categories. However, in the second year erosion was reduced to the very low to low level. This follows the trend in seeding reported by Robichaud et al. (2000) that seeding of herbaceous plants works to control erosion mostly from the second year onwards. Similar results from native plant seeding after the Rodeo-Chediski Fire of 2000 were reported by Garcia et al. (2005). Erosion during the first year after the fire was high in the "Severe" range for desertification (109 Mg ha^{-1}, Table 8.3), but it was reduced by half into the second year as forest herbaceous vegetation recovered. The seeding was ineffective at reducing or preventing desertification because of the timing differences between first storm events and plant germination. The results from the Rodeo-Chediski Fire of 2000 and the Wallow Fire of 2011 reinforce questions raised by Robichaud et al. (2000) on the efficacy of seeding in reducing post-fire erosion. Then, there is the whole issue of non-native plant introductions into seeded areas, even when "certified" seed is used. Burned Area Emergency Response treatments must be evaluated in a range of ecosystems to evaluate both their effectiveness at improving post-fire environmental conditions, and counteracting desertification.

Log erosion barriers have been used for decades to mitigate erosion in attempts to reduce the level of desertification. But, in a Western USA study of this BAER technique, the treatment was found to be ineffective at reducing erosion and hence, desertification (Robichaud et al. 2008). Although log erosion barriers were highly rated in professional surveys, they failed to provide adequate erosion prevention in storms with a greater than two year return period. The storms that produce runoff in excess of this interval are the ones that produce the high erosion rates that lead to desertification.

Additional monitoring and research is needed to adequately evaluate all the BAER treatments available to watershed managers to determine both cost effectiveness and ability to minimize desertification. Provisions and funds exist for land managers to monitor BAER treatments to get a quantification of reductions in erosion and exotic plant invasions. However, these opportunities are not being adequate utilized and the opportunity to guide future BAER treatments

There are several important management implications regarding BAER which were highlighted in Neary (2009):

1. Land managers need to be diligent in reducing fuel loads to prevent high severity wildfires. Prevention of catastrophic fires is much more cost effective than BAER treatments in both economic and environmental terms.
2. Some BAER techniques are effective in mitigating wildfires and some are not. Managers need to be aware of this and not rely on these mitigation techniques to be “magic fixes” that can make everything whole again.
3. Both new and old BAER techniques need to be evaluated across a range of ecosystems to determine if they are cost and environment effective in reducing erosion and preventing desertification.
4. Climate change is happening now and soils responses to wildfires can and will change, affecting future landscape productivity and sustainability.
5. Managers need to work closely with their staff, local university, agency, or consulting soil scientists to plan appropriate BAER and management responses to wildfire disturbances.
6. The BAER techniques that return some functionality to impacted soils (e.g., mulching) have the greatest probability of reducing desertification.

CONCLUSION AND SUMMARY

Human and naturally ignited fires from lightning altered and steered the trajectories of ecosystem development in most parts of the world. Mankind is now the primary source of forest and grass fire ignitions throughout the world although lightning still is a major factor in wildfire ignitions. As human populations have increased and industrialized in the past two centuries, fire starts have increased due to both sheer numbers of people and anthropogenic changes in the global climate. Recent scientific findings have bolstered the hypothesis that climate change is resulting in fire seasons starting earlier, lasting longer, burning greater areas, and being more severe. Computer models point to potential “hot spots” that will get temperature extremes and drought at their worst. The climatic change to drier and warmer conditions has the potential to aggravate wildfire conditions, resulting in longer fire seasons, larger areas of vegetation consumed, increased rates of erosion, more diversity loss, and higher fire severities. Wildfire is now driving desertification in some of the forest lands such as the western United States.

The areas of wildfire in the Southwest USA have increased dramatically in the past two decades from <10,000 ha yr^{-1} in the early 20th Century to over 230,000 ha yr^{-1} in the first decade of the 21st Century. Individual wildfires are now larger and produce higher severity burns than in the past. A combination of persistent climate change exhibited in drought, elevated temperatures, increased temperatures and reduced relative humidity, as well as excessive fuel loads and an abundance of ignition sources, have produced the perfect conditions for fire-induced desertification.

Desertification is about the loss of the land's proper hydrologic function, biological productivity, and other ecosystem services as a result of human activities and climate change. It now affects 75% of the earth's surface and over a billion people. In the past, desertification was considered a problem of only arid, semi-arid, and dry sub-humid areas. However, humid zones can undergo desertification with the wrong combination of human impacts. The Amazon region is an example of where forest harvesting, shifting cut and burn agriculture, and large-scale grazing are producing desertification of a tropical rain forest on a large scale. Some of the environmental consequences of wildfires are vegetation destruction, plant species and type shifts, exotic plant invasions, wildlife habitat destruction, soil erosion, floods, watershed function decline, water supply disruption, and air pollution. All of these are immediate impacts. Some impacts will persist beyond the careers and lifetimes of individuals. Small, isolated areas of fire produce noticeable localized desertification. But, the cumulative effect of multiple, large area, and adjacent fires can lead to landscape-level desertification.

Land managers need to be aware of these conditions and trends and devise management strategies to mitigate climate change effects. Vegetation management is now more important than ever. Physical fuels treatments and prescribed fire can go a long way in reducing the risks of high severity catastrophic wildfires in many areas. Fires in high elevation areas and wilderness will continue to be problematic. Climate change is a long-term problem that will affect wildfire size and severity and the process of desertification.

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