Effects of Wildfire on Soils and Watershed Processes

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ABSTRACT

Wildfire can cause water repellency and consume plant canopy, surface plants and litter, and structure-enhancing organics within soil. Changes in soil moisture, structure, and infiltration can accelerate surface runoff, erosion, sediment transport, and deposition. Intense rainfall and some soil and terrain conditions can contribute to overland runoff and in-channel debris torrents. Mineralization of organic matter, interruption of root uptake, and loss of shade can further impact water quality by increasing stream temperatures and nutrient concentrations. Where wildfires are unnaturally large and severe, watershed effects are likely to be negatively skewed.

Keywords: debris torrent; erosion; fire intensity; fire severity; infiltration; nutrients; runoff; salvage logging; sediment deposition; temperature; watershed restoration; wildfire

The late Dr. Harold Biswell of the University of California at Berkeley, known affectionately as "Harry the Torch," fiercely supported prescribed burning combined with thinning and pruning to create conditions that minimized the severity of wildfires and their effects. Considering impacts of fire on water quality, Dr. Biswell was adamant that research supported the notion that fire severity and location, not burning per se, determine soil and watershed responses to fire.

Recognizing Dr. Biswell and countless others who laid the groundwork for our current understanding, here we review the potential effects of wildfire on forest soils and watershed processes. These include: loss of surface litter and organic matter in the soil; development of water-repellant soil conditions; altered infiltration and surface runoff; dry ravel; rill and gully erosion; debris torrents, channel scour, and deposition; and increased solar radiation and nutrient release, leading to elevated stream temperatures and nutrient concentrations.

Fire and Soil

Many of the unique features of forest soils, such as the forest floor, decaying debris, and cycling of nutrients, can be dramatically altered by severe wildfire. Subsequent watershed effects are closely linked to these soil changes. During a wildfire, temperatures at the soil surface can approach 900° C (1,652° F). Because dry soil is a poor conductor of heat, at 5 cm (2 in.) below the surface the temperature is not likely to exceed 150° C (302° F) (DeBano 1981). High-temperature fires may completely consume the surface organic layers, with the organic material mineralized or volatilized during oxidation. The consequences can be exposed mineral soil, nutrient transformations, ash accumulations, near-surface soil particles bereft of binding organics, and water repellency.

The loss or transformation of surface litter and soil organic matter depends on local burn temperatures, which are controlled by such factors as fuel loads, types, and moisture contents, and fire weather. At higher temperatures, much of the mass of organic matter can be transformed into carbon dioxide and water vapor, with nutrients lost as gases or converted (mineralized) into forms more readily transported by surface runoff or drainage water. The nutrient most vulnerable to gaseous losses is nitrogen, which can be volatilized at relatively low temperatures (e.g., 200–500° C or 392–932° F). Phosphorus can be volatilized at high burn temperatures (e.g., 770° C or 1,418° F), whereas other mineral nutrients such as calcium, magnesium, and potassium are typically converted to oxides (often a major component of the light-colored ash remaining after fire) that are relatively soluble.

Water repellency results when volatilized organic compounds condense on cooler soil particles associated with steep temperature gradients below the soil surface. This results in negatively charged layers that repel water, thereby reducing infiltration (water movement into the soil surface) or percolation (water drainage within the soil). Reductions in the infiltration rate can be dramatic (e.g., one to two orders of magnitude), and sometimes create a "parking lot" or "tin roof" effect with very rapid surface runoff. "Any mineral soil containing more than a couple percent of organic matter is likely to become water repellent to some degree when heated" (DeBano 1981). However, coarse textured soils are more prone to water repellency than fine soils (Neary et al. 2004), as are fuels of certain species (e.g., chaparral vegetation). Light fires over moist soils tend to produce less water repellency than intense fires over dry soils.

Defining Burn Severity

Because resource effects are influenced so much by fire severity, systems for classifying burn areas have been developed. Confusion over existing assessment terminology led Debano et al. (1998) and Parsons (2003) to argue that burn intensity should simply describe the rate of burning (heat per area per time unit), whereas severity should characterize results of the burn, thus integrating burn intensity, duration, and site conditions. Parson's classification is aimed largely at "soil burn severity" to assess how soil changes from fire can impact hydrologic functions, as shown by some key excerpts closely adapted but truncated from those provided by Parsons (2003).

Soil burn severity. A term that qualitatively describes classes of fire-caused changes to soil hydrologic function, as evidenced by soil characteristics and surface fuel and duff consumption. Large diameter down, woody fuels, and organic soil horizons are consumed during long-term, smoldering, and glowing combustion. The amount of duff or organic layer reduction is also called depth of burn, or ground char. The amount and duration of subsurface heating determine the degree of soil burn severity, and can be inferred from fire effects on ground fuels (plants and other organic matter) and soils.

Descriptive Classes–Soil Burn Severity

These are guidelines to visual indicators only, and the boundaries between the classes often become "blurred" in real world situations.

Unburned to very low. Fire has not entered the area, or has very lightly charred only the litter and fine fuels on the ground; soil organic matter, structure, and infiltration unchanged.

Low. Low soil heating or light ground char occurs; mineral soil is not changed; leaf litter may be charred or partially consumed, and the surface of the duff may be lightly charred; original forms of surface materials, such as needle litter or lichens may be visible; very little to no change in runoff response.

Moderate. Moderate soil heating with moderate ground char; soil structure is usually not altered; decreased infiltration due to fire-induced water repellency may be observed; litter and duff are deeply charred or consumed; shallow light colored ash layer and burned roots and rhizomes are usually present; increase in runoff response may be moderate to high.

Figure 1. **Headwater reach scour following wildfire on Boise National Forest .**

High. High soil heating, or deep ground char occurs; duff is completely consumed; soil structure is often destroyed; decreased infiltration due to fire-induced water repellency is often observed; top layer of mineral soil may be changed in color (but not always) and consistence and the layer below may be blackened; deep, fine ash layer is present, often gray or white; all or most organic matter is removed; essentially all plant parts in the duff layer are consumed; increase in runoff response is usually high. High soil burn severity areas are primary treatment candidate sites if there are downstream values at risk.

This classification scheme assumes that soil conditions are the primary influences on hydrologic functions after wildfire. Weather events (e.g., antecedent conditions, storm size, rainfall intensity) and vegetation conditions also influence hydrologic (e.g., interception, evapotranspiration) and water quality (e.g., root strength, nutrient cycling, shade) functions. A soils focus may be suitable for screening for immediate site rehabilitation needs, but it may not capture more subtle or complex watershed responses, such as changes in stream temperature or nutrient concentrations.

Specific burn locations, patterns, and extents are also important in determining watershed responses. If riparian areas remain intact, for example, key

Figure 2. **Downstream deposition of sediment and wood following wildfire in a reservoir watershed in the Boise National Forest.**

functions of sediment storage, evapotranspiration, and shade may persist to some extent. Extensive wildfires that consume both upland and riparian sites create conditions conducive to severe hydrologic response. Although riparian areas appear less vulnerable to fire, some related research is equivocal (Everett et al. 2002), and there is substantial empirical evidence that severe wildfires can have major impacts on riparian areas.

Altered Watershed Processes

Neary et al. (2004) stated, "Wildfire is the forest disturbance that has the greatest potential to change watershed conditions." Several key watershed processes can be significantly altered by wildfire.

Dry ravel. Although sometimes overlooked because much of it may occur during or shortly after burning, the loss of surface and binding organics from severe fires contributes to dry ravel. This erosion process is the downhill movement of soil, organic material, and rocks in response to gravity. In western Oregon, Bennett (cited in Beschta 1990) found 224 m^3/ha (119 yd^3/ac) of sediment captured by metal troughs on steep slopes (>60%) in the first year after logging and prescribed burning that exposed mineral soil, compared with 17 m^3/ha (9 yd^3/ac) for logged sites left unburned. Sixty-four percent of the sediment captured on the burned sites moved within 24 hours after burning, indicating significant dry ravel, as no precipitation occurred.

Infiltration and runoff. Undisturbed forest soils have relatively high infiltration rates, in some areas (e.g., coastal Pacific Northwest) exceeding the intensities of even the most intense rainfall events. Wildfire can reduce infiltration by exposing mineral soil to raindrop impact and splash that can seal soil pores at the surface. This may be compounded by water repellency and reduced evapotranspiration from the loss of vegetation, sometimes resulting in dramatic changes in both annual and peak streamflows. Neary et al. (2004) reported that two streams draining the 1933 Tillamook Burn showed an increase in annual water yield of about 10% and in annual peak flow of about 45%. Other reported responses have been considerably higher. For example, 90- and 2,350-fold increases in peak flows were measured when intense rainfall followed the Rodeo-Chediski wildfire in 2002 in a ponderosa pine (*Pinus ponderosa*) forest in Arizona (Ffolliott and Neary 2003).

Surface erosion. After severe wildfires, reduced infiltration can lead to dramatic increases in surface erosion, often relatively insignificant in undisturbed forest soils. For example, after Colorado's Buffalo Creek fire, Landsberg and Tiedemann (2000) reported that heavy rains resulted in temporary closure of one of Denver's water treatment plants and months of cleanup for a water supply reservoir due to high turbidity and sediment loads. After the 1979 Bridge Creek Fire in central Oregon, McCammon and Hughes (1980) reported that rehabilitation efforts using log terraces captured about 139 m^3/ha (73 yd^3/ac) of sediment, presumably from surface erosion.

Slope failures and debris torrents. One of the puzzles about watershed response to fire is the apparent increase in slope failures, which generally are believed to result from positive soil pore pressures. This occurs when water creates buoyancy that separates and floats soil particles, often at a discreet failure zone. Fire may promote slope failures by reducing evapotranspiration and root strength, but a dominant effect is the diversion of water from infiltration to surface runoff, which tends to lower water pore pressures. Although fewer landslides might be expected, a fire and flood sequence with channel failures and debris torrents has often been observed. Some clarification was provided by Wells et al. (1987), who found fewer slope failures on hillsides but increased channel failures or debris torrents from concentrated flows in and near streams.

Stream sediment. Intense storms or rapid snowmelt can produce extreme stream sediment levels from accelerated runoff and erosion. For example, a moderate thunderstorm (1–5-year return interval) after the 1994 Rabbit Creek burn in Idaho resulted in a 1,000-year flood event and an estimated 382,320 m^3 (500,000 yd^3) of sediment deposited in the watershed's streams and reservoirs (Figures 1 and 2). Low-intensity burned or unburned areas in the watershed showed little response to the storm (John Thornton, Boise National Forest, personal communication).

Among the best-documented sediment responses following wildfire was the Entiat Forest in Washington, where paired study watersheds burned severely in 1970. Annual sediment yields increased 7–20 times the first year after burning, and intense storms in 1972 caused extreme sediment losses (up to 2,310 Mg/km^2 or about 6,600 tons/mi^2) from debris torrents (Helvey 1980). Research in the Entiat watersheds showed evidence that debris torrents have occurred periodically for centuries, with a frequency of as often as every 80–150 years.

Role of extreme events. A unique study by Kirchner et al. (2001) offered insights into the scale of erosion processes that may be associated with wildfire in the West. Mineral isotopes were used to estimate long-term (10,000 year) erosion rates for 32 watersheds in Idaho and compare them with rates based on gauging station data. Long-term rates using isotopes averaged 17 times higher than rates estimated from water quality records, a mismatch that may result from infrequent events that are not captured in short-term stream monitoring. Furthermore, extreme wildfire-related sediment events are likely to have been artificially reduced during the recent era of fire suppression. In the Southwest, wildfires are the primary causal agent for 80% of the long-term erosion (Swanson 1981).

Other Water Resource Effects

Other important water resource parameters can be affected by wildfires, including stream temperature, nutrients, and fish habitat.

Temperature. Although involving a very hot prescribed burn, detailed data from the Needle Branch drainage in western Oregon (Brown and Krygier 1970) provide insights about potential effects of severe wildfire on stream temperature. After nearly complete clearcutting (including riparian trees) of the 74.9-ha (185-ac) Needle Branch watershed in 1966 and subsequent slash burning, stream temperatures rose from 13° C (55.4° F) to 28° C (82.4° F) and juvenile fish mortality was observed. The following summer, temperature maximums in heavily exposed Needle Branch were 26–30° C (78.8–86.0° F), versus 14–15° C (57.2–59.0° F) for the well-shaded stream in the control watershed. In southwestern Oregon, reduced riparian shade after wildfire was associated with temperature increases in small streams from about 14 to 21° C (57.2–69.8° F) (Amaranthus et al. 1989).

Nutrients. Research on logging and prescribed burning helps supplement the few studies of wildfire effects on water quality in providing insights about potential effects of wildfires on stream nutrient concentrations. Elevated nitrogen, phosphorus, and base (Ca, Mg, K) concentrations have been observed after logging and burning and after wildfire (Beschta 1990, Neary and Hornbeck 1994). In most cases, concentrations return to preburn levels with the soil stabilizing and nutrient uptake functions of recovering vegetation. Both nitrogen and phosphorus occur in many forms, and their movement after wildfire may be associated with both drainage water and eroded sediments. Phosphorus (P) normally is not very soluble and is more often transported with sediment, so erosion control can effectively minimize its delivery to streams. In some cases the concentration of soluble P can increase following fire.

Fish habitat. Although postfire runoff and sediment can have immediate impacts on water quality and existing channel features, they can also have a role in the long-term maintenance of desirable fish habitat downstream. Miller and Benda (2000) studied recent landslides in Oregon and found they can have important benefits to channel and valley floor landforms. Waves of sediment and woody debris that move down through the channel system help create both in-channel and off-channel habitat features that are valuable for fish, especially during rearing and high flow periods. In-channel debris and sediment deposits also have been found to promote pool formation in larger channels and may be areas of stream cooling where flows move through the streambed.

Wildfire, Watersheds, and Forest Management

Scientific understanding of wildfire effects on watersheds is intersecting today with important forest issues and policies, particularly on federal lands. These include major initiatives for thinning forests to reduce wildfire severity, postfire salvage logging, and watershed restoration practices.

Management to reduce wildfire severity. A basic concept of fire science is that heat, oxygen, and fuel are needed for a fire to burn. Thus forest management that reduces fuels may help control wildfire severity. Unusually high fuel levels over large landscapes, combined with the capricious nature of wildfires, have made the study of the effects of fuel treatments on wildfire behavior very challenging. However, fire-fuel models and considerable field experience suggest that carefully designed forest thinning and fuel reduction treatments can significantly affect wildfire severity. For example, recent experience with the Hayman Fire in Colorado provided many insights and lessons about the conditions under which forest management was more or less successful in influencing fire behavior and effects (Graham 2003).

Salvage logging. Postfire salvage logging is used primarily to recover timber values, but may also be prescribed to reduce possible insect and disease outbreaks and fire recurrence, reduce safety hazards, and for watershed restoration (e.g., contour log dams). On federal lands the practice has been controversial, in part because of concerns that it may exacerbate the watershed impacts of wildfire. Although research on the watershed effects of postfire salvage is limited (McIver and Starr 2001), there is little evidence that carefully planned and conducted salvage harvest cannot be conducted so as to avoid significant impacts (Neary and Hornbeck 1994). For example, the control watershed on the Entiat Burn yielded more postfire sediment than those that were salvage logged (Helvey 1980), and more recent research of salvage harvest with locally appropriate practices (e.g., hand felling, logging over snow, no new roads) showed relatively low soil disturbance and sediment loss.

Watershed rehabilitation. Concerns about wildfire impacts often trigger postfire efforts to restore watershed conditions, such as the federal Burn Area Emergency Rehabilitation

(BAER) program. Recent reviews of such efforts have identified some promising practices, but also indicated that related monitoring protocols were inadequate for an accurate and comprehensive evaluation of the effectiveness of various restoration measures (Neary et al. 2004, Robichaud et al. 2000). Given the millions of dollars that have been spent annually to rehabilitate watersheds after wildfires, significant improvements in research and monitoring of restoration treatments appear warranted.

Key Concepts

• It is not fire per se, but the intensity and duration of burning that influences the severity of soil and hydrologic effects.

• Location of the fire in the watershed will influence the effect on runoff and water quality.

• Key changes with high-severity fires include loss of the forest canopy, surface litter, and binding organics, and increased water repellency.

• Reduced infiltration rates can promote overland flow and surface erosion, and runoff and sediment can contribute to debris torrents and extreme channel impacts.

• Long-term erosion rates in fire-prone landscapes may be higher than often believed, and postfire sediment pulses can have both positive and negative effects.

• Loss of riparian shade and oxidation of organic matter by wildfire can temporarily elevate stream temperatures and nutrient concentrations.

• Management practices to reduce wildfire severity, salvage timber, and restore watersheds show considerable promise, but enhanced monitoring and research are needed for further refinement.

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