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Forest Soil Disturbance: Implications of Factors Contributing to the Wildland Fire Nexus

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Wildfires and prescribed fires cause a range of impacts on forest soils depending on the interactions of a nexus of fire severity, scale of fire, slope, infiltration rates, and post-fire rainfall. These factors determine the degree of impact on forest soils and subsequently the need for post-fire soil management. Fire is a useful tool in landscape management but it can be benign or set off serious deteriorations in soil quality that lead to long-term desertification. If parts of the nexus are absent or not inherently risky, forest soil impacts can be relatively minor or nonexistent. A low severity prescribed fire on a small landscape unit with minimal fuel loading, slopes less than 10%, and no water repellency is unlikely to damage soil condition and functions with all but heavy rainfall. On the other hand, a high severity wildfire in a substantial area of heavy fuels with slopes >100% and water repellency may undergo serious soil damage with even moderate rainfall. Soil management is not likely to be needed in the former case but virtually impossible in the latter scenario. This paper examines thresholds in the nexus factors which can raise the risks of wildland fire from low and moderate to high. It documents the interactions of the fire nexus using several case histories in North America and elsewhere to demonstrate different degrees of soil impact.

Core Ideas

- **Wildfire is a major cause of forest soil disturbance.**
- **Fire severity, scale of fire, slope, infiltration rates, and post-fire rainfall are major factors.**
- **Soil management has limited potential for mitigating negative effects.**
- **Fire area and severity are on the increase.**
- **Climate change is causing wildfires to be hotter, windier, drier, and larger.**

Soil is the unconsolidated, variable thickness layer of mineral and organic matter on the Earth's surface that forms the interface between the geosphere and the atmosphere (Binkley and Fisher, 2012). Forest, range, and wildland soils are formed as a result of physical, chemical, and biological processes affecting geologic parent material over long time spans of centuries to millennia. For the most part, soil-forming processes occur gradually. However, disturbances of varying size, severity, and cause impose drastic changes in the otherwise consistent and continuous progression of pedogenesis (Phillips, 1993). Natural disturbances such as climate change, drought, flooding, insect outbreak, volcanic eruptions, earthquakes, and wildfire have always been contributors to soil formation by affecting vegetation development. Human activities in the Holocene have introduced or intensified disturbances that have contributed to the progression or retrogression of soil formation. These profound disturbances include forest clearing, urbanization, agriculture development, grazing expansion, exotic plant dispersal, desertification, prescribed fire, and wildfire (Bowman et al., 2011).

Fire has been an integral part of many of the world's ecosystems ever since vegetation developed as a fuel on the planet (Scott, 2000; 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 increased substantially with the development of terrestrial vegetation in a lightning-filled atmosphere of the Carboniferous Period (307 to 359 million years before the present) (Glasspool and Scott, 2013). Fire was one of the environmental and evolutionary pressures

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that led to the diversity of plant and animal life on Earth and influenced soil formation.

Recent scientific findings have supported the hypothesis that climate change is resulting in fire seasons starting earlier and lasting longer. Fires are exhibiting more extreme behavior, burning greater areas, and being more severe (Westerling et al., 2006). Computer models developed by a number of researchers (Tebaldi et al., 2006) point to the United States, Mediterranean nations, and Brazil as regions that will experience more frequently extreme fire behavior. The climatic change to drier and warmer conditions is already aggravating wildland fire conditions in the United States, the Mediterranean, and Australia. For instance, the wildfire season in the western United States is now four months longer than two decades ago. It starts earlier and lasts longer. California's wildfire season is now twelve months long. These conditions of longer wildfire seasons, higher temperatures, lower rainfall, lower relative humidity, and greater wind speeds are expected to continue well into the 21st century (Westerling et al., 2011).

Wildfire is a prime factor next to climate change driving desertification in some of the forestlands in the western United States, the Mediterranean area, Chile, and Australia, to mention a few. 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 (Lane, 2018). It is not necessarily the immediate creation of classical deserts (Walker, 1997). Classical deserts are just one type of "end point" of the desertification process. Although desertification is commonly thought of as land degradation that is a problem of arid, semiarid, and dry sub-humid regions of the world, humid regions such as Brazil and Indonesia are now experiencing desertification because of wide-scale deforestation and fire use. Individual wildfires are larger and produce higher severity burns than in the past (Keeley and Syphard, 2016). A combination of drought, climate change, fuel load build-ups, and increased ignition sources have produced the perfect conditions for fire-induced desertification and degradation of wildland soils (Neary et al., 2005; Neary and Leonard, 2015).

From 1983 to 2007, the United States had wildfires that burned a mean area of 2.6×10^6 ha yr^{-1} (USDA Forest Service, 2018a). The mean area burned in the next 10 yr (2008 to 2017) increased by almost 0.1×10^6 ha yr^{-1} to 2.7×10^6 ha yr^{-1}. The maximum area burned in any 1 yr increased slightly from 4.0×10^6 ha yr^{-1} to 4.1×10^6 ha yr^{-1}, but the minimum area burned each year in the 2008 to 2017 period nearly tripled from just under 0.5×10^6 ha to 1.4×10^6 ha. Clearly, wildfires and their effects are on the increase in the United States despite a decline in overall numbers in some regions (USDA Forest Service, 2018a). The western United States in particular has been experiencing in a substantial drought over the past two decades (Soulé 2006; Koch et al., 2014). This climate situation has fueled both the severity and size of wildfires, to impact both the scale and degree of soil disturbance.

Wildland fire can have positive, neutral, or negative impacts on ecosystems and soils. Many forest ecosystems and their soils developed in natural fire regimes (Borchers and Perry 1990; DeBano et al., 1998). The greatest negative impacts of wildfire disturbance on soils occur when fire severity, scale of fire, fuel loading, slope, infiltration rates, and post-fire rainfall factors converge in their worst possible conditions and combinations to create a nexus of unusual disturbance (Neary et al., 2012).

FIRE SEVERITY

Predisposing Conditions

The effects and severity of wildland fire are strongly influenced by fuel loads and climate (DeBano et al., 1998). Fuel loading is defined as the total dry weight of fuel per unit of surface area. Both live and dead vegetation contribute biomass material that makes up the fuel consumed in combustion. It is a good measure of the potential energy that might be liberated by a fire (Brown and Smith, 2000). Natural fuel loadings can vary from 0.5 Mg ha^{-1} in light fuels to >400 Mg ha^{-1} in heavy fuels (Neary and Leonard, 2015).

Brown and Smith (2000) described four different types of severity linked fire regimes that affect vegetation. The severity of the fire is crucial to understand the survival and subsequent structure of the dominant vegetation. The four regime classifications include understory fire, mixed severity fire, stand replacement fire, and no fire. Understory fires are usually non-lethal to the dominant vegetation and do not change the structure of the dominant vegetation. These fires are usually low severity ground fires typified by prescribed fires (Fig. 1). Mixed severity fires produce selective mortality in the dominant vegetation, dependent on the tree species and the matrix of severities. Stand replacing fires kill the above ground parts of the dominant vegetation and change the structure substantially (>80%). Most wildfires are a mix of all of the three fire regimes and may contained areas that are classified as non-fire regime.

There are six factors which affect the intensities of fires and the severity of vegetation and other ecosystem impacts which fires produce. These fuel factors are temperature, moisture, position, loading, continuity, and compaction (Neary et al., 2005). Temperatures needed for fuel ignition range between 204 and 371°C (DeBano et al., 1998). Fuel moisture is another controlling factor that depends on climate, plant species, and ages of the vegetation. Wet weather increases fuel moistures and age determines plant moisture content, older plants being drier than younger ones. Live fuel moisture is also determined by season and the presence of adequate soil moisture and groundwater. Dead fuel moisture contents are a function of atmospheric humidity, air and biomass temperature, and solar radiation. The position of fuels relative to the ground (subsurface, surface, and aerial) also determines ignition ease. Subsurface fuels are primarily live and dead roots as well as thick, organic layers, which are the last to ignite. Surface fuels consist of litter, grasses, and other herbaceous plants. Aerial fuels are those above the ground surface and consist of shrub and tree biomass. Fuel loads are usually measured as the mass per unit area. Continuity of fuel is the horizontal and vertical spacing of biomass and is referred to as continuous or patchy. The rate of combustion and the direction of fire movement are more predictable with continuous fuels. Patchy fuel ignition is more dependent on spa-

Fig. 1. Low severity prescribed fire in a ponderosa pine (*P. ponderosa*) forest of the Coconino National Forest, Arizona (Photo by D.G. Neary, USDA Forest Service).

tial arrangement so that direction of movement and even ignition are sporadic and uneven (Fig. 2). Lastly, vegetation ignition and combustion are a factor of fuel compaction. A tightly compacted litter or organic matter fire will burn at a low speed and intensity due to air supply limitations whereas grass fires will burn with a high rate of spread, high intensity, and low severity. Crown fires (Fig. 3) can also burn with a high rate of spread, high intensity, and high severity.

Drought is well-known as an inciting factor to wildfires, especially large, high severity ones. Dry weather reduces the moisture content of vegetation and makes the potential fuel susceptible to ignition at lower temperatures (DeBano et al., 1998). Low atmospheric relative humidity also contributes to vegetation desiccation. Low antecedent rainfall, low fuel and air relative humidities, high air temperatures, and wind round off the recipe for a high severity wildfire (Bessie and Johnson, 1995; Bradstock et al., 2010).

A good example of the climate conditions driving a large and high severity wildfire that produced significant soil disturbance was the “Black Saturday Kinglake Complex Bushfires” in Victoria, Australia (Cruz et al., 2012). The wildfire occurred in February 2009. It burned 100,000 ha in 12 h. The fire was moving at speeds up to 150 m min^{-1} and was spotting up to 35 km ahead of the flame front. Air temperatures were >45°C and wind speeds were 80 to 100 km h^{-1}. Fire line intensities were rated at 88,000 kW m^{-1}.

Background

The commonly accepted term for describing the ecological effects of a specific fire is fire severity (Keeley, 2009; Neary and Leonard, 2015). The term fire severity describes the magnitude of the disturbance and, therefore, reflects the degree of change in ecosystem components. Severity integrates both the heat pulse above ground and the heat pulse transferred downward into the soil (Borchers and Perry, 1990). Fire severity is dependent on the nature of the fuels available for burning, fire duration, climate, and the combustion characteristics that occur when vegetation and forest floor fuels are ignited (Simard, 1991). Soils are affected by both the combustion of surface organic horizons (Byram, 1959), and the heat pulse into the mineral soil (DeBano et al., 1998).

Fire intensity, in a strict thermodynamic sense, describes the rate of energy release per unit length of fire line (Keeley, 2009). It is concerned mainly with the rate of aboveground fuel consumption and, therefore the energy release rate. The faster a given quantity of fuel burns, the greater the intensity and the shorter the duration (Alexander, 1982). Because the rate at which energy can be transmitted through the soil is limited by the soil’s thermal properties, the duration of burning is critically important to the effects on soils (Campbell et al., 1995). Most energy released by flaming combustion of for-

Fig. 2. Low severity prescribed fire on the Cascabel Watersheds, Coronado National Forest, 2008 (Photo by D.G. Neary, USDA Forest Service).

est and rangeland fuels is not transmitted downward into the mineral soil (DeBano et al., 1998). Therefore, fire intensity is not a good measure or predictor of the associated changes that occur in physical, chemical, and biological properties of the soil. High intensity and fast moving grass fires and crown fires often 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 and soil (Ryan, 2002). In this case, the surface litter is blackened (charred) but not consumed (Fig. 4). Numerous examples of this phenomenon occurred during the Australian bushfires of 2009 (Nyman et al., 2013).

If wildfires consume substantial surface and ground fuels, it is a good indication that the residence time was is greater, and more energy was transmitted into the soil. In such cases, a "white or orange ash" layer is often the only post-fire material left on the soil surface (Neary et al., 2005; Neary and Leonard, 2015). Presence of this type of ash is a good visual clue that a fire has affected soil physical, chemical, and biological properties. This is the case in parts of the Brins Fire in north central Arizona (Fig. 5). The wildfire burned up the entire organic horizon, small shrubs, and small diameter branches of trees.

Fig. 3. High severity stand replacing fire, Taylor Complex Fire, Alaska, 2004 (Photo courtesy of USDA Forest Service).

The term fire severity is used to indicate the level of fire effects on different ecosystem components (e.g., vegetation, soil, water, wildlife) (Ryan, 2002; Neary and Leonard, 2015). Thus, a low severity fire may useful in restoring and maintaining a variety of ecological attributes that are generally viewed as positive. Fire-adapted longleaf pine (*P. palustris*) and ponderosa pine (*P. ponderosa*) ecosystems are good examples of this beneficial effect. In contrast, a high severity fire may be a dominant, albeit infrequent, and unwelcomed disturbance in a non-fire adapted ecosystem (e.g., spruce *Picea* spp.). This type of wildfire is abnormal in a fire-adapted ecosystem (Fig. 5 and 6). All high severity fires have significant negative ecosystem impacts that affect ecological processes. In the case of fire-related biological, chemical, and physical impacts, the long-term functioning of the soil system can be significantly altered for decades, centuries, or millennia.

Fire Severity Classification

Soil heating is commonly shallow even when surface fires are intense (Ryan, 2002). Fire severity can be classified using both remote and on-the-ground techniques (French et al., 2008). Remote burn severity assessment methods provide the ability to make assessments quickly over large landscape areas.

A combination of fire intensity classes with depth of burn (char) classes has been used to develop a two-dimensional matrix approach to defining fire severity (DeBano et al., 1998). This system is based on two components of fire severity:

Fig. 4. Low severity prescribed fire in an Emory oak (*Quercus emoryi*) savanna with charred grass clusters (*Bouteloua* spp.) remaining from a rapidly moving surface fire, Peloncillo Mountains, Coronado National Forest, Arizona (Photo by D.G. Neary, USDA Forest Service).

Fig. 5. Gray to red ash remaining after high severity fire resulted in complete forest floor consumption and near complete above ground removal of a *P. edulis–Juniperus spp.* (pinyon-juniper) stand in the 2006 Brins Fire, Coconino National Forest, Arizona (Photo by D.G. Neary, USDA Forest Service).

1. An aboveground heat pulse due to radiation and convection associated with flaming combustion, and
2. A belowground heat pulse due principally to conduction from smoldering combustion where duff is present or radiation from flaming combustion where duff is thin or absent.

Ryan (2002) combined surface fire characteristic classes and depth of burn classes to revise the fire severity matrix (Table 1). By this nomenclature, two burned areas can be contrasted as having had, for example, an active spreading-light depth of burn fire (Fig. 1) versus an intense-moderate depth of burn fire, or a high severity deep soil burn (Fig. 5 and 6). The matrix provides an approach to classifying the level of fire severity for soils and ecological studies at multiple scales.

In the fire literature, there is common usage of a one-dimension rating of fire severity (DeBano et al., 1998). The single-adjective rating describes the overall severity of the fire and usually focuses primarily on the effects on the soil resource but also can include vegetation effects. The fire severity rating in Table 1 provides guidance for comparing the two-dimensional severity rating and for standardizing the use of the term. At the spatial scale of the stand or community, fire severity needs to be based on a sample of the distribution of fire severity classes. DeBano et al. (1998) and Neary et al. (2005) then developed the following criteria shown in Table 2 to rate burn severity.

Composite Burn Index

The criteria for defining the burn severity class boundaries are somewhat arbitrary but were selected on the basis of experience recognizing that even the most severe of fires have spatial variations due to random variations in fire environment (fuels, weather, and terrain), and particularly localized fuel conditions. Key and Benson (2005) developed a series of procedures for documenting fire severity in the context of field validation of satellite images of fire severity. Their procedures result in a continuous score, called the Composite Burn Index, which is based on visual observation of fuel consumption and depth of burn in several classes of fuels and vegetation. In most situations, depth of burn is the primary factor of concern when assessing the impacts of fire on soil and water resources. Depth of burn relates directly to the amount of bare mineral soil exposed to rain-splash, the depth of lethal heat penetration, the depth at which a hydrophobic layer will form, the depth at which other chemical alterations occur, and the depth to which microbial populations will be affected. As such, it affects many aspects of soil erodibility and hydrologic response to wildfires (Gresswell, 1999).

However, depth of burn is not the only controlling factor (Ryan, 2002). For example, in the surface microenvironment, shaded and exposed, surface and crown fires can be expected to affect post-fire species dynamics regardless of the depth of burn. In a surface fire, needles are killed by heat ris-

Fig. 6. High severity fire evidence on the Coon Creek Fire area, Sierra Ancha Experimental Forest,Tonto National Forest, Arizona, with white ash, water repellency in the soil surface, and complete vegetation combustion (Photo by D.G. Neary, USDA Forest Service).

Table 1. Two-dimensional fire severity matrix that relates fire intensity and depth of burn in soil to one-dimensional, relative fire severity ratings (Modified from Neary et al. 2005).

Fire behavior	Depth of burn (Unburned, Light, Moderate, Deep) and relative fire severity rating (LOW, MEDIUM, HIGH)			
	Unburned	Light	Moderate	Deep
Crowning	LOW: Radiation and convection burn of foliage MEDIUM: Fire burn over wetlands	MEDIUM: Crown fire over wet soil or litter HIGH: Crown Fire over bare mineral soil	MEDIUM: Residual duff or root mat scorched HIGH: Duff or root mat consumed	HIGH: Aboveground vegetation consumed
Running	LOW: Radiation and convection burn of foliage	MEDIUM: Crown fire over wet soil or litter HIGH: Crown Fire over bare mineral soil	MEDIUM: Residual duff or root mat scorched HIGH: Duff or root mat consumed	HIGH: Aboveground vegetation consumed
Spreading	LOW: Radiation and convection burn of foliage	LOW: Radiation and convection burn of foliage	LOW: Residual duff or root mat present HIGH: Residual duff and root mat consumed	MEDIUM: Forest canopy remains HIGH: Aboveground vegetation consumed
Creeping	LOW: Radiation and convection burn of foliage	LOW: Radiation and convection burn of foliage	LOW: Residual duff or root mat present MEDIUM Residual duff and root mat totally burned (gray ash) HIGH: Residual duff and root mat gone (white or orange ash)	MEDIUM: Forest canopy remains HIGH: Site vegetation consumed (white or orange ash)

ing above the fire (Dickinson and Johnson, 2001), thereby retaining their nutrients. Thus, litterfall of scorched needles versus none in crown fire areas can be expected to affect post-fire nutrient cycling. Thus, a lethal stand-replacement crown fire (a fire that kills the dominant overstory) represents a more severe fire treatment than a lethal stand replacement surface fire even when both have similar depth of burn.

Soil and Watershed Response

Prescribed fire conditions (generally low fire severity) as depicted in Fig. 5 are on the lower parts of fire severity and resource response curves. These conditions are typically characterized by lower air temperature, higher relative humidity, and higher soil moisture burning conditions, where fuel loading is low and fuel moisture can be high. They produce lower fire intensities and, as a consequence, lower fire severity leading to reduced potential for subsequent damage to the soil. Prescribed fire, by its design, usually has minor impacts on the soil resource (Morris et al., 2014).

Fire at the other end of the severity spectrum more nearly represents conditions that are present during a wildfire, where temperatures, wind speeds, and fuel loadings are high, and humidity and fuel moisture are low (Fig. 6). In contrast to prescribed burning, wildfire often has a major effect on soil and watershed processes, leading to increased sensitivity of the burned site to vegetative loss, increased runoff, erosion, reduced land stability, and adverse aquatic ecosystem impacts (Pyne et al., 1996; Neary and Leonard, 2015).

The flood flow shown in Fig. 7 is indicative of watershed responses initiated by short return-period rainfall events. It occurred 15 d after the Schultz Fire of 2010 and originated on steep slopes (>100%) that had 40% high severity and 27% moderate severity fire, and involved a 1000 m elevation drop in 5 km, from watershed crest to urban impact zone (Neary et al., 2012). Watersheds in mountainous regions across the range of severities respond to

Table 2. Fire burn severity classes modified by DeBano et al. (1998) and Neary et al. (2005).

Fire severity	Description
Low	Less than 2% of the area is severely burned, less than 15% moderately burned, and the remainder of the area burned at a low severity or unburned (visible as black ash).
Moderate	Less than 10% of the area is severely burned, but more than 15% is burned moderately, and the remainder is burned at low severity or unburned (visible as gray ash).
High	More than 10% of the area has spots that are burned at high severity, more than 80% moderately or severely burned, and the remainder is burned at a low severity (visible as white or orange ash).

Fig. 7. Flood flows after the Schultz Fire of 2010 crossing into urban areas, Coconino National Forest, Arizona (Photo by D.G. Neary).

storm events very differently than those in coastal plains, savannas, steppes, or glaciated regions where relief is at a minimum. That is one of the reasons why the most devastating wildfire impacts to soils occur in semiarid steeplands subjected to large scale, high severity fires (Fig. 8).

SCALE

Scale is another determinant of the degree of disturbance impact on forest, range, and wildland soils. Fire disturbance to a few square meters of soil is inconsequential compared to that of hundreds of hectares or entire watersheds (DeBano et al., 1998). Fires are becoming increasingly more severe and affecting larger land areas as wildfire seasons have expanded and climate conditions have become drier, hotter, and windier. Thus, the impacts of wildfire on soils in the 21st Century have accelerated and expanded (Neary and Leonard, 2015). 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 (US National Park Service, 2018). The worst was a 2.0×10^{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 3.4×10^{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 United States 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, 2008; Koch et al., 2014).

Fig. 8. Severe erosion of a Mollic Eutroboralf deep cobbly sandy loam soil on 100% slopes on the San Francisco Peaks after the high severity 2010 Schultz Fire, Coconino National Forest Arizona. (Photo by K. Koestner, USDA Forest Service).

Global Scale

Wildfire is now working in tandem with climate change, driving desertification in forestlands such as the western United States, the Mediterranean area, Chile, and Australia. Individual wildfires are now larger and produce higher severity burns than in the past (Keeley and Syphard, 2016). A combination of drought, climate change, fuel load build-ups, and increased ignition sources have produced the perfect conditions for fire-induced soil damage and desertification (Neary, 2018).

From 1983 to 2007, the United States had wildfires that burned an average area of 2,587,831 ha yr^{-1} (USDA Forest Service, 2018a). During the next 10 yr (2008 to 2017) the average area burned increased by almost 100,000 ha yr^{-1} to 2,681,177 ha yr^{-1}. The maximum burned area increased slightly to 4,097,648 ha yr^{-1}, but the minimum area burned each year in that

10-yr period tripled. Individual fires have morphed into the category of "Mega Fires". These fires are >30,000 ha in size, extraordinary in complexity, and resistance to control (Adams, 2013; Heyck-Williams et al., 2017). Clearly, wildfires and their destructive effects are on the increase in the United States (USDA Forest Service, 2018a). The western United States in particular has been experiencing in a substantial drought over the past two decades that has fueled the expansion of wildfires and their ecosystem impacts (Soulé, 2006).

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 3-yr period (2003–2005). In 2005, over 338,000 ha of forestland burned (Neary, 2018). This was a 77% increase over the 10-yr 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 4-d period burned over 45,000 ha. Measured soil impacts have included erosion and organic matter thermal decomposition (De la Rosa et al., 2012).

Chile battled wildfires in 2017 on a scale never seen before (McWethy et al., 2018). 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. Chile has seen a substantial increase in wildfires from the 5200 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 (A.S. Leon, Univ. of Chile, pers. comm., 2018).

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, 4000 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 h^{-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 worldwide trend, linked to climate change, not isolated to the United States and Canada. Warmer temperatures, windier conditions, and drought across fire-prone regions of the world are aggravating wildfire frequency, size, and severity, thus increasing the rate of soil deterioration and desertification at a global scale (Neary, 2018; Lane, 2018).

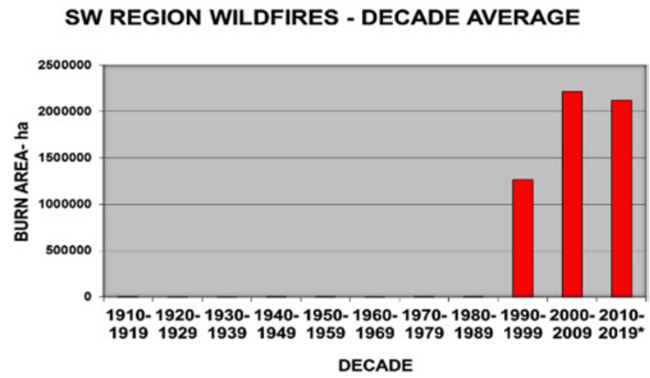

Fig. 9. Southwest Region, USDA Forest Service, wildfires by decade, all land ownerships, 1910 to 2017, burned area in hectares. Wildfires in the decades prior to 1990 were less than 50,000 ha per decade and thus barely show up on the y-axis. The solid bar of the 2010 to 2019 decade does not include all areas burned in 2019. (USDA Forest Service, 2018c).

Regional Scale

An example of regional scale impact due to wildfires is presented by the US Southwest. This region is currently in a two to three decades long drought (Koch et al., 2014). Climate change projections have this area of the United States 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 yr related to wildfires is likely to continue. The area burned by wildfire in this region has increased dramatically in the past two decades (Fig. 9).

Records of 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 7300 ha until 1990 (USDA Forest Service, 2018b). The frequency and size of wildfires increased significantly with decadal wildfire area exploding over 1.2 orders of magnitude. The combination of climate change induced drought, increased fuel loads, changed fire weather, and more ignition sources pushed the forest and grasslands of the region over the edge (DeBano et al., 1998; Neary et al., 2005). The decadal area of wildfire is still increasing as the drought persists and excessive fuel loads remain a problem. The area burned in the region has stabilized at a new level of about 220,000 ha for the past two decades, 32-fold the pre-1990 burn area.

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). Other regions in the western United States had the same conditions. The fire season was suddenly widened by over 100 d, and, in the instance of California, became twelve 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 Fig. 10. These fires started as single-tree ignitions from lightning and then

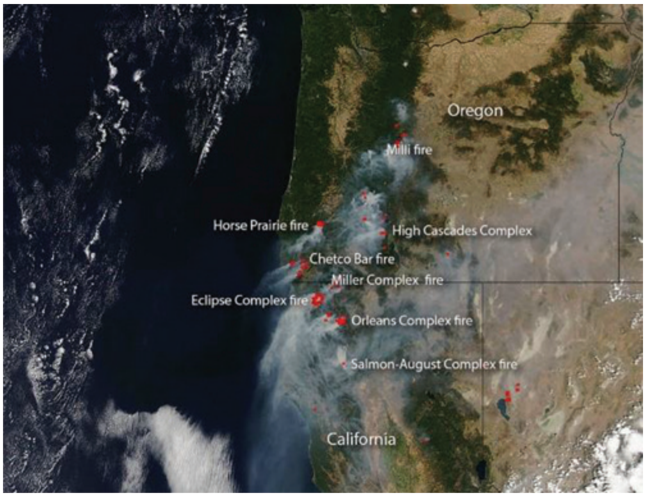

Fig. 10. Multiple fire complexes within a region of northern California and southwestern Oregon during the summer of 2017 recorded by MODIS satellite imagery (Photo from Lloyd, 2017).

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 impacts and desertification.

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 and Syphard, 2016). Examination of two recent wildfires in the western United States where there was a substantial amount of post-fire data presents a good picture of the degree of local scale desertification.

The Schultz Fire of 2010 burned 6100 ha of the Coconino National Forest, on the east flanks of the San Francisco Peaks, Arizona (Neary et al., 2012) (Fig. 11). 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 (*P. ponderosa*) with mixed conifer at the higher altitudes (*Picea* spp., *Abies* spp.), and aspen *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 (30 to >100%).

The Rim Fire of 2013 was the fourth largest wildfire in California's recorded history (Fig. 12). The fire began in August during the 2013 California wildfire season. It was the fourth-

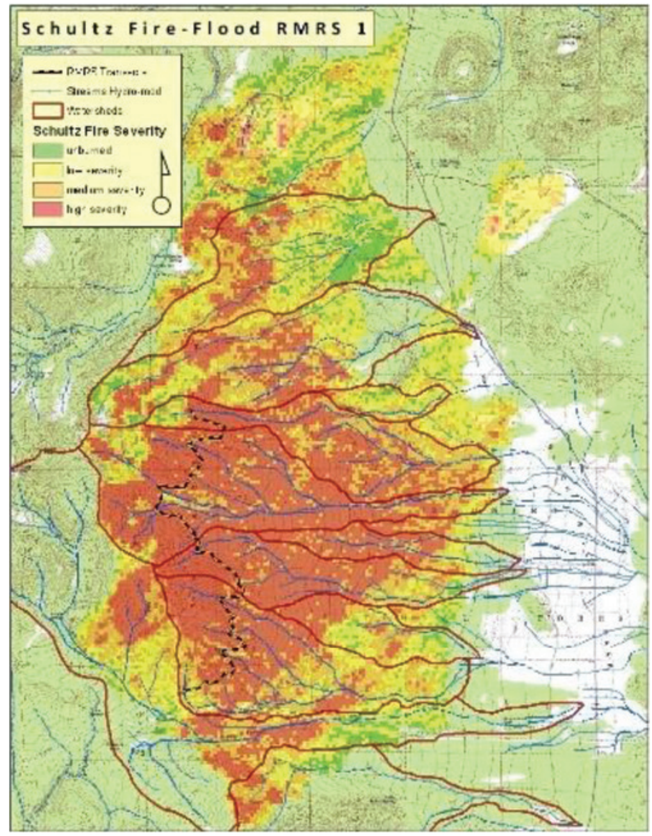

Fig. 11. Burn severities on the Schultz Fire, Coconino National Forest, Arizona, 6100 ha, 2010; burn severities in color on the map legend (USDA Forest Service, 2018b).

largest wildfire in California's history, having burned 104,134 ha. The Rim Fire was surpassed in 2017 by the Thomas Fire as the third-largest California wildfire. As large as it was, the Rim Fire was one-half of the biggest wildfire in modern history in the Southwest, the Wallow Fire.

The Rim Fire started in an illegal campfire during a fire ban on the Stanislaus National Forest, blew up due to drought, strong winds, high fine and heavy fuel loads low humidity and steep topography (Yosemite National Park, 2013). The fire also burned parts of the backcountry in the Yosemite National Park. It burned in multiple vegetation types consisting of chaparral, mixed oak species (*Quercus* spp.), ponderosa pine (*P. ponderosa*), Jeffrey pine (*P. jeffrey*), sugar pine (*P. lambertiana*), white fir (*Abies concolor*), and red fir (*A. magnifica*) (Kane et al., 2015). Some of the high severity areas shown in Fig. 12 are the size of the Schultz Fire (Fig. 11). Slopes ranging from 30 to >100% were key inciting desertification factors in both fires.

The degree of desertification and adverse soil impacts caused by both of these fires was due to the amount of high severity fire, erosion, and type conversion. Tree vegetation on high severity parts of both fires was consumed and converted to a grass/herbaceous/shrub community that will take centuries to convert back to forest. In addition, post-fire runoff on the high severity sites removed a substantial amount of "A" horizon material, leading to a loss of organic matter, nutrients, and productivity potential.

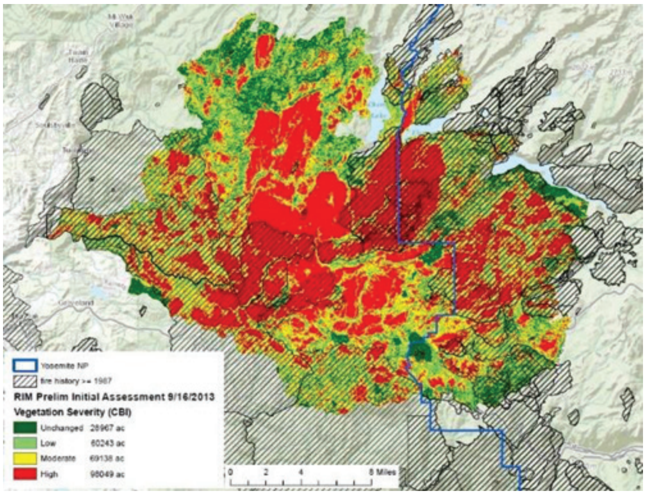

Fig. 12. Burn severity map of the Rim Fire, Stanislaus National Forest, California, 104.134 ha, 2013 (California Water Science Center, 2017).

SLOPE

Slope is one of the major factors that determines the velocity of surface runoff and associated erosion from any hillslope after a wildfire (Freeze, 1980; Sharpley, 1985; Neary, 2011). Other factors include rainfall amount and intensity, the presence of water repellency, antecedent soil moisture, soil infiltration capacity and hydraulic conductivity, surface roughness, surface cover, depression storage, and management history. Fox and Bryan (2000) demonstrated that slope gradient is a major influence on runoff velocity which in turn increases the sediment transport capacity of runoff flows. Inter-rill erosion rates increase with the square root of the slope gradient. Moss (1988) previously reported that inter-rill erosion rates are directly proportional to runoff velocities determined by slope.

Examples of the slope effect have been observed by many researchers and managers (Hendricks and Johnson, 1944; DeBano et al., 1998; Neary et al., 2005). Hendricks and Johnson (1944) measured soil loss from a high severity fire in Arizona. Annual soil loss that was 72 Mg ha^{-1} on 43% slopes rose to 369 Mg ha^{-1} on 75% slopes. Neary et al. (2012) estimated that soil erosion losses from >100% slopes reached 1500 Mg ha^{-1} from a Mollic Eutroboralf deep cobbly sandy loam the first year after wildfire.

Two examples of slope effect can be seen in runoff from the Rodeo-Chediski Fire of 2002 and the Schultz Fire of 2010 (Fig. 13 and 14). The former shows water sitting of the surface of a low gradient (<0.5% slope) area of high severity fire portion of a ponderosa pine stand (Ffolliott et al., 2010). The latter demonstrates very violent flow off of >100% slopes that also were burned at a high severity. The flood flow in Fig. 14 was a hyper-concentrated sediment flow that was transporting sediment materials in excess of 1 m in diameter. At the photo point the slope was reduced to about 60% but the energy of the flow was still there. The erosive power of this flow was due to high flow velocity, and the mechanical abrasion produced by large sediment clasts.

Sediments above the photo point consisted of finer “A” horizon materials, “B” horizon fines and coarse-textured sediments, and much coarser “C” horizon clasts. These were excavated by the high velocity flows and channel cutting (Neary et al., 2012). In some instances, the down cutting in drainage channels amounted to 5 m or more.

Fig. 13. Slight surface runoff beginning in a water repellent soil of a high severity burn area characterized by very low slope after the 2002 Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, Arizona (Photo by D.G. Neary).

RAINFALL

Rainfall is the energy source that results in forest soil disturbance (Neary and Leonard, 2015). The other factors that contribute to soil disturbance modify the effect of rainfall. It can be an enigma if instrumentation is not in place to accurately measure rainfall. Burned Area Emergency Response teams use historical records to estimate potential post-fire flows and soil disturbance. On some fires, rain gages get deployed in a timely fashion. This process gets complicated when wildfires are large and occur over steep terrain. Remote sensing technology like Doppler radar are useful in sorting out the intensity of rainfall and providing meteorological data to support flood watches and warnings (Hufford et al., 1998).

Short duration storms that are characterized by high rainfall intensity and low volume have been associated with high stream peakflows and significant erosion after fires (Neary and Ffolliott, 2005). In the western United States, high intensity, short duration rainfall is relatively common (Farmer and Fletcher, 1972). Five-minute peak rainfall rates (I_{5p}) of 213 and 235 mm h^{-1} have been associated with peakflows from recently burned areas that were increased five fold that for adjacent, unburned areas (Croft and Marston, 1950). A 15-min rainfall burst at a rate of 67 mm h^{-1} (I_{15p}) after the 2000 Coon Creek Fire in Arizona produced a peakflow that was seven-fold greater than the previous peakflow during 40 yr of streamflow gauging. Moody and Martin (2001) reported on a 30 min threshold for peak rainfall intensity (I_{30p}) of 10 mm h^{-1}, above which flood peakflows increase rapidly in the Rocky Mountains. Spigel and Robichaud (2007) collected rainfall intensity on 12 areas burned by wildfire in the Bitterroot Valley of Montana. They measured precipitation intensities that ranged from 3 to 15 mm in 10 min (I_{10p}). The high end of the range was an equivalent to 75 mm h^{-1} (greater than a 100-yr return interval). It is these types of extreme rainfall events, in association with altered watershed condition, that produce large increases in stream

Fig. 14. High turbidity, hyper-concentrated sediment flood flow originating from >100% slopes after the Schultz Fire, Coconino National Forest, Arizona (Photo by A. Stephenson, USDA Forest Service).

peakflows and erosion in conjunction with other site factors such as slope, cover, infiltration, geology, etc.

After the Schultz Fire in 2010 in Arizona, the burned area received numerous precipitation events that were a mixture short-duration and long duration storms with low and high rainfall amounts (Neary et al., 2012). The largest event was characterized by an I_{10p} peak rainfall of 24 mm, resulting in numerous debris flows, historic floods and substantial hillslope erosion (Fig. 7 and 14). Rainfall may have been in excess of this rate since gages were not yet deployed on higher elevations of the fire scar.

A study of debris flows was initiated after the Station and Jesusita wildfires California in 2009 (Kean et al., 2011). Debris flows were initiated after 15-min peak rainfall intensities (I_{15p}) of 12 mm h^{-1} in the San Gabriel Mountains and 56 mm h^{-1} in the Santa Ynez Mountains. Geology appeared to be an important factor in the rainfall response (granitic bedrock in the former and sedimentary in the latter).

INFILTRATION

The combustion of the forest floor, rainfall intensity, and the creation of water repellency in soils are the most significant factors affecting infiltration following post-fire rainfall. Development of water repellency involves both physical and chemical processes (DeBano et al., 1998). Although hydrophobic soils have been observed since the early 1900s (DeBano 2000a, 2000b), fire-induced water repellency was first identified after wildfires on chaparral watersheds in southern California in the early 1960s. There was an awareness of water repellency earlier in the 20th Century, but it had been referred to simply as the "tin roof" effect because of its effect on infiltration. In some regions of the world (southern California, Mediterranean, Australia, etc.) both the production of a fire-induced water repellency and the loss of protective vegetative cover play a major role in the post-fire runoff and erosion.

Normally, dry soils have an affinity for adsorbing liquid and vapor water because there is strong attraction between the mineral soil particles and water. In water repellent soils, however, water droplets "bead up" on the soil surface where it can remain for long periods and in some cases will evaporate before being absorbed by the soil (Fig. 15). Water, however, will not penetrate some soils because the mineral particles are coated with hydrophobic substances that repel water. Consequently, there is a wide range of saturated hydraulic conductivities (K_{sat}) reported in the literature (Neary 2011) (Table 3). Values of K_{sat} in undisturbed forest soils are generally >120 mm h^{-1} but have been reported to be as low as 5 mm h^{-1} and greater than 1000 mm h^{-1}. Water repellency has been characterized by measuring the contact angle between the water droplet and the water-repellent soil surface. Wettable dry soils have a liquid-solid contact angle of nearly zero degrees. In contrast, water-repellent soils have liquid-solid contact angles around 90 degrees.

Fig. 15. Appearance of a water droplet that is "balled up on a water repellent soil" (From DeBano, 1981 and DeBano et al., 2005; Photo by L.F. DeBano).

A hypothesis by DeBano (1981) describes how a water-repellent layer is formed beneath the soil surface during a fire, noting that organic matter accumulates on the soil surface under vegetation canopies during the intervals between fires. During fire-free intervals, water repellency occurs mainly in the organic-rich surface layers, particularly when they are proliferated with fungal mycelium. Heat produced during the combustion of litter and aboveground fuels vaporizes organic substances, which are then moved downward into the underlying mineral soil where they condense in the cooler underlying soil layers. The layer where these vaporized hydrophobic substances condense forms a distinct water-repellent layer below and parallel to the soil surface. The magnitude of fire-induced water repellency depends on several parameters, including the severity of the fire, the type and amount of organic matter present, temperature gradients in the upper mineral soil, the texture of the soil, and the water content of the soil (DeBano, 1981; Doerr et al., 2000).

Although there is a fairly clear correlation between high severity fire and saturated hydraulic conductivity (K_{sat}) reductions in the literature, some anomalies exist (Neary, 2011). Researchers in Australia have reported development of water repellency similar to wildfires in completely unburned watersheds (Sheridan et al., 2007). In addition, some moderate and high severity wildfires have not reduced K_{sat} to any significant extent. This could be due to soil physical properties, quality of the vegetation, or fire dynamics peculiar to the specific sites and soils studied or the characteristics of the wildfire. Soil K_{sat} reductions of 20 to 48% are commonly reported after wildfires. Some studies have documented K_{sat} reduc-

Table 3. Examples of changes in soil saturated hydraulic conductivity (K_{sat}) after wildfires and prescribed fires (Adapted from Neary, 2011). See Table 2 for severity definitions.

Location	Forest type	K_{sat} Unburned	Burned	Depth	Reference
		mm h^{-1}		cm	
Australia	Eucalypt woodland	92	74	0–10	Greene et al., 1990
	Eucalypt forest	45	35	0–5	Nyman et al., 2013
	Eucalypts summer	490	855	0–5	Sheridan et al., 2007
	Eucalypts winter	1409	459	0–5	Sheridan et al., 2007
France	Pine forest	210	155	0–6	Fox et al., 2007
Greece	Fir (moderate/high severity)	812	510/69†	0–10	Blake et al. 2009
	Oak (moderate/high severity)	263	263/289	0–10	Blake et al. 2009
Greece	Pine forest	432	360	0–5	Novák et al., 2009
Turkey	Oak/pine woodland	105	55	0–5	Ekinci, 2006
United States	Douglas fir and pine	789	170	0–3	Parks and Cundy, 1989
	Douglas fir and pine (low severity)	77–81	60–89	0–5	Robichaud, 2000
	Douglas fir and pine (high severity)	77–81	30–84	0–5	Robichaud, 2000

† Moderate/high severity.

tions of 88 to 92% with high severity wildfire. Reductions of this magnitude can have significant impacts on post-fire hydrological responses such as peakflows, soil erosion, and flooding. Because of the anomalies in K_{sat} reductions, it is difficult to state that there is a common threshold related to wildfire.

RUNOFF

Wildfire is the forest disturbance that has the greatest potential to change soil watershed condition (Binkley and Fisher, 2012). It exerts a tremendous influence on the hydrologic conditions of watersheds depending on a fire's severity, duration, and frequency. This is particularly true in regions where frequent fires, steep terrain, vegetation, and post-fire seasonal precipitation interact to produce dramatic impacts (DeBano et al., 1998; Neary et al., 2005). Watershed condition, or the ability of a catchment system to receive and process precipitation without ecosystem degradation, is a good predictor of the potential impacts of fire on water and other resources (such as roads, water supply infrastructure, recreation facilities, riparian vegetation, and so forth).

Disruption of the organic surface cover and alteration of the mineral soil by wildfire in combination with intense rainfall, steep slopes, and reduced infiltration can produce changes in the hydrology of a watershed well beyond the range of historic variability (Neary and Leonard, 2015). Low severity fires rarely produce adverse effects on watershed condition. High severity fires usually do the most damage and are good predictors of soil degradation (Moody et al., 2008) (Fig. 4, 6, 14, and 16). Most wildfires are a chaotic mix of severities, but in parts of the world, high severity is becoming a dominant feature of fires since about 1990 (DeBano et al., 1998; Neary et al., 1999; Robichaud et al., 2000). Successful management of watersheds in a post-wildfire environment requires an understanding of the changes in watershed condition and hydrologic responses induced by fire. Flood flows are the largest hydrologic response, and runoff is the most damaging mechanism producing erosion, soil degradation, infrastructure damage, and human fatalities (Neary et al., 2012) (Fig. 14 and 15).

Peak flows are a special subset of runoff that deserve considerable attention because of their erosive power. The effects of forest disturbance from wildfires on storm peak flows are highly variable and complex. These flows originate in first order drainages as rills and gullys where their impacts are more diffuse (Fig. 3). Peak flows coalesce into larger channels (Fig. 14 and 15) where they produce some of the most profound impacts that land managers have to consider (Fig. 16). The magnitude of increased peak flow following fire (0 to 2232-fold) is more variable than streamflow increases and is usually well out of the range of responses produced by forest harvesting (Neary et al., 2005). Increases in peak flow as a result of a high severity wildfire are generally related to a variety of processes including the occurrence of intense and short duration rainfall events, slope steepness on burned watersheds, and the formation of soil water repellency after burning (DeBano et al., 1998). Post-fire streamflow events with excessively high peak flows are often characteristic of flooding regimes. Peak flows are important events in channel formation, sediment transport, and sediment redistribution in riverine systems (Rosgen, 1996). These extreme events often lead to significant changes in the hydrologic functioning of stream systems and geomorphology (Fig. 14). Peak flows are important factors to consider in the design of structures (such as bridges, roads, dams, levees, commercial and residential buildings, and so forth). Fire has the potential to increase peak flows well beyond the normal range of variability observed in watersheds under fully vegetated conditions. For this reason, understanding of peak flow response to fire is one of the most important aspects of understanding the effects of fire on water resources.

Low severity, prescribed fires have little or no effect because they do not substantially alter watershed condition. Severe wildfires produce a greater range of variability and have much larger effects on runoff and peak flows (Kean et al., 2011). Campbell et al. (1977) documented the effects of fire severity on peak flows. A moderate severity wildfire increased peak flow by 23-fold, but high severity wildfire increased peak flow response three orders of magnitude to 407-fold greater than undisturbed conditions. Krammes and Rice (1963) measured an 870-fold increase in

Fig. 16. Urban flooding from runoff near Flagstaff, Arizona, after the 2010 Schultz Fire, Coconino National Forest (Photo by D.G. Neary).

Fig. 17. Deep channel incision on the Waterline Road, Coconino National Forest, Arizona, after the 2010 Schultz Fire. Exposed pipe is part of the Flagstaff, Arizona, water supply system that was cut in 27 places by flood flows (Photo by D.G. Neary, USDA Forest Service).

peak flow in California chaparral. Watersheds in semiarid lands are much more prone to these enormous peak flow responses due to interactions of fire regimes, soils, geology, slope, and climate (Swanson, 1981). Following the Rodeo-Chediski Fire of 2002, peakflows were orders of magnitude larger than earlier recorded. The estimated peak flow on a gauged watershed that experienced high severity stand-replacing fire was almost 900-fold that measured pre-fire (Ffolliott and Neary, 2003). A subsequent and higher peakflow on the severely burned watershed was estimated to be 6.57 $m^3 s^{-1}$ or about 2232-fold that measured in snowmelt runoff prior to the wildfire. This peak flow increase represents the highest known relative post-fire peak flow increase that has been measured in the ponderosa pine forest ecosystems of the Southwestern United States but was on the lower end of range of specific discharges measured by Biggio and Cannon (2001). Specific discharges after the Schultz Fire in Arizona were not measured but the channel incisions were evidence of substantial peak flows on slopes that were 100% or greater (Fig. 17).

Another concern is the timing of stormflows or response time. Burned watersheds respond to rainfall faster, producing more highly erosive "flash floods." They also may increase the number of runoff events. Hydrophobic conditions, bare soils, and litter and plant cover loss will cause flood peaks to arrive faster and at higher levels. Flood warning times are reduced by "flashy" flow, and higher flood levels can be devastating to property and human life. Recovery times after fires can range from years to many decades (DeBano et al., 1998). Still another aspect of the post-fire peak flow issue is the fact that the largest discharges often occur in small areas. Biggio and Cannon (2001) examined runoff after wildfires in the Western United States. They found that specific discharges were greatest from relatively small areas (1 km^2). The smaller watersheds 1 km^2 in their study had specific discharges averaging 193.0 $m^3 s^{-1} km^{-2}$), while those in the next higher sized watershed category (up to 10 km^2) averaged only 22.7 $m^3 s^{-1} km^{-2}$. Even larger watersheds produced lower specific discharges.

So, the net effect on watershed systems and aquatic habitat of increased peak flows is a function of the area burned, watershed characteristics, and the severity of the fire. Small areas in flat terrain subjected to prescribed fires will have little if any effect on water resources, especially if Best Management Practices are used. Peak flows after wildfires that burn large areas in steep terrain can produce significant impacts, but peak flows are probably greatest out of smaller sized watersheds less than 1 km^2. Burned Area Emergency Response (BAER) techniques may be able to mitigate some of the impacts of wildfire on peak flow, but the ability of these techniques to moderate the impacts of rainfalls that produce extreme peak flow events is not likely (Robichaud et al., 2000, 2009).

THE NEXUS AND IMPACT ON SOILS

A nexus is a connected group or series of factors which can be linked to cause an action or disturbance of some consequence. For wildfires, the fire nexus leading to soil disturbance consists of fire severity, wildfire scale, slope, rainfall, and infiltration conditions (Fig. 18). These factors, in and of themselves, do not necessarily lead to soil disturbance. But when they combine into the fire nexus they can produce profound disturbances in soil systems.

Knowledge of disturbance thresholds is important for understanding and management of post-wildfire soil disturbance. The severity threshold is moderate severity (DeBano et al., 1998). High fire severity is definitely a warning sign that major impacts to soil integrity and sustainability may occur.

Wildfires happen at all sizes and scales. Soil disturbance becomes problematic in the mid-range of small wildfires (>4000 ha) and becomes critical for landscapes in the zone of megafires (>40,000 ha) (Adams, 2013; Stephens et al., 2014; Jones et al., 2016).

Low slopes (<10%) do not generate high velocity peakflows that cause significant soil erosion. Even with high severity wildfires, low slopes limit the damage to soil systems. However, mobilization of nutrients can be a factor in soil desertification on low gradient slopes (DeBano et al., 1998). The slope threshold for significant disturbance in combination with the other fire nexus factors is 30%. Above that degree of slope even Burned Area Emergency Response measures become ineffective (Robichaud et al., 2009).

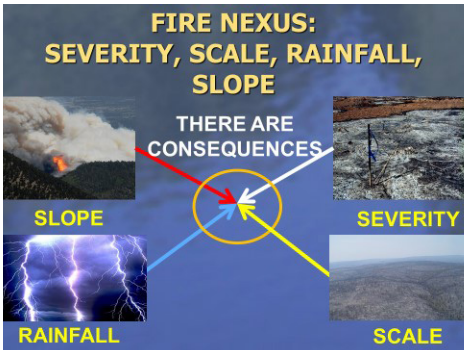

Fig. 18. Wildfire nexus.

The peak rainfall intensities that mark the threshold for setting off surface runoff, erosion, and flooding are variable depending on other contributing factors and the soils. Moody and Martin (2001) reported on a 30-min post-fire threshold for peak rainfall intensity (I_{30p}) of 10 mm h^{-1}. Cannon et al. (2011) determined that a similar I_{30p} threshold of 15 mm h^{-1} was critical for setting off sever surface runoff and erosion. Spigel and Robichaud (2007) found that an I_{10p} threshold of 75 mm h^{-1} was the most significant rainfall intensity for producing erosion and soil disturbance.

Because of the anomalies in K_{sat} reductions and the discovery of reduced K_{sat} in undisturbed forest soils, it is difficult to state that there is a common infiltration reduction threshold related to wildfire (Neary, 2011). High severity wildfire is commonly associated with the development of water repellency and aggravated surface runoff (DeBano, 2000a, 2000b). Water repellency is an inciting factor until erosion, mechanical disturbance, or climate-related disturbances break up the hydrophobic layer and erosion cuts into deeper soil horizons.

The wildfire nexus cannot be predicted because of uncertainty but the relative risk of it occurring can be understood if the important factors are taken into account (Miller and Ager, 2012). Steep slopes and high fuel loads are key indicators that significant soil disturbance could occur if intense rainfall follows fire events. This risk is certainly higher during the first year after fire events but could be delayed by years or even a decade.

SUMMARY AND CONCLUSIONS

Wildfires and prescribed fires cause a range of impacts on forest soils depending on the interactions of a nexus of fire severity, scale of fire, slope, infiltration rates, and post-fire rainfall. These factors determine the degree of impact on forest soils and subsequently the need for post-fire soil management. Fire is a useful tool in landscape management but it can be benign or set off serious deteriorations in soil quality that lead to long-term desertification. If parts of the nexus are absent or not inherently risky, forest soil impacts can be relatively minor or nonexistent. A low severity prescribed fire on a small landscape unit with minimal fuel loading, slopes less than 10%, and no water repellency is unlikely to damage soil condition and functions with all but heavy rainfall. On the other hand, a high severity wildfire in a substantial area of heavy fuels with slopes >100% and water repellency may undergo serious soil damage with even moderate rainfall. Soil management is not likely to be needed in the former case but virtually impossible in the latter scenario. This paper examined thresholds in the effects of the nexus factors which can raise the risks of wildland fire disturbance to soils from low and moderate to high. Significant soil disturbance can occur at, below, or above these general thresholds depending the unique circumstances of each fire. When all of the factors that make up the NEXUS are operating, there is high risk of ecosystem disturbance that will affect productivity and other ecosystem services.

CONFLICTS OF INTEREST

There are no conflicts of interest involved with the development of this manuscript.

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