CHAPTER

12 Restoring fire to forests: Contrasting the effects on soils of prescribed fire and wildfire

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12.1 Introduction

12.1.1 Fire-evolved ecosystems

Fire is a dynamic process, predictable but uncertain, that varies over time and landscape space. It is an integral component of most temperate wildland ecosystems and has shaped plant communities for as long as vegetation and lightning have existed on earth (Pyne, 1982; Scott, 2000). Wildland fire occurs across a spectrum ranging from low severity, localized prescribed fires to landscape-level, high-severity wildfires that affect vegetation, soils, water, fauna, air, and cultural resources (Brown and Smith, 2000; Smith, 2000; Sandberg et al., 2002; Neary et al., 2005; Zouhar et al., 2008; Bento-Gonçalves et al., 2012). Knowledge of fire effects has risen in importance to land managers because fire, as a disturbance process, is an integral part of the concept of ecosystem management and restoration ecology. Fire is an intrusive disturbance in both managed and wildland forests. It initiates changes in ecosystems that affect the composition, structure, and patterns of vegetation on the landscape. It also affects the soil and water resources of ecosystems that are critical to overall functions and processes (DeBano et al., 1998).

Most forest, shrubland, and grassland ecosystems have evolved with wildfire to some degree or another. Wildfire is a frequent occurrence in natural forest, grassland, and shrubland ecosystems (Pyne, 1982). It occurs less frequently in forest ecosystems such as jack pine (*Pinus banksiana*), lodgepole pine (*Pinus contorta*), but is more common in longleaf pine (Pinus *palustris*), and ponderosa pine (*Pinus ponderosa*) (White and Harley, 2016). Fire is an important ecological factor in those latter two ecosystems. Concerns exist among wildland managers that introduction of prescribed fire as a management

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tool will cause unintended and deleterious disturbances to ecosystem functions and processes (Neary and Leonard, 2015). Risks certainly exist, but the reintroduction of prescribed fire to forest ecosystems is a critical component of management-directed restoration activities needed to prevent catastrophic, high-severity wildfire that poses an even greater risk to forests. The objective of this paper is to evaluate and contrast the risks and impacts to forest soils created by the increased use of prescribed fire in forest management, especially where it is a component of restoration programs.

12.1.2 Fire classification

The general character of fire that occurs within a particular vegetation type or ecosystem across long successional time frames, typically centuries, is commonly defined as the characteristic fire regime. The fire regime describes the typical or modal fire severity that occurs. But it is recognized that, on occasion, fires of greater or lesser severity also occur within a vegetation type. For example, a stand-replacing crown fire is common in long fire-return-interval forests (Fig. 12.1).

The fire regime concept is useful for comparing the relative role of fire between ecosystems and for describing the degree of departure from historical conditions (Hardy et al., 2001; Schmidt et al., 2002). Discussion of the development of fire regime classifications based on fire characteristics and effects has been presented by several authors (Agee, 1993; Brown, 2000). Combinations of factors, including fire frequency, periodicity, intensity, size, pattern, season, and

FIGURE 12.1 High severity, stand-replacing wildfire.

Photo courtesy USDA Forest Service.

Table 12.1 Comparison of fire regime classifications (Hardy et al., 1998, 2001; Brown, 2000).

Hardy et al. (1998, 2001)			Brown (2000)	
Fire regime group	**Frequency (years)**	**Severity**	**Severity and effects**	**Fire regime**
I	0–35	Low	Understory fire	1
II	0–35	Stand replacement	Stand replacement	2
III	35–100 +	Mixed	Mixed	3
IV	35–100 +	Stand replacement	Stand replacement	2
V	>200	Stand replacement	Stand replacement	2
			Nonfire regime	4

depth of burn severity, and fire periodicity, season, frequency, and effects, have been used to map fire regimes in the Western United States (Table 12.1) (Heinselman, 1978; Hardy et al., 1998).

The fire regimes described in Table 12.1 are defined as follows:

- *Understory fire regime:* These fires are generally nonlethal to the dominant vegetation and do not substantially change dominant vegetation structure. About 80% of the aboveground dominant vegetation survives fires. This fire regime applies to fire-resistant forest and woodland vegetation (Fig. 12.2).
- *Stand replacement fire regime:* Fires of this type are lethal to most of the dominant aboveground vegetation. About >80% of the aboveground dominant vegetation is either consumed or dies, substantially changing the aboveground vegetative structure. This regime applies to fire-susceptible forests and woodlands, shrublands, and grasslands (Fig. 12.3).
- *Mixed fire regime:* In this fire regime class, severity of fires varies between nonlethal understory and lethal stand replacement fires. Variations could occur in space or time and within the same fire. Spatial variability occurs when fire severity varies, producing a spectrum from understory burning to stand replacement within an individual fire. Small-scale changes in the fire environment (fuels, terrain, or weather) and random changes in weather and plume dynamics produce this type of variability. While this type of fire regime has not been explicitly described in previous classifications, it commonly occurs in some ecosystems because of fluctuations in the fire environment (DeBano et al., 1998; Ryan, 2002). Complex terrain favors mixed severity fires because fuel moisture and wind vary on small spatial scales. Second, temporal variation in fire severity occurs when individual fires alternate over time between infrequent surface fires and long-interval stand replacement fires (Brown and Smith, 2000; Ryan, 2002). Temporal variability also occurs when periodic cool-moist climate cycles are followed by warm dry periods leading to cyclic (multiple decade level) changes in the role of fire

FIGURE 12.2

Understory fire regime: grass and emory oak savanna fire in a southern Arizona woodland, Coronado National Forest.

Photo by Daniel G. Neary, USDA Forest Service, Rocky Mountain Research Station.

in ecosystem dynamics. In moist upland forests, reduced fire occurrence during a wet cycle leads to increased stand density and fuel build-up. Fires that occur during the transition between cool-moist and warm-dry periods can be expected to be more severe and have long-lasting effects on patch and stand dynamics (Kauffman et al., 2003).

- *Nonfire regime:* Fire is not likely to occur in this vegetation type because of wet conditions (Fig. 12.4). However, fires have been documented in swamps and riparian areas previously thought to be fire proof.

Fire-related changes associated with fire severity contribute to diverse responses in the water, soil, floral, and faunal components of the affected ecosystems because of the interdependency between fire severity and ecosystem response. Both immediate and long-term responses to fire occur (Fig. 12.5). Immediate effects occur as a result of direct heating (e.g., damage to living cells) and from chemicals mobilized in ash created by biomass combustion. The response of biological components can be both dramatic and rapid. Another immediate effect of fire is the release of gases and other

FIGURE 12.3

Stand replacement fire regime: *Eucalyptus* stand replacement fire, Victoria, Australia.

Photo courtesy Chris Dicus, California Polytechnic State University.

FIGURE 12.4

Nonfire Regime: East Fork of the Black River, Apache-Sitgreaves National Forest, Arizona.

Photo by Alvin L. Medina, USDA Forest Service, Rocky Mountain Research Station.

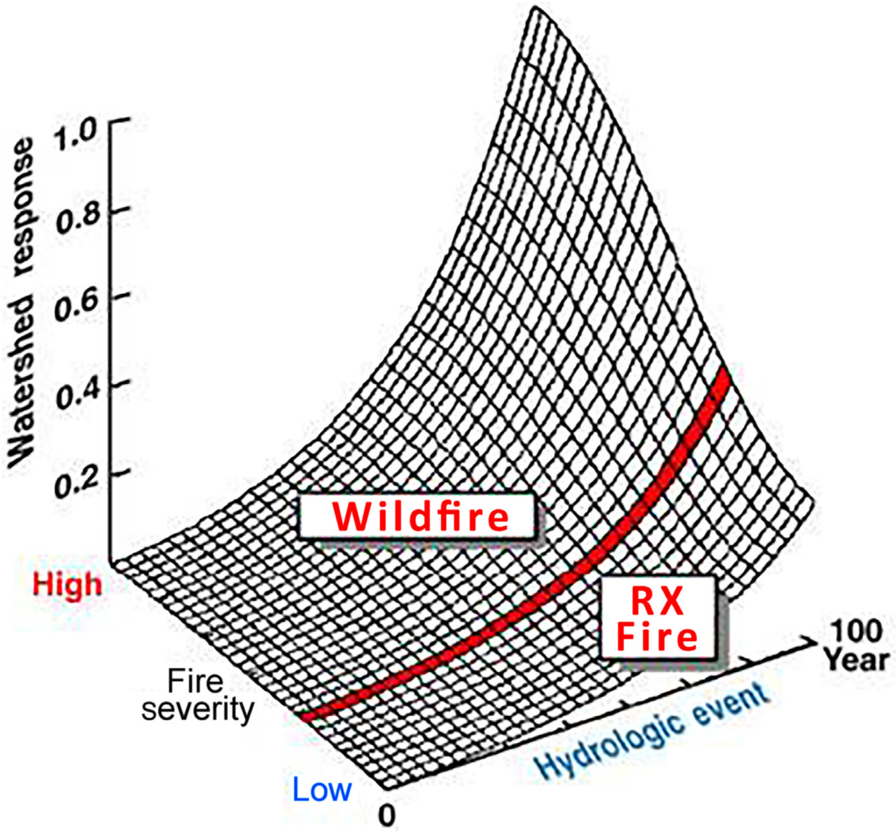

FIGURE 12.5

A conceptual model of watershed responses to wildfire severity.

From Neary, D.G., Ryan, K.C., DeBano, L.F. (Eds.), 2005. Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. General Technical Report RMRS-GTR-42 Volume 4. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, p. 250.

air pollutants produced by the burning of vegetation and soil organic matter (Dicosty et al., 2006). The long-term fire effects on soils and water are usually subtle, can persist for years following the fire, or may even be permanent as occurs when soils are disturbed by post—fire erosion (DeBano et al., 1998; Ryan et al., 2012). Other long-term fire effects arise from the relationships between fire, vegetation, soils, hydrology, nutrient cycling, and site productivity (Wright and Bailey, 1982).

12.1.3 Prescribed fire

An example of prescribed fires that are low in severity is shown in Fig. 12.2. They occur on the lower zones of the fire severity and resource response curve (Fig. 12.5, Neary et al., 2005). The weather conditions for prescribed fires in forests are typically lower air temperature, higher relative humidity, lower wind speeds, and higher soil moisture. Also, prescribed fires are usually conducted when fuel loading is low and fuel moisture is moderate to high. These conditions produce lower fire intensities and, as a consequence, lower fire severity, leading to a reduced potential for damage to soil and water resources. Prescribed fire, by its design, usually has minor impacts on vegetation, soil, water, and other resources. However, if fire is applied to maintain a desired type of vegetation, the impact on other vegetation could be major. For example, prescribed fire has a major impact on woody vegetation in mesic prairies, where it prevents a state change to shrubland or forest. Likewise, in longleaf pine, prescribed fires have a major impact on vegetation, including higher plant community diversity and altered community structure, since they are designed to maintain a grass—longleaf pine savanna (Brown and Smith, 2000).

The difference between wildfire and prescribed fires in shrublands is mainly the ignition source, the amount of fuel, weather, winds, resultant fire severity, and the rate at which the plant canopy is consumed. During wildfires the entire plant canopy can be consumed within a matter of seconds, and large amounts of heat are transmitted to the soil surface and into the underlying soil. The contrast in soil surface temperatures between wildfires and prescribed fires in shrubland ecosystems is remarkable, with peak soil temperatures of about 450°C in prescribed fires, but nearly 1500°C in high severity wildfires (DeBano et al., 1998). Not surprisingly, the difference in soil resource damage between the two conditions is significant. In contrast to wildfires, brush can be prescribe-burned under cooler and wetter conditions (e.g., higher fuel moisture contents, lower wind speeds, higher humidity, and lower ambient temperatures) such that fire behavior is less explosive and heat output is less. Under these cooler burning conditions the shrub canopy may be not be entirely consumed, and in some cases, a mosaic burn pattern may be created (particularly on north-facing slopes).

The general effects of fire in grassland on soil physical properties depend on a number of factors and range from very minor to serious (Pyne, 1982; DeBano et al., 1998). Since grassland fires are often rapidly moving with the wind and have much less fuel than that in brush and forest ecosystems, soil heating is significantly lower, and therefore physical damage is much less than what occurs during crown, surface, or smoldering fires. In general, physical impacts of fire on soil systems include alterations in soil physical properties, development of water repellency, and erosion (DeBano, 2000; Doerr et al., 2000). Comparisons of wildfire and prescribed fire in grassland ecosystems show few differences in soil impacts, particularly when wildfire severities are low (DeBano et al., 1998; Neary and Leonard, 2015). On the other hand, high severity wildfires that occur under adverse climate conditions and fuel loads can produce strong negative effects on soil properties.

12.1.4 Wildfire

All fires produce a range of severities. Wildfire that is at the far end of the severity spectrum (left side of Fig. 12.5) more nearly represents conditions that are present during a wildfire. Severity is frequently high where temperatures, wind speeds, and fuel loadings are high, and humidity and fuel moisture are low.

In contrast to prescribed fires, wildfires often have a major effect on vegetation, soil, and watershed processes, leading to increased sensitivity of burned sites to significant vegetative loss, increased runoff, erosion, reduced land stability, and adverse aquatic ecosystem impacts (Agee, 1993; DeBano et al., 1998; Scott, 2000). Fuels such as slash piles, decomposing logs, and thick layers of litter burn for long periods in wildfires and accentuate soil resource damage (Rhoades et al., 2004, 2015).

Another difference between prescribed fires and wildfires is the scale of burning. Prescribed fires are usually less than 400 ha in size although prescribed natural fires, managed like normal prescribed fires but initiated naturally, sometimes exceed 10 times that size. Small wildfires range in size from 400 to 40,000 ha. Megafires are those in excess of 40,000 ha and can exceed 1×10^6 ha (Stephens et al., 2014). Several individual forest wildfires in North America in the 19th Century and early 20th Century burned over 1.2×10^6 ha. The size of fires prior to the historical ones of the 19th Century is unknown, but wildfires and deliberate ignitions by Native Americans were definitely part of the presettlement North American environment (Frost, 1998). More recently, a series of fires in 2011 in Texas consumed over 1.6×10^6 ha of grassland and savanna, and in 2019, wildfires consumed in excess of 1.0×10^7 ha of land area in Australia. Fires of this scale clearly have the potential to produce serious effects on natural resources and human infrastructure over large landscapes (Wright and Bailey, 1982).

12.2 Fire effects

12.2.1 Combustion

Energy generated as heat during the combustion of aboveground and surface fuels provides the driving force that causes a wide range of changes in soil properties during a fire (DeBano et al., 1998). *Combustion* is the rapid physical−chemical decomposition of organic matter that releases the large amounts of energy stored in fuels. These fuels consist of dead and live standing biomass, fallen logs, surface litter (including bark, leaves, stems, and twigs), humus, soil organic matter, and roots. Importantly, the material that soil scientists consider the topmost genetic horizon in a soil profile (the O horizon) is composed entirely of these combustible fuels. During the combustion process, heat and a mixture of gaseous and particulate byproducts are vented into the air. When ignited, flames are the visual evidence of the combustion process.

Three components are needed in order for a fire to ignite and initiate the combustion process (DeBano et al., 1998; Neary et al., 2005). First, burnable fuel must be available. Second, sufficient heat must be applied to the fuel to raise its temperature to point where flammable organics volatilize. Lastly, sufficient oxygen (O_2) must be present to keep the combustion process going and to maintain the heat supply and oxidative source necessary for fuel ignition.

A common sequence of physical processes occurs in fuels before the energy contained in them is released and transferred upward, laterally, or downward. There are five physical phases during the course of a fire, namely, preignition, ignition, flaming, smoldering, and glowing (DeBano et al., 1998). Preignition occurs first when fuels are heated sufficiently to dry out and start the initial thermal decomposition (pyrolysis). After ignition the three final phases are flaming, smoldering, and glowing combustion in the presence of O_2. When active flaming begins to diminish, smoldering increases, and combustion diminishes to the glowing phase, which finally leads to extinction of the fire.

12.2.2 Soil heating

Heat produced during the combustion of aboveground fuels is transferred to the soil surface and downward through the soil by several heat transfer processes (radiation, convection, conduction, vaporization, and condensation) (DeBano et al., 1998; Neary and Leonard, 2015). *Radiation* is the transfer of heat from bodies not in contact with one another. *Conduction* is the transfer of heat by molecular activity from one part of a substance to another, or between substances in contact. *Convection* is a process whereby heat is transferred from one point to another by the mixing of one portion of a fluid (in this case combustion gases) with another fluid. *Vaporization* of water occurs when it is heated to a temperature at which it changes from a liquid to a gas. *Condensation* occurs when water changes from a gas to a liquid with the simultaneous release of heat. The combined mechanisms of vaporization and condensation provide a conduit for the transfer of both water and organic materials through the soil during fires (DeBano et al., 1998). Vaporization and condensation are important in fire behavior since they function in providing a more rapid transfer of heat through soils.

The mechanisms for the movement of heat into different ecosystems components vary considerably. Although heat is transferred in all directions, large amounts are preferentially lost into the atmosphere by radiation, convection, and mass transfer (DeBano et al., 1998). It has been estimated that only about 10%−15% of the heat energy released during the combustion of aboveground fuels is absorbed and transmitted by radiation directly downward to the litter, or mineral soil if surface organic layers are absent (DeBano, 1974; Raison et al., 1986). Within the fuels, most of the heat transfer is by radiation, convection, and mass transfer. In dry soils, convection and vaporization and condensation are the most important mechanisms for heat transfer. In a wet soil, conduction can contribute significantly to heat transfer. Movement of heat through mineral soil is an important thermodynamic process because it produces heating and changes in soil physical, chemical, and biological properties

12.2.3 Severity

In any discussion of the effects of fire on soils, it is important to differentiate between fire intensity and fire severity. The terms are not the same and are frequently confused (Hartford and Frandsen, 1992; DeBano et al., 1998; Neary and Leonard, 2015). *Fire intensity* is used to describe the rate at which a fire produces thermal energy. It is most quantified in terms of heat release per unit length of fire line. *Fire severity*, on the other hand, is a more qualitative term that is used to describe ecosystem impacts to fire and is especially useful for describing the effects of fire on soil and water components (Simard, 1991). Severity reflects the amount of heat energy that is released by a fire and the degree that it affects the soil and water resources. Fire severity has been classified based on visual postfire criteria at burned sites and has been categorized simply as low, moderate, and high-fire severity. Detailed descriptions of the appearances of these three severity levels for timber, shrublands, and grasslands can be found elsewhere (DeBano et al., 1998; Neary et al., 2005; Neary and Leonard, 2015). The level of fire severity depends upon:

- Length of time fuel accumulates between fires and the amount combusted (fuel load and fuel consumption).
- Properties of the fuels (size, flammability, moisture content, mineral content, etc.).
- The effect of fuels on fire behavior during ignition and combustion phases.
- Heat transfer to the soil during combustion of aboveground and surface fuels.

High-intensity fires can result in high severity changes in the soil, but this is not always the case. Low-intensity smoldering fires in roots or litter can cause extensive soil heating and produce large changes in the adjacent mineral soil. In contrast, high severity crown fires may not cause substantial heating at the soil surface because they sweep so rapidly over a landscape. Under these conditions, little heat generated during combustion is transferred downward to the soil surface.

12.2.4 Water repellency

The creation of *water repellency* in soils involves both physical and chemical processes (Fig. 12.6). It modifies physical processes such as infiltration and water movement in soils. Fire-induced water repellency was first identified on severely burned chaparral watersheds in southern California in the early 1960s (DeBano, 2000). Both the production of fire-induced water repellency and the loss of protective vegetative cover have played a major role in postfire runoff and erosion in some areas where large human population centers are situated immediately below steep, unstable shrubland watersheds. High severity wildfires are much more likely to produce extensive areas of water repellent soil layers than prescribed fires. Very localized zones of water repellency occur on prescribed fires, but these "spots" are unlikely to have any effect of watershed-level response and erosion.

Normally dry soils have an affinity for adsorbing liquid and vapor water. In water repellent soils, however, the water forms beads, ponds, and rills on soil surfaces where it can remain for long periods and in some cases will evaporate before being absorbed by the soil (DeBano et al., 1998). Water will not infiltrate

FIGURE 12.6

Rain ponding on a water repellent soil in the Rodeo–Chediski Wildfire of 2002, Apache-Sitgreaves National Forest, Arizona.

Photo by Daniel G. Neary, Rocky Mountain Research Station, USDA Forest Service.

into soils where the mineral particles are coated with hydrophobic organic compounds that repel water. Water repellency is produced by soil organic matter and can be found in both fire and nonfire environments (DeBano, 2000). Water repellency can result from the following processes involving organic matter:

- irreversible drying of soil organic matter;
- coating of mineral soil particles with leachates from organic materials;
- coating of soil particles with hydrophobic microbial byproducts;
- intermixing of dry mineral soil particles and dry organic matter; and
- vaporization of organic matter and condensation of these substances on mineral particles.

The magnitude of fire-induced water repellency depends upon a number of fire, edaphic, and climate parameters (Simard, 1991; Doerr et al., 2000). Although these occur with most fires, severity is mostly problematic with wildfires, not prescribed fires.

- the severity of the fire
- type and amount of organic matter present
- temperature gradients in the upper mineral soil
- texture of the soil
- water content of the soil

The more severe the fire, the deeper the formation of the water repellent layer, unless the fire temperatures are so hot that they destroy the surface organic matter. Most vegetation and fungal mycelium contain hydrophobic compounds that induce water repellency. Steep temperature gradients in dry soil enhance the downward movement of volatilized hydrophobic substances. Finally, soil water affects the movement of hydrophobic substances during a fire because it affects heat transfer and the formation of steep temperature gradients. Some studies in chaparral vegetation indicated that sandy and coarse-textured soil was the most susceptible to fire-induced water repellency (DeBano, 1981). However, other research has indicated that water repellency frequently occurs in soils other than coarse-textured ones (Doerr et al., 2000).

12.2.5 Effect of water repellency on post–fire erosion

Fire affects the processing of water and interactions with the soil in two ways. First, if the burned soil surface is unprotected due to complete combustion of the organic horizons, rain drop impact can loosen and disperse fine soil and ash particles. This situation can result in sealing of soil surface pores, reducing infiltration. The material that soil scientists consider the topmost genetic horizon in a soil profile (the O horizon) is composed entirely of combustible fuels. Second, soil heating during a fire can produce a water-repellent layer at or near the soil surface, lowering the saturated hydraulic conductivity, and further impeding water infiltration into the soil (Neary, 2011).

The severity of water repellency in surface soil horizons decreases over time due to repeated raindrop impacts, soil heating and cooling, freeze/thaw cycles, rodent activity, soil arthropod actions, and root growth (DeBano et al., 1998; Neary and Leonard, 2015). Water repellency deeper in the soil (10–15 cm) is more problematic since some of the mechanisms that produce surface repellency breakdown do not function at depth. It is only high-severity wildfires that have the energy release needed to form deep water repellency. Prescribed fires do not have the heat output that wildfires generate. Localized spots of very limited size such as under downed logs may occur. On a landscape scale, prescribed fires do not pose the risks that wildfires do with respect to the formation of water repellent layers and the associated erosion problems.

Sediment yields usually are the highest the first year after a fire and then decline in subsequent years (Neary et al., 2005). However, if precipitation is below normal, the peak sediment delivery year might be delayed until years 2 or 3. In semiarid areas, postfire 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 is a major factor in determining the amount of sediment yielded during periods of rainfall following fire (Table 12.2). There is growing evidence that short-duration, high-intensity rainfall (greater than 50 mm h^{-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 (Robichaud et al., 2009).

Table 12.2 Sediment losses the first year after prescribed fires.

Location	Management activity	First year sediment loss
		Mg ha^{-1}
South Carolina	Unburned (*loblolly pine*)	0.027
	Understory prescribed fire	0.042
North Carolina	Unburned (*southern hardwoods*)	0.002
	Semiannual prescribed fire	6.899
Mississippi	Unburned (*scrub Oak*)	0.470
	3-year prescribed fire	1.142
Texas	Unburned level terrain (*juniper*)	0.025
	Prescribed fire level terrain	0.029
	Unburned 15%–20% slope	0.076
	Prescribed Fire 15%–20% slope	1.874
	Unburned 43%–54% slope	0.013
	Prescribed fire 43%–54% slope	8.443
Oklahoma	Unburned (*mixed hardwoods*)	0.022
	Annual prescribed fire	0.246
Arkansas	Unburned (*shortleaf pine*)	0.036
	Slash prescribed fire	0.237
California	Unburned (*ponderosa pine*)	0.001
	Understory prescribed fire	0.001
Montana	Unburned (*larch, douglas fir*)	0.001
	Slash prescribed fire	0.150
Arizona	Unburned (*chaparral*)	0.001
	Prescribed fire	3.778

Adapted from Neary, D.G., Ryan, K.C., DeBano, L.F. (Eds.), 2005. Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. General Technical Report RMRS-GTR-42 Volume 4. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, p. 250.

Soil erosion following fires can vary from under 0.1–15 Mg ha^{-1} $year^{-1}$ in prescribed fires (Table 12.2), and from <0.1 Mg ha^{-1} $year^{-1}$ in low severity wildfire, to more than 369 Mg ha^{-1} $year^{-1}$ in high-severity wildfires on steep slopes (Table 12.3) (DeBano et al., 1998; Neary et al., 2005; Robichaud et al., 2009). Best Management Practices (BMPs) certainly have value in reducing sediment losses from prescribed fires. Wildfires, on the other hand, due to their very nature of being unplanned and often unmanageable, they do not lend themselves to being mitigated by BMPs.

The use of prescribed fire presents managers with alternatives for minimizing the damage done to the soil. The least amount of damage occurs during cool-burning, low-severity fires. These fires do not heat the soil substantially, and the changes in most soil properties are only minor and are of short duration. However, the burning of concentrated fuels (e.g., slash, large woody debris) can

Table 12.3 Sediment losses the first year after wildfires.

Location	Management activity	1st year sediment loss
		Mg ha^{-1}
Washington	Unburned (*mixed conifer*)	0.238
	Wildfire	2.353
California	Unburned (*chaparral*)	0.043
	Wildfire	28.605
California	Unburned (*chaparral*)	5.530
	Wildfire	55.300
Arizona	Unburned (*chaparral*)	0.096
	Wildfire	28.694
Arizona	Unburned (*chaparral*)	0.175
	Wildfire	204.000
Arizona	Unburned (*mixed conifer*)	0.001
	Wildfire 43% slope	71.680
	Wildfire 66% slope	201.600
	Wildfire 78% slope	369.600
Arizona	Unburned (*Pinus ponderosa*)	0.003
	Wildfire low severity	0.080
	Wildfire moderate severity	0.300
	Wildfire high severity	1.254
Idaho	Unburned (*grass and brush*)	0.030
	Wildfire moderate severity	0.125
	Wildfire high severity	1.538

Adapted from Neary, D.G., Ryan, K.C., DeBano, L.F. (Eds.), 2005. Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. General Technical Report RMRS-GTR-42 Volume 4. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, p. 250.

cause substantial damage to the soil resource, although these long-term effects are limited to only a small proportion of the landscape where the fuels are piled. These types of fire use should be avoided whenever possible. The burning of organic soils is also a special case where extensive damage can occur unless burning prescriptions are carefully planned. The effects of prescribed fires on soils in the eastern part of North America (where the majority of prescribed fires take place on the continent) have been reviewed by Callaham et al. (2012).

12.2.6 Climate

Recent climate change analyses suggest that much of the Western United States and other regions world-wide have a high probability of continuing or developing and future drought into the next 20–30 years, with associated increase in risk for wildfire. The cumulative impacts of warmer and drier climate, with ancillary disturbances such as insect outbreaks, urbanization, and the spread of exotic grasses will potentially increase the risk of wildfire. Prescribed fire will continue to be an important tool in reducing the risks of wildfire in this drought environment (Neary and Leonard, 2015). Fire regimes are representative of long-term patterns in the severity and occurrence of fires (Brown, 2000). They reflect the interdependence of several factors in the fire nexus, including climate, fuel accumulation, variability of soil and topographic properties, and ignition sources. Climate will remain a neutral discriminating factor between prescribed fires and wildfires.

12.2.7 The fire nexus

A "nexus" is defined as a connected group or series of factors which can be linked to cause an action or disturbance of some consequence. For prescribed fires and wildfires the fire nexus leading to soil disturbance consists of severity, scale, slope, rainfall, and infiltration conditions. These factors, in and of themselves, do not necessarily lead to soil disturbance. But when they combine into the fire nexus, they might produce profound disturbances in forest grassland, and shrubland ecosystems. Knowledge of disturbance thresholds is important for understanding and management of postfire vegetation and soils.

The severity threshold is moderate severity (DeBano et al., 1998). Prescribed fires rarely have large areas of moderate fire severity. High fire severity is common in wildfires and definitely a warning sign that major impacts to soil integrity and sustainability may occur.

Fires occur at all sizes and scales. Prescribed fires are generally <400 ha so size is not a major contributor to the fire nexus. Size and accompanying soil disturbance becomes problematic in the midrange of small wildfires (>4000 ha), and becomes critical factor for landscapes in the zone of megafires ($>40,000$ ha) (Adams, 2013; Stephens et al., 2014; Jones et al., 2016).

The disturbance threshold for slope is 30%. Above that, Burned Area Emergency Response measures become less effective and soil disturbance becomes more severe (Robichaud et al., 2009). Low slopes ($<10\%$) do not generate high velocity peak flows 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 (DeBano et al., 1998). Slope is a neutral discriminating factor between prescribed fires and wildfires. Prescribed fires on steep slopes might respond like wildfires if severities are high and the forest floor is combusted.

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. Peak rainfall intensities are reported as the I_{30p} where I is the intensity, 30 is the time period, and p is peak rainfall. An I_{30p} of 10 mm h^{-1} has been reported by some investigators as a critical threshold while others reported an I_{30p} threshold value of 15 mm h^{-1} (Moody and Martin, 2001; Adams, 2013). Others found that an I_{10p} threshold of 75 mm h^{-1} was the most significant rainfall intensity for producing erosion and soil disturbance (Spiegel and Robichaud, 2007).

Because of the anomalies in saturated hydraulic conductivity (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 fire (Neary, 2011). High severity wildfire is commonly associated with the development of water repellency and aggravated surface runoff. This may also occur in prescribed fires due to natural repellency processes (DeBano, 2000). Water repellency is an inciting runoff factor after fire 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 in the occurrence and magnitude of nexus factors, but the relative risk can be understood if the important components are considered (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.

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 postfire rainfall. These factors determine the degree of impact on forest soils and subsequently the need for postfire soil management. Fire is a useful tool in landscape management that can be benign or can 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 or watershed functions under any but very heavy rainfall conditions. On the other hand, a high severity wildfire in a substantial area of heavy fuels, with slopes >100%, and development of water repellency may undergo serious soil damage with even moderate rainfall. Soil management is not likely to be needed in the former case but may be virtually impossible in the latter scenario. Of course, these scenarios represent opposite ends of a spectrum, and nearly every combination of the components involved in the fire nexus may be encountered in the field. Understanding the interactions of these components will improve the responses of managers as they make decisions about restoration of burned forest soils.

12.3 Trends

12.3.1 Prescribed fire use

Prescribed fire is an important management tool and has been growing in frequency in the past several decades as land manager understand more clearly its role in the ecology of forest ecosystems. The general conditions of prescribed fire conditions in relation to soil and water resource responses are depicted in

Fig. 12.5 on the lower portion of the fire severity and resource response curve (Neary et al., 2005). 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. These conditions produce lower fire intensities and, as a consequence, lower fire severity leading to reduced potential for subsequent damage to soil and water resources. Prescribed fire, by its design, usually has minor impacts on soil and water resources.

In the past, State and Federal agencies have been slow to respond to changing fire management needs. But now communities which were once more concerned about smoke issues have increased awareness of the threats posed by large wildfires. Stakeholders are urging land management agencies to accelerate the use of prescribed fire as part of a package of treatments to reduce fuels and fire risks. In addition, there is pressure on agencies to reduce fire suppression costs, which can often consume 50% or more of annual budgets. More recently, the first eight of US National Forest revised management plans in the southern Sierra Nevada region of California proposed placing 50% of their management areas in prescribed and managed natural fire zones (North et al., 2015). Another 155 National Forests are working on revised land-management plans that incorporate increased use of prescribed fire.

The number of prescribed fires in the United States over the past 20 years has increased from 279 in 1998 to 450,335 in 2018 with the largest increase in state and other land-management entities (National Interagency Fire Center, 2019). Areas burned in the same period have increased from 359,086 to 2,574,286 ha. The number of wildfires declined over the 1998–2018 time period but the area burned increased by a factor of 6.6. There were 196 wildfires over 40,470 ha with the largest reaching a size of 528,374 ha. Clearly, use of prescribed fires has increased to attempt to reduce the numbers and sizes of wildfires.

12.3.2 Fire size and severity

The trend of a growing occurrence of fire around the world brings with it many of the consequences both direct and indirect (Liu et al., 2018). This analysis indicated that the future for potential wildfire increases significantly in fire prone regions of North America, South America, central Asia, southern Europe, southern Africa, and Australia. Fire potential is projected to increase in these regions, from currently low-to-future moderate potential or from moderate-to-high potential. The increased fire risk is driven by climate warming in North and South America and Australia, and by the combination of temperature increases and desertification in the other regions. The analysis in Liu et al. (2018) indicates that future increases in wildfire trends will require substantial investment of financial resources and management actions for wildfire disaster prevention and recovery.

In a discussion to the contrary the argument is made that there is evidence of reduced fire worldwide today than centuries ago (Doerr and Santin, 2016). Regarding fire severity, limited data are available. They indicate evidence of little change in the western United States and declines in the area of high severity fire compared to 18th and 19th century conditions. The authors argue that direct fatalities from fire and economic losses also show no clear trends over the past 30 years (Doerr and Santin, 2016). Trends in indirect impacts are insufficiently quantified to be examined in any significant degree.

On the other hand, an analysis of large wildfire trends in the western United States reported a significant increase in fire numbers and area burned (Dennison et al., 2014). This was particularly true in southern mountain regions with drought. The reported increase of wildland fires in these areas has amounted to 355 km^2 $year^{-1}$. An analysis of wildfire in Russia demonstrated and acceleration of wildfire in the 21st Century as a result of climate change (Shvidenko and Shchepashchenko, 2011). Trends in wildfire on US Forest Service lands from 1970 to 2002 were examined in a 2005 paper in the Journal of Forestry (Calkin et al., 2005). The authors reported that the number of large fires has more than doubled over this period and the area burned has increased fourfold. The number of fires and area burned by wildfires in eastern Spain from 1941 to 1994 documented increasing fire activity in southern Europe (Piñol et al., 1998). During this time period the areas and numbers of fires were increasing significantly and were associated with high fire hazard indices.

Wildfire appears to be on the increase globally but not uniformly. Drought and elevated temperatures are major factors contributing to wildfires and the hazards they pose to natural ecosystems and humans. Wildfire sizes and severity thus have the potential to present significant hazards to human health and safety and infrastructure in the 21st Century (DeBano et al., 1998; Brown and Smith, 2000).

12.4 Desertification

Desertification is an ecosystem disturbance of considerable concern in many regions of the world. It 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). It is not necessarily 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 the desertification process. Although desertification is commonly thought of as land degradation that is a problem of arid, semiarid, and dry subhumid regions of the world, humid regions such as Brazil and Indonesia are now experiencing desertification because of wide-scale deforestation and fire use.

Three salient features of desertification are soil erosion, reduced biodiversity, and the loss of productive capacity, such as the transition from forests to shrublands or from grassland dominated by perennial grasses to one dominated by perennial shrubs (Aubreville, 1949). 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 wildfire 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 (Walker, 1997; Black, 1997). It affects one-third of the earth's surface and over a billion people (MacDonald, 2000). 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 (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 straightforward, 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. Fire-induced desertification has many of the same consequences as other causes of desertification 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. 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). Repeated 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 (McGuire and Youberg, 2019). Other environmental effects add to the degree of desertification (Geist and Lambin, 2004). Low severity prescribed fires do not contribute to desertification in any appreciable manner so they can be used in environmentally sound fire management programs.

12.5 Summary and conclusion

This chapter examined the effects on soils of restoring prescribed fire to forests that have been managed under the paradigm that all fire is deleterious to ecosystem health. More specifically it contrasted the effects on soils of desired prescribed fire and undesirable wildfire. Prescribed fire is being used with increasing frequency to prevent catastrophic wildfires. In situations where forests have become overstocked due to fire exclusion, mechanical thinning, and removal of excess biomass by harvesting and prescribed fire is necessary to put these forests in ecological conditions whereby accidental or natural ignitions of wildfire do not explode into high-severity wildfires. Well-planned and controlled prescribed fires do not reach the severities or sizes that result in significant soil and other resource damage. Wildfires pose a definite risk to soil health and conditions. Prescribed fires do not. Ecologically sustainable forest management can certainly utilize prescribed fire as a tool to achieve objectives and reduce the risks of catastrophic wildfires. Once restored, forest stands can be maintained in a low wildfire risk category by periodic prescribed fires.

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