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ECOLOGICAL RESTORATION INSTITUTE

Working Paper 43

Fires and Soils in Frequent-Fire Landscapes of the Southwest

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SOUTHWEST FIRE SCIENCE CONSORTIUM

Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability … Restoration attempts to return an ecosystem to its historic trajectory" (Society for Ecological Restoration International Science and Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The Southwest Fire Science Consortium (SWFSC) is a way for managers, scientists, and policy makers to interact and share science. SWFSC's goal is to see the best available science used to make management decisions and scientists working on the questions managers need answered. The SWFSC tries to bring together localized efforts to develop scientific information and to disseminate that to practitioners on the ground through an inclusive and open process.

ERI working papers are intended to deliver applicable science to land managers and practitioners in a concise, clear, non-technical format. These papers provide guidance on management decisions surrounding ecological restoration topics. This publication would not have been possible without funding from the USDA Forest Service and the Southwest Fire Science Consortium.

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Cover photo: Forests and soils interact so strongly that any major change in one of them leads to a reshaping of the other. Impacts of restoration treatments and fires on soils always depend strongly on site-specific details, but too many factors make forest soils complex and variable and there is no one-size-fits-all prescription. *Photo by ERI*

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Executive Summary

Forests and soils interact so strongly that any major change in one of them leads to a reshaping of the other. Fires consume fuels in a few hours that it took vegetation years or decades to produce. Forest soils are both sensitive and robust in relation to forest restoration treatments and fires. Fires change soils in major ways, including direct consumption of some of the organic matter that forms soils, and heating and altering the physical, chemical and biological features within the soil. The impacts of fires tend to increase with the quantity of fuels consumed, with high spatial variation across a site. Erosion typically increases slightly after fires, but sometimes the increases are so large that downstream roads, bridges, and homes are threatened. Erosion risk depends strongly on the consumption of the forest soil O horizon (sometimes called "duff"), because high-intensity rain falling on mineral soil surfaces can easily exceed the absorption capacity of the soil. The absorption capacity of mineral soils can also be reduced after fire by the development of water-repelling (hydrophobic) microsites. Fires burn organic matter that contains carbon and nitrogen, oxidizing them to gaseous forms. The loss of nitrogen (N) from burning fuels equals about ten pounds of N lost for every ton of fuel consumed. The impacts of restoration treatments and fires on soils always depend strongly on site-specific details, such as soil type, moisture conditions at the time of the fire, and spatial variation across landscapes. Prescriptions for local situations can be improved over time if each operational unit includes a learning opportunity, with a pocket-science approach of varying treatment intensities in small areas to find out what happens when a treatment is omitted (a control) or intensified (with extra fuel or burning under more extreme weather conditions).

Introduction

Soils are the foundation of forest ecosystems, and variations in soils across landscapes and through time lead to major differences in forest composition, structure and growth. Pre-settlement ponderosa pine forests in northern Arizona that developed on soils with basalt parent material supported 50% more trees per acre than stands on limestone-derived soils (Abella and Denton 2009). Stands on both soil types had clumped spatial distributions, but clumps averaged almost twice as many trees on basalt-derived soils. Limestone-derived soils had double the understory plant diversity and cover found on basalt-derived soils (Abella et al. 2015). These differences likely resulted from interacting legacies of soils on overstory and understory vegetation, and the vegetation influenced fire behavior, which in turn affected soils and vegetation. The responses of forests to restoration treatments also depends heavily on soils. Thinning dense stands led to greater increases in understory diversity on limestone-derived soils, but greater understory cover on basalt-derived soils (Abella et al. 2015).

Forest management and forest fires occur at scales of patches, stands and landscapes, and soils may be characterized at the same scale. For example, an old-growth forest of ponderosa pine in central Colorado had an average of 2.2% carbon (C; carbon comprises about half of the structure of organic matter, so 2.2% C would be about 4.4% organic matter) in the top 6 inches of the mineral soil (Figure 1), or about 15 tons of carbon per acre. This single value accurately represents a 22-acre stand, but great variation underlies the average. About 20% of the stand had almost twice this average soil C, and 5% of the stand had half the average amount. The intensity of fires and the ecological impacts may show similar variations across a stand. These numbers can also be examined in a spatial context,

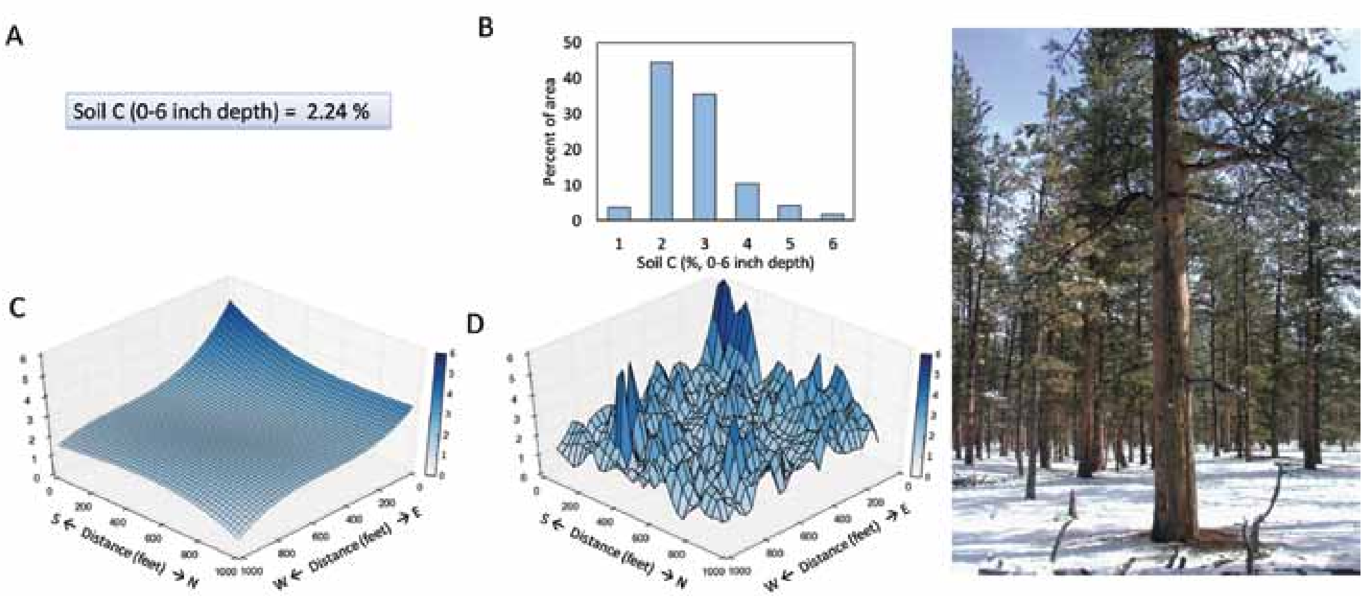


Figure 1. The C content of soils was sampled in a 50 ft. x 50 ft. grid across a 22-acre old-growth stand of ponderosa pine in the Manitou experimental forest in central Colorado. The information might be condensed into a single average (A, without information on variation or spatial patterns), or represented as a distribution of values (B, with no spatial pattern), as an average tendency across the stand (C), or with full information (D, data from S. Boyden).

and one corner of the stand averaged double the C of another corner. The average spatial trend across the stand is comprised of great variations at a scale of 50 feet, and 3-fold variations in soil C are common at this finer scale. These fine-scale details would be difficult to include explicitly in any management scheme, but it's important to keep in mind that average stand values do not mean low variability within stands (in soils, in vegetation, and in fires).

Forest tree roots may be found in the organic horizons (O horizons) that forms the topmost layer of forest soils, and in the underlying mineral horizons that have organic matter mixed with particles of clay, sand, and rocks. Forest in frequent-fire landscapes typically have most of their roots confined to the mineral soil, as the O horizons are often dry. But O horizons are important to roots even where roots only within the mineral soil. The air-spaces within the O horizon moderate temperature fluctuations in the mineral soil, and act as a mulch layer to reduce evaporation. The O horizon is a major sponge with high infiltration rates during severe rainstorms, preventing erosion. A large portion of the nutrients taken up by roots are released by decomposition within the O horizon. The terms "duff" or "forest floor fuels" are used in the fire community to describe the soil O horizons, but it's important to recognize that burning duff is burning soil.

The variability of soils is similar to the variability in fire behavior and fire impacts when frequent-fire landscapes ignite. Patchy variations in fuels combine with variations in space and time in wind, temperature and humidity to lead to very non-uniform fire behaviors and post-burn conditions (Figure 2). Of course, some very intense fires (particularly in forests with long intervals between fires) may lead to more uniform post-burn conditions. This variation includes impacts of legacies created by surviving plants and seeds. Surviving plants, both trees and understory vegetation, can facilitate rapid post-burn recovery of the forest mosaic of overstory trees and understory grasses and forbs. Fires may burn for longer periods and at higher sustained temperatures where dry woody fuels are present, such as stumps and downed logs, and where O horizons are deep (such as around the bases of trees). The time for recovery tends to increase with the intensity of fires.

Figure 2. An intense fire burned most of the ponderosa pine crowns and the soil O horizon in this patch of forest, but the vagaries of the flames left some small patches of unconsumed O horizon where some plants survived (A), and the seed bank can rapidly provide new plants. Under dry conditions, stumps (B) and downed logs (C) flame and smolder for longer periods, sending more heat into the soil, sterilizing seed banks and altering soils in ways that may not recover for many years (D). Burning fuels in slash piles (E) restricts the impacts of fire to patches within a site, but increases severity of effects within the patches.

How Fires Affect Soils

Fires release tremendous amounts of heat, essentially converting the energy accumulated from years (or centuries) of plant production into heat in a matter of minutes or hours. A typical light surface fire in frequent fire landscapes might burn about 7 tons/acre of wood and soil organic matter, releasing the equivalent heat of about 1 quart of gasoline on every square yard of a forest. The energy release is much higher under large woody material and piles of slash, with energy release rising to the equivalent of 4 to 6 gallons of gasoline per square yard.

The effect of all this energy depends on a variety of factors, including how much fuel burns, how long the burning lasts, and the moisture content of the soil (Figures 3, 4, 5). Fine fuels, such as grasses and pine needles, burn quickly with too little heat release to have much effect on soils. Piles of slash (needles and branches) provide more fuel that takes longer to burn, releasing large amounts of heat over hours. Soil temperatures under slash piles with small-diameter materials may reach temperatures of 900 °F for a few hours (Figure 4). Piles of coarser woody material may not reach as high a maximum temperature in the soil, but the heat penetrates more deeply and lasts longer.

Fires under dry conditions raise soil temperatures much more than fires would under moister conditions (Figure 5). The presence of water keeps temperatures below 200 °F as energy is consumed in evaporating water. Soil water is also a good conductor of heat, so more heat is transferred out of the topmost soil into deeper layers (which heat up, but maybe not to lethal levels).

High soil temperatures kill roots, microbes, and seeds, but there does not seem to be a clear threshold of temperature that applies broadly. As a rule of thumb, temperatures above about 140 °F may kill most tree roots (Neary et al. 1999, Busse et al. 2010), so the regions of Figure 4 that are green may be relatively safe for roots. Where the color in Figure 4 shifts to yellow-green, most roots would die. Temperatures above 200 °F may come close to sterilizing the soil (though absolute sterilization would take higher temperatures). The biological impacts depend on both temperature and duration of temperature, and a general expectation might be that heating soil to 140 °F for half an hour would kill most (or all) plant roots, bacteria, and soil fauna (Pingree and Kobliar 2019). The ecological importance of this biotic loss may not be high, however, as recolonization seems to be common within a year or so. Fungi may be more resistant, or recover more quickly; in some cases, fungi even showing positive growth responses after this degree of heating (responding to increase availability of resources, and reduced competition). Temperature of 900 °F can also alter the minerals in soils, breaking apart clay particles into component pieces (Ulrey et al. 1996).

Burning Duff is Burning Soil

The fuel characteristics of a forest are fundamentally important for fire behavior and impacts, and major "surface" fuels include woody materials, fallen branches, and decaying needles. Thinking of these materials as fuels may miss the importance they have as components of the forest soil. Soil science includes O horizons as a major characteristic feature of forest soils, not as a forest floor or a duff layer. Harvesting experiments that removed the soil's O horizons have often found larger impacts on future site productivity than from removing tree boles or post-logging slash (Binkley and Fisher 2020). Typical O horizons in frequent-fire landscapes range from 10 to 25 tons/acre, and low-intensity surface fires generally consume about 10 to 25% of these horizons. Experiments with fire return intervals as short as a few years have shown large reductions in O horizon mass, coupled with increased organic matter in the upper mineral soil (A horizons). The spatial pattern of fires within stands leads to variable consumption of O horizons (Figure 1A). The recovery time for O horizons partially consumed in fires typically range from a few years to a decade (or more), as litterfall from surviving and reestablishing vegetation rebuild the horizon.

Fire intensities can be extreme in some frequent-fire landscapes, as a result of unusually high accumulations of fuels during fire-free intervals, or in response to very severe fire

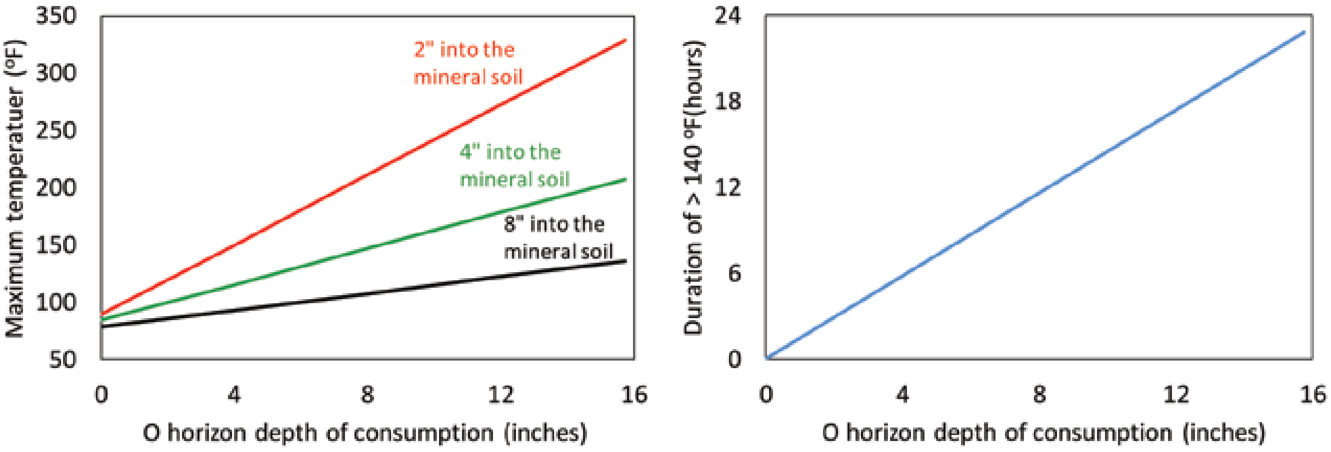


Figure 3. The heat transferred into the mineral soil from burning soil O horizons (also called duff or forest floor fuels) increases with the increasing amount of consumption (left). The impacts on soil seed banks and microbial communities may increase with the amount of time the soil is heated beyond 140 °F, and of course that time is longer when more of the O horizon is consumed (right; based on data from Kreye et al. 2020 for longleaf pine forests).

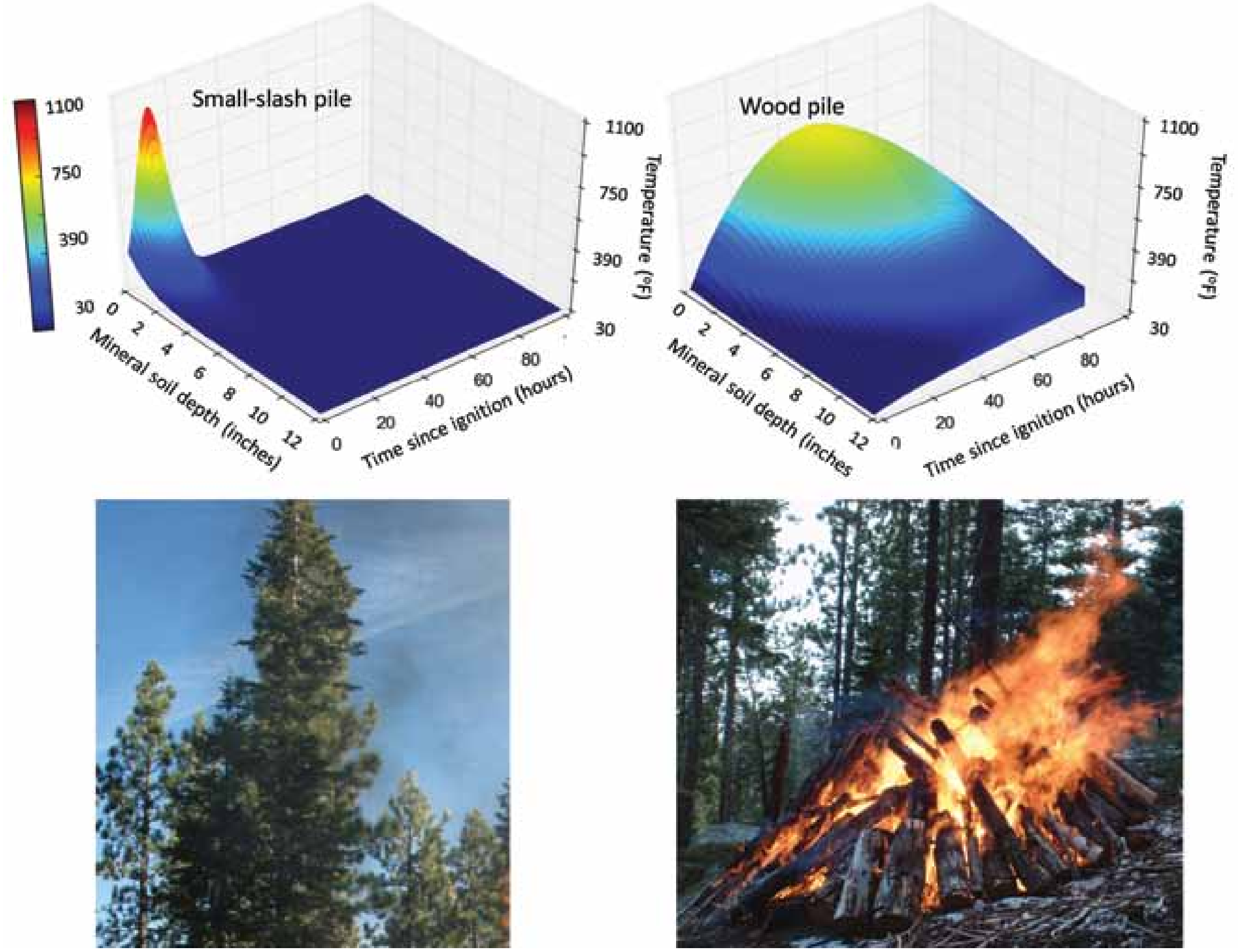


Figure 4. Temperature profiles differed substantially when slash piles of different diameter materials were burned. The left X axis shows soil depth, and the right X axis shows the time since the fire started. Piles of small-diameter slash (left) burned quickly, and the rapid rate of energy release heated the top 2 in of mineral soil to over 900 °F. Rapid consumption of the small material led to cooling over a period of several hours, minimizing the opportunity for heat to reach deeper into the soil. Burning of coarser woody material took longer for soil to heat, as well as lower maximum temperatures (right). However, the heating impacts reached much deeper into the soil, and lasted for two days (from data of Busse et al. 2013, photos from Matt Busse).

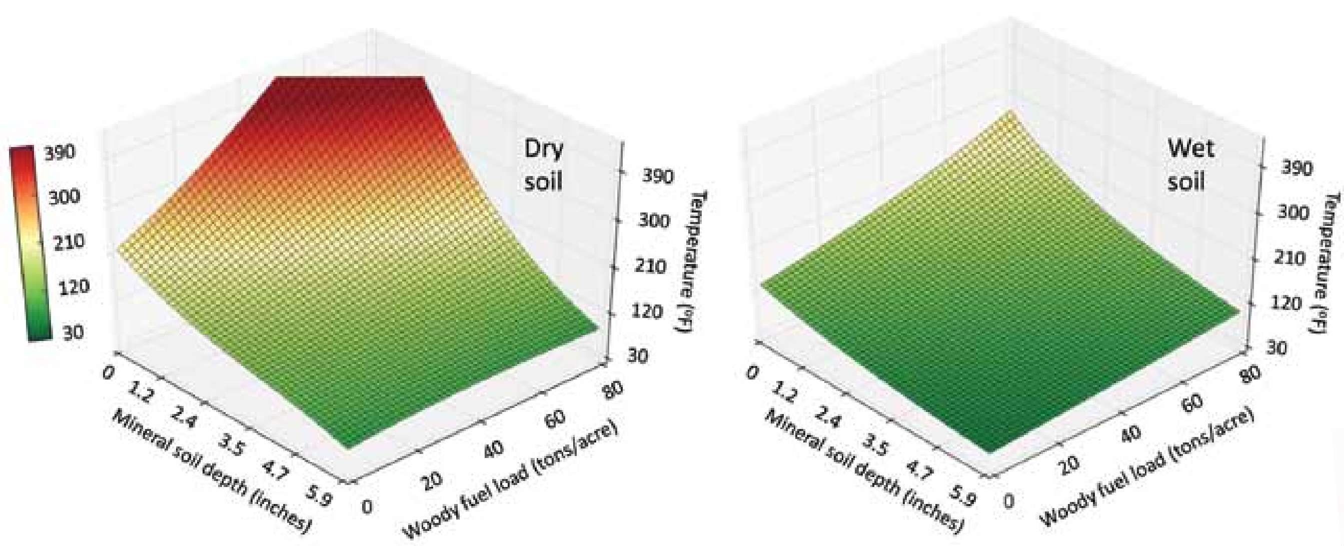


Figure 5. Fires under dry conditions lead to greater transfer of heat into soils (from data of Busse et al. 2010).

Figure 6. The Dome area in the Jemez Mountains in northern New Mexico burned severely in 1996 (Dome Fire), and then again in 2011 (Las Conchas Fire). The fire weather in 2011 was so severe that the O horizon and downed woody material were completely consumed over large areas. The "ghosts" of logs from trees killed in the 1996 fire are evident across the landscape. Three years later, rapidly resprouting of Gambel oak and nitrogen-fixing New Mexican locust dominated the revegetating plant community. *Photos by Craig Allen*

weather. The most intense fires not only consume virtually all surface fuels (and O horizons, Figure 6), but they also burn organic matter within the upper mineral soil. It is difficult to determine the amount of organic matter that is burned within the mineral soil during intense fires. The 2002 Biscuit Fire in southeastern Oregon burned through pine-dominated landscapes, removing all of the O horizon over large areas. Careful attention to sampling of the mineral soil revealed that organic matter losses from the A horizon were even larger than the losses from the O horizon (Bormann et al. 2008). Post-fire wind losses of fine mineral material were about 55 tons/acre, which would be near the upper end of water-erosion losses after fires. The recovery period for soil organic matter after very severe fires remains unclear (Neary et al. 1999), but the time scale would be decades and more likely centuries.

Erosion After Fire Ranges from Very Little to Massive

Most fires in frequent-fire landscapes generate too little erosion for concern. However, a minority of cases have huge erosion losses with major impacts on down-stream ecosystems and communities. The most common rates of erosion after forest fires are a few tons/acre, but about 10% of fires led to more than 80 tons/acre of erosion (Figure 7). The loss of soil from forests may have impacts on the recovery of the forests, but this issue has not received much research. If the nitrogen (N) concentration of eroded sediments was a typical 0.02%, then even 70 tons/acre of soil erosion would be a loss of about 30 to 40 pounds of N per acre, less than the direct losses of N from combustion in high-intensity fires (see Figure 7). Some of the eroded material is deposited down slope, and the amount of charcoal, ash and other fire-modified forms of organic matter may be twice as great in lower-slope (depositional) areas as compared to the average across a burned site (Abney et al. 2017).

Concerns about erosion deal mostly with off-site issues. Post-fire erosion is a major geomorphologic agent, renewing downstream riparian terraces and changing steam ecology (Benda et al. 2003). Severe erosion after a fire in the Tahoe Basin (Carroll et al. 2007) led to the addition of more than 200 tons/acre of sediments onto a floodplain, along with 800 pounds of N per acre, illustrating the key role of post-fire erosion and deposition in shaping productive riparian ecosystems. Of course, floodplains are also common sites for homes, roads, bridges and other infrastructure, and post-fire erosion and floodwaters cause substantial damage.

The primary driver of post-fire erosion is the intensity of rainfall in the period before vegetation reestablishment. The primary soil factor determining the response to intense rainfall is the presence or absence of the O horizon. The organic matter in the O horizon is a very absorptive sponge, rapidly absorbing water and retaining large volumes that are released slowly over period of hours and days. Indeed, most studies of the

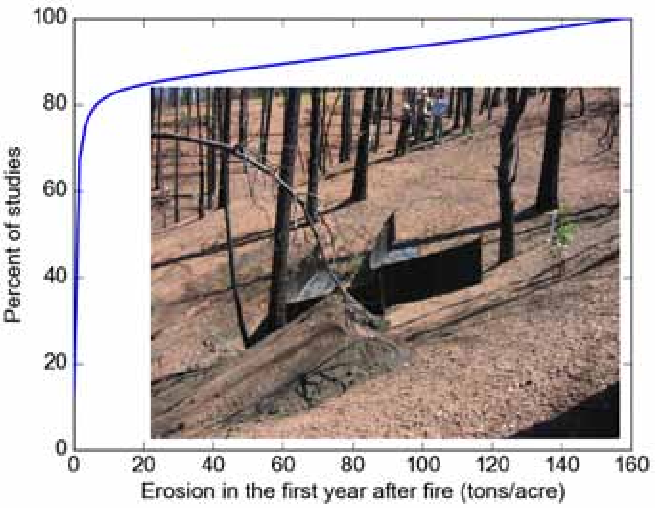


Figure 7. Most forest fires do not lead to high rates of erosion; about 80% have less than 8 tons/acre of erosion in the first year after fire (from data compiled by Robichaud et al. 2000). Some sites have much higher rates, especially with the combination of factors such as intense fire, steeper slopes, and highly erodible soils (with coarse texture and low organic matter). All three of those factors combined to generate high erosion after this fire in a ponderosa-pine forest on granite-derived soils in central Colorado. The curtains established to gauge erosion had to be shoveled out repeatedly.

infiltration rates of forest soils begin by removing the highly absorptive O horizon to examine the more limited infiltration rates of mineral soils. When fires consume this high-infiltration sponge, the exposed mineral soils may allow water infiltration too slowly to keep up with intense rainfall, leading to overland flow and erosion.

A secondary factor in the susceptibility of post-fire soils to intense rainfall is the development of water-repellent microsites (hydrophobicity). The process of combustion involves the heat-driven breakdown of large organic molecules into smaller ones. The small organic molecules evaporate (volatilize) and ignite when temperature and oxygen concentrations are high enough. The burning of the small, volatile organic molecules gives light to flames. Some of the molecules diffuse downward into the soil, where conditions are too cool for them to ignite. Instead, the organic molecules cool and condense onto soil surfaces, and the organic coatings make it difficult for water drops to be absorbed into the soil. This hydrophobicity issue accounts for a typical decrease in mineral soil infiltration rates of 40 to 80% after fires (Robichaud et al. 2000, Martin and Moody 2001).

The spatial and temporal variability in forest soils emphasized above is especially important in the connection between hydrophobicity and erosion. An assessment of the spatial distribution of hydrophobicity in central Colorado found that burned sites did have a higher prevalence of hydrophobic points in a 50 ft. x 50 ft. grid (Figure 8). The unburned site also showed some hydrophobicity in about 5-10% of the sample points, increasing to about 30% in the burned site. The spatial arrangement of soil infiltration capacities (Figure 9) may be more important than the average, because a hydrophobic point adjacent to a point with high infiltration capacity would have low erosion potential. Overland runoff would be likely only for large patches of spatially contiguous hydrophobic soils.

Hydrophobicity varies in time as well as space. Dry soils are more hydrophobic (whether burned or not) than moist soils, and post-fire hydrophobicity typically declines to background levels within a year or two (MacDonald and Huffman 2004).

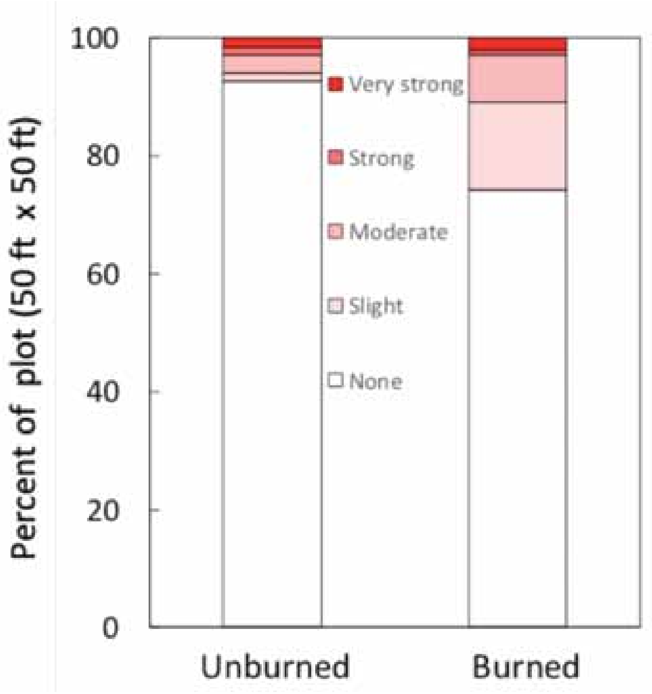


Figure 8. Most points within a 50 ft. x 50 ft. grid in central Colorado showed no hydrophobic tendencies. About 5-10% of points in the unburned plot were hydrophobic, compared to about 30% for a plot within the Hayman Fire (Woods et al. 2007).

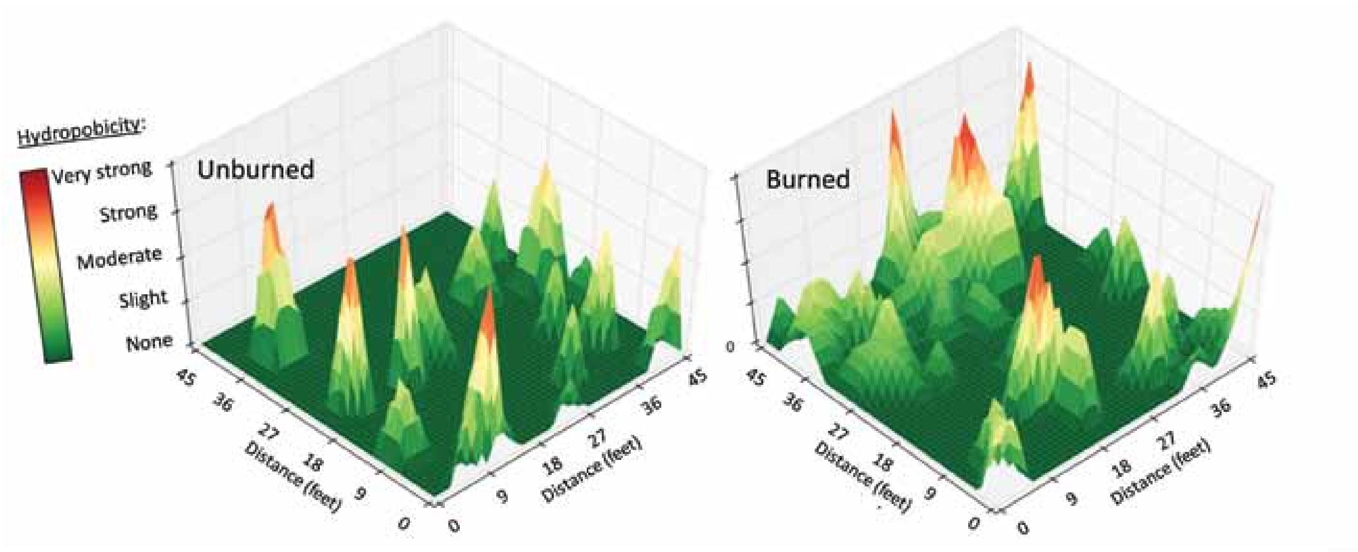


Figure 9. The spatial pattern of hydrophobicity influences how water moves during heavy rain events. Adjacent points that are hydrophobic foster overland flow and erosion, whereas hydrophobic points surrounded by high-infiltration points pose less risk. Although the Hayman Fire increased the prevalence of hydrophobic sites (right, same data as in Figure 8), the risk of overland flow was increased less than if the soils were more uniform (from data in Woods et al. 2007).

Fires Are the Major Cause of Nutrient Loss from Frequent-Fire Landscapes

Many studies have examined rates of nutrient loss in water leaching from forests into streams, but in the frequent-fire landscapes of the Southwest the major losses of nutrients occur with fires (Johnson et al. 2008). The two major pathways of nutrient losses in fire are direct combustion of organic matter, and post-fire erosion.

Fires burn off large amounts of organic matter, carbon (C), and nitrogen (N) from soils, and some of the material left after the fire is substantially altered. Heating of organic matter affects the bonds holding large molecules together, producing smaller compounds that may later be more accessible to microbial decomposition. Large amounts of organic matter may be burned only partially, leaving behind a wide range of materials in soot, ash, and charcoal. Soil organic matter generally lasts for a period of decades in soils, but fire-altered materials may have turnover times of a few centuries (though the actual rates of charcoal decomposition in forest soils may be higher than previously thought, Abney and Berhe 2018).

Soil nutrient supplies commonly limit the growth of forests and understory vegetation around the world, with the most critical nutrient stress varying among soil types and vegetation. Surprisingly little information is available on the extent of nutrient limitations in frequent-fire forests of the Southwest, but low soil nitrogen (N) limited growth of both trees and understory vegetation in some experiments (Powers 1982, Binkley et al. 2003, Boyden and Binkley 2016). The major form of N stored in vegetation and soils is in organic molecules, where N is bound with C. The fate of N in burning organic matter mirrors that of C. Fires combust the organic matter, with C being oxidized to form gases (primarily carbon dioxide, CO_2) while the N is also oxidized to form various gases (NO, N_2O, N_2). Sometimes the combustion loss of N has been mistakenly called "volatilization," but just like C, the loss of N is a burning process (oxidation) not an evaporating process.

Organic matter is typically comprised of about 0.5% nitrogen, and the loss of N in fires averages about 0.5% of the fuel consumption (Figure 10). Typical surface fires in frequent-fire landscapes would have 5 to 15 tons/acre of fuel consumption, with N losses of 50 to 150 pound/acre. High-intensity fires occur in frequent-fire landscapes where fuel accumulations are atypically high, or when weather conditions support intense fire behavior. Fuel consumption in high-intensity fires can exceed 50 tons/acre, with N losses of more than 500 pounds/acre.

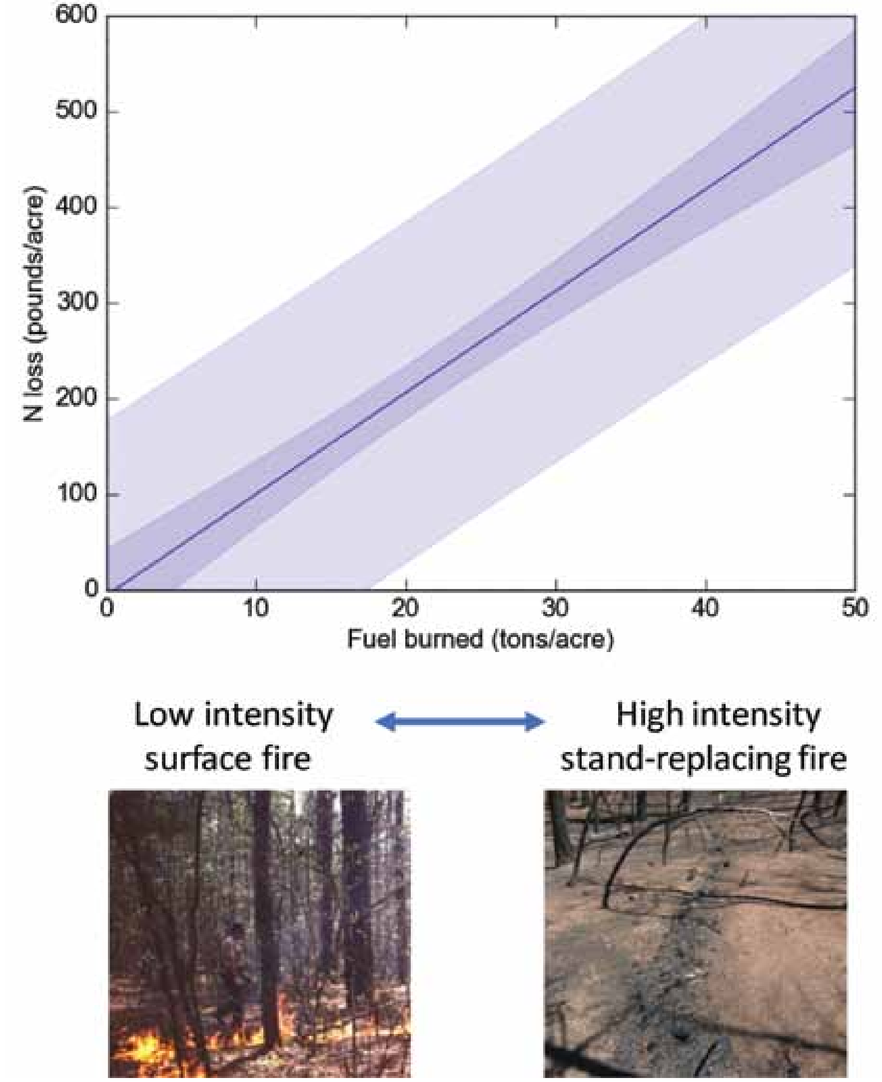


Figure 10. The loss of nitrogen (N) in fires results from the same burning reactions that consume organic matter, so the loss of N matches the N content of the fuel consumed. A compilation of 42 estimates of N losses in fires showed a loss of about 10 pounds of N per ton of fuel consumed (r2 = 0.89). The darker shaded region is the 95% confidence interval for the highly significant overall trend, and the light shade shows that individual cases vary substantially around the average trend (95% of the cases would occur within the bounds of the light-shade area; based on data compiled in Binkley and Fisher 2020).

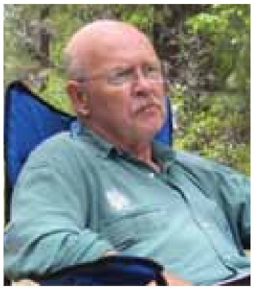
The N lost from fires is replaced only very slowly, from N deposited in rainfall, and from N fixation (the conversion of atmospheric N_2 into organic-N forms). Typical rates of N addition to southwestern forests are so low (on the order of 2 to 5 pounds of N per acre annually) that decades or centuries would be needed to restore the N lost in combustion.

Although N is always lost when organic matter burns, the supply in the soil available to plants usually increases after fire. This would be analogous to losing money from a bank account, but increasing the amount of cash on hand for immediate use. A global review of fire effects concluded that N supply to plants after fires generally increases by about 1/3 (and phosphorus (P) supply by 1/2; Dijkstra and Adams 2015). Losses of P in fire are generally small (unless substantial erosion occurs), but the various pools of P-containing molecules tend to increase substantially (Butler et al. 2018). These increases result from direct chemical effects of heating, the release of nutrients from cells of microbes killed in the fire, and the alteration of the physical environment (soils are often wetter and warmer after fire). The availability of nutrients to surviving or establishing plants would also be high owing to an initial lack of competition with other plants.

Fires also alter the chemistry of cation nutrients, such as calcium, magnesium, and potassium. These elements are not burned (oxidized) by the fire (as C and N are), and they remain behind in the soil unless wind or water erosion physically removes them. The burning of organic matter containing cation nutrients entails consumption of acidity (H^+) to form water, resulting in alkaline (high pH) ash and soils. The rise of soil pH can be quite large after fires, from one to two units. The leaching of ash into the soil, combined with reestablishment of plants and nutrient cycles gradually lowers soil pH over a period of years to decades.

The combined effects of high temperatures, changing chemistry, and altered environmental conditions after fires means that almost every aspect of soil biology changes after fires. Forest soils contain large banks of seeds that might germinate after fire, but intense fires (such as burning slash piles) can kill more than 95% of the seeds stored in soil (Korb 2004). Bacterial communities are more sensitive to fire effects than fungal communities, and the diversity of the communities after fire decrease for bacteria and may or may not increase for fungi (Hart et al. 2005, Reazin et al. 2016). Generalizations about post-fire changes in soil biology may not be very useful for two major reasons. Soils vary hugely at relatively small scales, from less than a millimeter in soil aggregates to feet and yards across stands. The behavior of fires also varies across scales, leading to a very wide array of biological impacts. The second reason is that the state-of-knowledge does not provide strong insights into the connections between changes in soil biology and implications for plants or other ecosystem components. Soil biology is fundamentally important, but not yet linkable to broader forest connections.

How to Consider Forest Soils When Planning Restoration Treatments and Managing Fires



A former outreach director for ERI, Doc Smith, was fond of saying that people want "a solution that'll work everywhere, all the time, starting right now." It would be easy to recommend general approaches to sustaining soils as part of restoration treatments or fire operations. Unfortunately, too many factors make forest soils so complex and variable that no one-size-fits-all prescription could be very helpful. Three general ideas might be broadly useful to keep in mind.

1. Forest Soils Are Sensitive, Flexible, and Robust

There is no single way for a forest soil to be. Soils differ substantially across space and over time, and most soils function quite well. Some soils grow trees better than others, and some respond to events such as fire or restoration treatments more strongly than others. If a single goal happened to be important, such as maximizing tree growth regardless of understory vegetation or fire risk, then some soils would be clearly "better" than others. Forests in frequent-fire landscapes of the Southwest rarely fit into categories of maximizing single uses, so a wide array of soil conditions is not a problem. When fires or restoration treatments change vegetation, soils generally are well suited for growing more grasses or shrubs while dominance of trees is low (Figure 5). Long periods with less fire may lead to soils supporting more trees, and all of these variations seem to work.

If forest soils can be so variable in time and space, do soils need to be considered when thinking about fire impacts or prescriptions for restoration treatments? The good news is that there's no reason to expect that only one outcome would be acceptable or desirable for soils. The cautionary news is that some changes might be quite undesirable, and worth avoiding. A productive approach might be to identify potential "undesirable outcomes" (Matonis et al. 2016) for soils, and to consider what precautions might be built into plans and operations to reduce risks of undesirable outcomes.

2. Key Decisions Focus on Fire Intensity and Spatial Heterogeneity

The typical condition of forest soils includes high variation at scales of feet and yards. Intense fires might override that background variation, removing legacies of large trees or patches dominated by grasses, or where the O horizons were thick or thin. Historical low-intensity, frequent fires may have promoted soil diversity within patches of trees and other vegetation. Mixed-severity fires may have promoted diversity at scales of acres and stands. Decisions about forest restoration treatments, fire prescriptions, and responses to natural fire ignitions may have opportunities to influence whether soils end up more diverse or more homogenized. Diversity of soils likely increases when outcomes foster

Figure 11. A large forest restoration area on the Kaibab Plateau used repeated fires to reduce fuel loads and change forest structure (left). Retention of an adjacent, untreated control (right) ensured future opportunities to learn from the restoration project, and to help visiting colleagues understand what was accomplished by the restoration treatment.

spatial diversity in plants at scales of feet and patches within stands (focused research might be needed to give confidence to this expectation). Uniformity of treatments would not be an important goal from the perspective of sustaining soils, and may be counter-productive if forest diversity is a goal.

Intense fires change soils more than less-intense fires, but there is no general reason to foster either level of intensity. The ecological legacies of fires depend in part on intensity of burning, but the outcomes are not automatically more or less undesirable. High-intensity fires on highly erodible slopes may lead to floods that deposit sediments in riparian areas (rejuvenating the ecosystems), or floods that take out bridges and homes. Decisions about fire intensities need to consider the heterogeneity of off-site land uses.

Decisions can also consider whether management actions would be helpful for amelioration of undesirable outcomes of fires. Slash-pile burning reduces fuels that might otherwise support uncontrolled intense fires, but the tremendous release of heat kills seeds stored in soils and partially sterilize microbial communities. Management options that include burning slash in piles could also include ameliorative practices such as mulching, scarification, seeding (of trees, grasses, or forbs), and fertilization (Rhoades et al. 2015, Miller et al. 2015). Prescriptions for ameliorative treatments might depend on earlier decisions about size and numbers of slash piles to be created and burned within a stand. Small piles are cheaper to create and have less impact on underlying soils, and large piles are more expensive to create and leave larger impacts on soils. But larger piles also mean fewer piles within a stand, and operational logistics could lead to decisions to use larger piles (which means fewer piles to ignite and monitor) with amelioration treatments at fewer locations within each stand.

3. Each Management Unit Can Be a School-House: Pocket Science

Extrapolating insights from one site to another would be powerful if local variation weren't important, but forest soils are at least as variable as the forests that grow on them. The responses to fires or restoration treatments on one site may not apply very well to other sites. This is the same problem faced by health care providers: medical science provides great general insights, but every patient needs to be evaluated carefully for a unique set of history, symptoms, and opportunities. Resource management needs to be tailored for specific cases, and the outcomes of decisions may not always provide the hoped-for outcomes.

A pocket-science approach can ensure that learning is a central goal of management, and that operations are designed with simple features that foster learning (Binkley et al. 2018). If an entire management unit is treated consistently from corner to corner, there is little opportunity to gain insight about "what would have happened if we had …?" Why not provide a learning opportunity by prescribing that one corner will be left untreated, or another small plot will receive double the intensity of the overall unit? The pocket science approach gives opportunity to see if the outcomes would have been different if the treatment had been different. Expensive experimentation might be needed to establish strong confidence in the response levels to treatments, but a simple pocket science approach might be strong enough to identify misconceptions or to highlight unanticipated risks (Figure 11). Managers typically would not have much time for intensive monitoring measurements, but most of the outcomes that would be important to recognize might show up in carefully planned repeat photography. A set of pocket science locations also provides a valuable school for touring colleagues, encouraging productive conversations and innovative thinking.

Pocket science opportunities for forest soils and fires might be relatively easy to develop. The layout of restoration treatments that include fire could include portions where fire is not applied. More creatively, a uniform treatment could be applied across a unit with an untreated portion left in the center; after fuels and fire risks were lowered for the whole unit, the residual plot could be burned at a higher intensity. Should land managers be concerned about the nutrient losses associated with low- or high-intensity fires? Small plots (such as 50 ft. x 50 ft.) could be fertilized to see how much the recovering vegetation might be influenced by nutrient supplies. Post-fire erosion control treatments could be applied to small areas even when budgets don't allow widespread application. The possibilities for pocket science projects are large, as are the opportunities for gaining both case-specific and general insights about how forest soils respond to restoration treatments and fires.

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