Section 5—Soils

Soils are the interface between forest vegetation, waters, air, and land. Soils are featured in this synthesis because of their foundational role in maintaining sustainable, productive forests and watersheds. Disturbances can potentially cause excessive soil erosion and loss of productivity.

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Chapter 5.1—Soils

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Summary

When managing for resilient forests, each soil's inherent capacity to resist and recover from changes in soil function should be evaluated relative to the anticipated extent and duration of soil disturbance. Application of several key principles will help ensure healthy, resilient soils: (1) minimize physical disturbance using guidelines tailored to specific soil types; (2) evaluate changes in nutrient capital and turnover, perhaps using simple balance sheets; and (3) recognize effects on organic matter and soil biota. Because of fire suppression, accumulations of litter and duff in many Sierra Nevada forests that evolved with frequent fires may exceed levels that occurred historically and may now represent novel conditions. As a result, proportionately higher pools of nutrients may exist aboveground than in the past. Repeated prescribed burns may be designed to consume fuels in patches to temper nutrient losses and other undesired effects. Extensive areas of high-severity fire pose risks to long-term soil quality by altering soil bulk density, structure, water-holding capacity, and nutrient content in ways that ultimately contribute to declines in soil resilience. A recent synthesis report published by the Pacific Southwest Research Station (Busse et al. 2014) provided a current review of soil science relevant to forest management.

Introduction

Soil is in many ways the lifeblood of nearly all terrestrial ecosystem functions. Beyond just a growth medium for plants, soils store and mete out water and nutrients, fostering growth of vegetation, animal, and human communities. Soil also degrades toxins, sequesters carbon, and is home to an unimaginable number and diversity of organisms, each of which contributes to soil processes and functions. Enthusiasts richly describe soil as the "porous rind," "living mantle," and even the "ecstatic skin of the earth" (Logan 1995). Soil is easily manipulated, and management actions can simultaneously have a mix of positive and negative impacts on soil functions or plant growth. By and large, many management and other disturbance effects on long-term soil sustainability remain unknown (Powers et al. 2005) (see box 5.1-1). There is still much to learn about basic nutrient storage pools, appropriate sampling schemes (Harrison et al. 2011), and the chemical importance of rocks

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within and below the soil (Johnson et al. 2012, Morford et al. 2011). With up to 20 000 km (12,427 mi) of fungal mycelia in a cubic meter (1.3 yd^3) of soil (Pennisi 2004), it can be difficult to untangle the many complex processes that encourage plant growth and distribute water and solutes through the soil and among roots. However, it is known that if we manage our soil poorly, civilizations themselves may ultimately erode (Montgomery 2012).

Box 5.1-1

Long-Term Soil Productivity Experiment

Researchers established the National Long-Term Soil Productivity Research Program in response to concerns about possible losses in soil productivity on national forests resulting from soil compaction and organic matter removal. The study is well-represented in the synthesis area, with six sites including Blodgett (University of California); Challenge and Rogers (Plumas National Forest); Aspen, Bunchgrass, and Cone (Lassen National Forest); Wallace (Eldorado National Forest); and Central Camp, Owl, and Vista (Sierra National Forest) (Powers 2002). Results from the first 10 years of the study show that compaction can increase soil water availability in sandy soils, leading to improvements in vegetation growth. However, growth may be inhibited in compacted clay soils (Gomez et al. 2002a, 2002b). Further, productivity impacts were measured from fairly extreme treatments, such as complete removal of surface organic matter (Powers et al. 2005). However, Powers et al. (2005) cautioned that longer term results are needed to evaluate impacts to soils.

When managing for resilient forests, each soil's inherent capacity to resist and recover from changes in soil function should be evaluated relative to the anticipated extent and duration of soil disturbance.

Following a perturbation, the functional or structural integrity of a soil may change. The magnitude of change reflects the resistance of the soil, with more resistant soils showing little change in soil function after a disturbance. The degree and rate of recovery describe the soil's resilience. Together, the concepts of soil resistance and resilience can be useful when considering management impacts on vital soil functions (Seybold et al. 1999). The temporal and spatial scales of resistance and resilience may also influence management decisions. For example, creating a parking lot at a trailhead will cause a significant change in soil hydrologic function owing to vegetation loss and compaction, but it may be considered allowable or desirable if it affects only a very small proportion of a stand or watershed, or reduces the overall impact of a more dispersed parking area. On the other hand, multiple timber harvesting entries may reduce the soil hydrologic function across a broad area if increasingly more land is compacted without allowing the soil's structural integrity to recover between entries. When managing

for resilient forests, each soil's inherent capacity to resist and recover from changes in soil function should be evaluated relative to the anticipated extent and duration of soil disturbance.

Sierra Nevada Geology and Soils

The Sierra Nevada, often described solely by its massive granite core, in fact embodies a rich and complex geologic history. In general, the range comprises three rock groups: the famed granitic batholith, older metamorphosed rocks that were invaded by the batholithic magma, and younger volcanic and sedimentary post-batholithic rocks. Sierra Nevada granite formed as igneous magma that intruded below the surface rock and cooled beneath it. Millions of years of erosion and weathering have removed much of the older surface layers, exposing the granite core. In the northern half of the range, the older metasedimentary and metavolcanic features are seen in an elongated band along the western flank. These highly varied features include slate, schist, quartzite, greenstone, serpentine, and many other rock types. The southern Sierra Nevada has undergone greater uplift, so much of the older rock surrounding the granite intrusion has been removed, and granitic rocks dominate the terrain. In some places, however, roof pendants of the ancient metamorphic rocks can be seen atop their granite base. In more recent geologic history, volcanic eruptions deposited tuff and andesite flows upon the older granitic and metamorphosed basement. These surfaces predominate east of the Sierra Nevada crest as well as in the north, extending to the eastern Cascade Range and the Modoc Plateau. Uplift, faulting, and repeated glaciations have further sculpted the Sierra Nevada landscape, carving the rock and depositing till and sediments in their wake.

Sierra Nevada soils are highly varied, reflecting the combined influence of climate, topography, biological activity, and parent material over millennia. The resulting soil landscape is a diverse mosaic of varying soil color, depth, texture, water-holding capacity, and productivity. Generally speaking, many soils of the Sierra Nevada are weakly developed and classified as Entisol or Inceptisol soil orders. These often occur at higher elevations and ridge positions, where cold temperature regimes and steep topography limit soil development, but they also occur on resistant parent materials at lower elevations. Developmentally young soils are typically shallow and coarse textured, with little clay development and rapid infiltration rates. Many form on granitic bedrock. On the west slope, mid-elevation soils typically exhibit greater development, support the most productive forests of the range, and include Alfisol and Ultisol soil orders. These soils are deeper, have greater structure and color development and fewer rock fragments, and are enriched with clay. These characteristics enhance the soil's ability to store nutrients and water.

Climate patterns strongly influence soil development and nutrient cycling processes. As elevation and precipitation increase, soil pH and base saturation tend to decrease as a result of greater leaching and decreased evapotranspiration. Soil carbon (C) tends to increase with elevation. Soil depth, color development, and organic horizon thickness and decay rates reach a maximum at mid elevations, with decreases both above and below (Dahlgren et al. 1997). Microbial activity tends to be greatest when soils are both warm and moist. The Mediterranean climate of the Sierra Nevada produces a prolonged summer drought, limiting decomposition rates because of moisture limitation during the warmest months. Aspect also influences soil development and processes, with more weathering and deeper, richer soils forming on mesic north slopes compared to xeric south-facing slopes. Besides water, nitrogen (N) is typically the most limiting factor to plant growth in forest systems (Vitousek and Horwath 1991). In California's forests, the mineral soil is the primary nitrogen (N) reserve, storing 65 to 90 percent of ecosystem N capital (Johnson et al. 2008, 2009). Within forest soil profiles, both N and C are concentrated at the surface, and typically decline with depth (Zinke and Stangenberger 2000). Recent research has shown that nutrient hotspots occur at sites on both the west (Johnson et al. 2011) and east (Johnson et al. 2010) slopes of the Sierra Nevada, with point-scale increases in available N and other important nutrients.

Although simplified patterns of Sierra Nevada geology and soil properties can help describe the regional setting, a tremendous variety of local conditions exists throughout the range. Parent material can be an important factor in soil conditions. For example, soils formed on serpentine have unique nutrient properties, including a low calcium-to-magnesium ratio and high accumulations of heavy metals, which tend to support sparse and sometimes endemic vegetation. Likewise, bands of ancient metasedimentary slate may underlie highly leached and weathered soil, with low levels of base cations and low productivity, whereas an adjacent soil on a more recent andesitic flow may support a robust stand with rich nutrient reserves. Parent material has also long been used as an index of soil erodibility. In the Sierra Nevada, soils formed from decomposed granite tend to be highly erodible (André and Anderson 1961), whereas metasedimentary soils are more stable. Local knowledge of geology and soil conditions is essential in understanding the potential of, and management concerns in, a particular landscape.

Priorities in Soil Management

Regardless of overall land management strategies, application of several key principles will help ensure healthy, resilient soils. Although the list below is not by any means exhaustive, the following considerations are straightforward, easy to grasp, and easy to apply in practice.

Prevent Soil Loss

Maintaining soil in place is often the highest soil management priority. Soil erosion is a natural process—over the ages, mountains erode, alluvial valleys form, and lakes fill in. However, in human time scales, soil erosion is considered acceptable when it is in equilibrium with rates of soil formation. Soil formation rates vary by location, but have been estimated around 2 to 4 Mg • ha • yr^{-1} (1 to 2 t • ac • yr^{-1}) for forest soils. When spread uniformly across an area, this represents an annual gain of a few tenths of a millimeter (0.01 in). Visually, sheet erosion at this rate may be imperceptible, though modeling programs such as the Water Erosion Prediction Project are frequently used to estimate losses through model simulations. Accelerated erosion resulting from management activities that exceeds the background rate of soil formation is typically considered unacceptable. Owing to the time scale at which soils form, prolonged soil erosion is perceived as effectively irreversible. When soil is lost, so is the rooting medium in which plants grow, as well as nutrients, C, organic matter, and the ability to hold water (Page-Dumroese et al. 2010). These properties are generally concentrated at the soil surface, so surface erosion can have greater impacts than soil loss from lower horizons (Elliott et al. 1999). These losses can permanently impair site quality where soil is removed, yet productivity may be enhanced where it is deposited. Excess sedimentation into lakes and streams, however, can reduce water quality and aquatic habitat. Maintaining soil cover is the easiest way to prevent accelerated erosion. Using model simulations, Page-Dumroese et al. (2000) found that in many cases, 50 percent ground cover could prevent accelerated erosion rates. Citing several other studies, Robichaud et al. (2010) suggested that levels of exposed bare soil less than 30 to 40 percent following forest thinning can generally keep soil erosion rates “acceptably low.” Maintaining soil onsite is essential to continued ecological function, and timeframes for recovery of lost soil and the functions it provides are far greater than human lifetimes.

Minimize Physical Disturbance

Forest management practices, especially those using mechanized equipment, are likely to disturb the soil. Many soils are easily compacted by heavy machines, which also displace organic and mineral horizons during turning maneuvers. Forest floor displacement, especially when combined with compaction, leaves soil vulnerable to erosion. Mineral soil displacement can affect soil quality by removing surface material, which is generally richer in nutrients, organic matter, and habitat than underlying subsoil. In cases where a residual canopy exists, litter accumulation and recovery of lost or displaced soil cover can be achieved in a matter of years. Com-

paction effects on forest soils have been studied for over 60 years (Munns 1947, Steinbrenner and Gessel 1955), and they remain an important management concern today. Physical soil changes from compaction have been enumerated by many (see Page-Dumroese et al. 2006), and can include decreases in soil porosity, rooting volume, and aeration, and increases in soil bulk density, strength, water content, runoff, and erosion. Compaction impacts are site-specific, with varied effects on forest stand productivity (Gomez et al. 2002a). One of the easiest ways to prevent compaction is to operate machines when soils are at their driest. This is especially true of soils with high clay content, which develop high soil strength—and compaction resistance—as they dry. Operationally, treatment operations can be timed to delay more vulnerable sites to later in the summer to allow for greater soil drying. Once compacted, recovery of bulk density or soil strength can take many decades. Recovery rates are influenced by management history, including the number of harvest events in a stand and soil moisture conditions during the harvest, as well as soil and site attributes, such as soil texture, rock fragment content, and freeze-thaw cycles (Page-Dumroese et al. 2006). Equipment and operating conditions can be specified to limit soil compaction. These well-known guidelines typically are tailored for soil texture, rock content, and organic matter, and they include using low-ground pressure equipment and operating when soils are dry, frozen, or under substantial snow (e.g., see table 1). Compaction can be mitigated by techniques such as subsoiling, which typically uses a winged implement to lift and shatter the compacted layer without inverting the soil. When properly applied, subsoiling can increase soil infiltration, allow deeper root elongation, and foster increased plant growth. These practices are not without their own risks, however, and may cause rilling and erosion when improperly applied on moderate to steep slopes. Preventing or limiting compaction typically is quite feasible, and in most cases is preferable to relying on post-compaction mitigation practices.

Table 1—Compaction risk ratings based on texture class and coarse fragments

Compaction hazard	Texture class	Coarse fragments > 2 mm
Low	Sandy	Any amount
	Any texture	Greater than 70 percent
Moderate	Loamy texture	Any amount
High	Clayey	Any amount
	Silty	Less than 35 percent

Adapted from Forest Service Region 5 Detrimental Compaction Risk Rating Guide (USDA FS 2006).

Evaluate Changes in Nutrient Capital and Turnover

Forest management can directly and indirectly change nutrient stores at a site. Vegetation harvest removes nutrients in wood and/or crowns, immediately affecting local nutrient pools (Powers 2006). Reductions in canopy cover and altered microclimate can also change the rates at which organic matter decomposes and nutrients cycle from organic to inorganic forms. Fire short-circuits this decomposition pathway, rapidly cycling nutrients tied up in organic matter (Knoepp et al. 2005). Heat from prescribed fire operations volatilizes nutrients, including N, most of which is typically lost as gas during forest floor combustion. Some N may move downward into the soil in forms chemically available to plants and microbes. To evaluate the nutrient impacts of different treatment strategies, forest managers may find it useful to assess the scale of nutrient removal relative to existing pools, and the local mechanisms and rates of nutrient replenishment. Understanding sources and rates of nutrient inputs and outputs allows estimations for future condition and potential recovery. These are discussed in more detail in the following sections.

Recognize Effects on Organic Matter and Soil Biota

Organic matter is considered a cornerstone of soil quality, enabling soil to perform important biological, chemical, and physical functions. As a habitat and nutrient source, organic matter supports soil biota; it also has an extremely high capacity to retain and exchange water and nutrients, and it contributes to soil structure, aggregation, and stability. Soil biotas are essential to many basic soil processes, including formation of soil structure and porosity, organic matter decomposition, atmospheric N fixation, and enhanced nutrient uptake by plants. From single-celled bacteria to complex arthropods and vertebrates, soil organisms are the lifeline between plants and mineral soil. Soil inhabitants tend to concentrate near their food sources at the soil surface, where organic matter and roots are most abundant. Soil biological indicators can be used to detect environmental changes, but their use in land management is limited by taxonomic challenges and their inordinate numbers, and by inefficient analytical protocols and a lack of understanding about them (Andersen et al. 2002). Our understanding of soil biodiversity is in its infancy. For example, less than 10 percent of soil microarthropod populations have been explored (André et al. 2002), and more than 1,000 species of new fungi are described each year (Hawksworth 2001), though not all exclusively occupy soil habitat. Symbiotic associations between plants and fungi, known as mycorrhiza, are well known, but how these intricate mycelial pipelines operate to transmit water and influence plant establishment remains under investigation (Plamboeck et al. 2007). Soil organisms are

generally outside the scope of forest management. However, managing for organic matter is a complementary strategy to ensure biologically healthy soil.

Management Effects on Soils

Mechanical Forest Restoration and Fuel Treatments

Thinning to reduce hazardous fuels or improve forest health in dense Sierra Nevada stands often involves the removal of hundreds of stems per hectare. Though these are typically small-diameter materials, the intensive mechanical operations used to harvest and treat them have raised questions about long-term soil impacts, including compaction, erosion, and nutrient removal. These concerns are not new to forest management, but novel treatments in managed landscapes require careful evaluation of new and cumulative impacts on soil quality.

Physical soil disturbance—

Mechanical thinning treatments in the Sierra Nevada typically use conventional harvest techniques, including heavy equipment operating as harvesters (feller-bunchers and cut-to-length harvesters), skidders, or forwarders. In contrast to traditional commercial stand thinnings that remove fewer, larger trees, forest restoration treatments often aim to remove or process large quantities of small stems. Operationally, this may require that equipment traverse a large proportion of the treatment area in order to access and remove material. Although this equipment footprint can increase the risk of soil compaction from vehicle traffic and soil displacement from vehicle turning, careful operations and application of best management practices (BMPs) can avoid excessive disturbance. Treatment monitoring is essential to allow for feedback to contract officers and operators. Further, monitoring can provide data to track effectiveness of BMPs at minimizing soil and water quality impacts.

Mechanical fuels treatments and restoration thinning can be conducted with minimal exposure of bare mineral soil. In several southern Sierra Nevada studies, bare soil exposure 1 to 3 years after treatment did not differ between treated stands and controls, regardless of whether slash material was left on site (Wayman and North 2007) or piled and burned (Berg and Azuma 2010). Although bare soil can contribute to surface erosion, Berg and Azuma (2010) found no evidence of rilling following forest thinning on predominantly granitic soils. In an erosion study focused on the northern and central Sierra Nevada, Litschert and MacDonald (2009) studied mechanical harvest units, 2 to 18 years after treatment, that were thought to have erosion or sedimentation problems. They evaluated approximately 200 of these units on a range of parent materials and found evidence of soil erosion (i.e., rills or

sediment plumes at the lower unit boundary) in only 19 instances. In all thinning units, the erosion was traced to a skid trail rather than the harvest area in general.

Steep slopes are typically more vulnerable to runoff and erosion, but they are increasingly identified as high priority areas for thinning treatments. To prevent excessive soil disturbance, most public lands in the Sierra Nevada exclude mechanical operations from slopes with gradients above 30 to 35 percent. No studies have examined ground-based operations on steep slopes of the Sierra Nevada, but Cram et al. (2007) studied disturbance and erosion on intermediate (10 to 25 percent) and steep (26 to 43 percent) slopes in a thinned New Mexico mixed-conifer forest. Although operations on steep slopes generally cause more soil disturbance, Cram et al. (2007) found that maintaining soil cover and minimizing large areas of bare soil can be sufficient to prevent increased erosion and sedimentation levels. Equipment has been developed to operate on steep and sensitive areas, including a variety of skyline systems (Elliot et al. 2010) and even more novel approaches, including harvesters that walk on legs rather than roll on tires and tracks (Jaffe and O'Brien 2009).

Skid trails and associated compaction are likely the greatest physical impact of mechanical forest restoration and fuel reduction operations.

In addition to bare soil exposure, skid trails and associated compaction are likely the greatest physical impact of mechanical forest restoration and fuel reduction operations. The spatial extent and arrangement of skid trails depends on the material removed as well as slope, terrain, and proximity to temporary or permanent roads. Much of the compaction on skid trails occurs during the first few machine passes (Williamson and Nielson 2000). Cut-to-length harvest systems, in which only tree boles are taken off site, have been shown to reduce the amount of compaction when boles are forwarded over slash-covered trails. Compared to whole-tree harvests that were yarded with skidders, cut-to-length systems produced a smaller compacted footprint with a lower degree of bulk density change (Han et al. 2009). Although heavy slash mats help buffer the impacts of machine traffic, they break down after multiple equipment passes and their effectiveness at minimizing compaction decreases (Han et al. 2006). Many Sierra Nevada stands have legacy skid trails from previous harvest entries, and re-use of existing trails could limit cumulative compaction impacts. This can be problematic, however, when previous skid trails or landings are located in drainages or sensitive areas, do not access the necessary part of the unit, or are poorly suited for contemporary harvest methods. Roads are often a large contributor to cumulative watershed effects owing to compaction, erosion, and sedimentation to streams. Erosion from roads is discussed in Section 6 of this synthesis, "Water Resources and Aquatic Ecosystems."

Mastication treatments in particular have raised concerns about soil compaction, because masticators may need to operate well away from skid trails to reach standing trees, shrubs, or slash. Like slash mats, masticated material may help

buffer the compacting forces of heavy equipment (Moghaddas and Stephens 2008), but soil moisture remains a key factor in susceptibility to compaction. Recent findings in the Sierra Nevada have shown that compaction effects on tree growth are complicated and can vary with soil texture. Growth in pine plantations less than 10 years old was negatively affected in compacted clay soils, responded neutrally to compacted loam, and increased in compacted sandy loam soil (Gomez et al. 2002a, 2002b). Compaction compresses large pores, so coarse-textured soils may have more capillary ability when compacted, holding more water and enhancing tree growth. Soil compaction is a reversible process, but recovery can take many years. Soil recovery is greatly enhanced by freeze-thaw processes, but soil texture may also play a key role in recovery rates. In plantations grown in compacted soils, bulk density recovery after 5 years was slower in fine-textured soils than coarse-textured ones (Page-Dumroese et al. 2006).

Box 5.1-2

Compaction

Soils are easily compacted, even with just a few machine passes. Recovery following compaction is a slow process, often requiring decades. Mitigation techniques, such as subsoiling, are not without their own risks and effects, and should be considered far less desirable options than preventing compaction in the first place. Operationally, compaction can be minimized by:

- Operating when soils are dry; moist soils are more susceptible to compaction and will compact to a greater depth than dry soils
- Operating when soils are frozen or under deep snow
- Using equipment with minimal ground pressure
- Limiting equipment to designated trails, and reusing trails where feasible
- Using boom-mounted equipment, which requires less ground travel
- Traveling over deep slash layers where feasible

Results from the Long Term Soil Productivity experiment show that compaction can increase soil water availability in sandy soils, leading to improvements in vegetation growth. However, growth may be inhibited in compacted clay soils (Gomez et al. 2002a, 2002b).

Effects on soil nutrients—

Forest restoration thinning and fuels treatments are commonly achieved through whole-tree harvest techniques. For more than 40 years, this practice has raised concerns about nutrient loss and long-term site productivity because branches and foliage are removed along with the tree stems (Kimmins 1977, Tamm 1969). However, most research has evaluated whole-tree clearcut harvests, and surprisingly few studies have addressed impacts of whole-tree thinning. Thinning typically removes far less biomass than clearcut prescriptions. For example, fuels reduction thinning projects in dense Sierra Nevada stands removed an average of 12 percent of the standing live volume (Collins et al. 2007), which was equivalent to 21 percent of the basal area in those areas (Stephens and Moghaddas 2005). Fuels reduction treatments in dense stands typically reduce basal area by 20 to 45 percent (Boerner et al. 2008b), while retaining a majority of the standing volume on site. Fuels are often thinned from below, so understory, suppressed, and intermediate trees are removed before codominant or dominant trees. These lower crown positions have proportionately less canopy biomass (Reinhardt et al. 2006) and, therefore, fewer canopy nutrients than the dominant overstory. Using clearcut-based studies to infer nutrient loss impacts following fuel reductions could grossly overestimate effects on soil nutrient pools and stand productivity. In any case, studies of stands greater than 15 years old suggest that whole-tree clearcut impacts to soil C and N stocks diminish with time (Jandl et al. 2007, Johnson et al. 2002, Jones et al. 2008, Walmsley et al. 2009), and nutrient recovery in thinned stands would likely be much quicker.

Few whole-tree thinning studies have been conducted in U.S. forests, and studies on fuels reduction thinning in the Sierra Nevada are even fewer. Johnson et al. (2008) compared whole-tree and cut-to-length thinning in a Sierra Nevada east-side pine forest. Whole-tree harvest methods removed approximately three times more N than cut-to-length methods. Because limbs and tops were left on site, the cut-to-length system left two to three times more C and N content in the forest floor than the whole-tree harvest. However, neither harvest system removed more than a few percentage points of the ecosystem N capital of the sites (Johnson et al. 2008). In a fuels reduction study in dry forests of central Oregon, Busse et al. (2009) compared the effects of whole-tree harvest, bole-only removal, and thinning without biomass removal on vegetation responses. Through periodic measurements in the 17 years following the treatments, they found no differences in tree growth, shrub cover, or herbaceous biomass among treatments. Busse and Riegel (2005) estimated that this whole-tree thinning removed 4 percent of ecosystem N, whereas bole-only harvest removed 1 percent. Compared to the other residue treatments, the whole-tree harvest did not reduce the site potential or soil nutrient status of the relatively infertile sites

included in that study (Busse and Riegel 2005). It's likely that many Sierra Nevada forests are similarly resistant to N reductions, but the potential losses must be considered in the context of the total amount of N on site and sources of N inputs over time. Fertile sites with deep, rich soils tend to be more resilient to whole-tree harvests than poor sites, such as shallow soils over bedrock or coarse-textured soils (Raulund-Rasmussen et al. 2008). More nutrients are generally exported during whole-tree harvests from fertile sites than from nutrient-poor sites, but higher levels of nutrient inputs and cycling rates often allow for rapid replacement of the lost nutrients.

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Balance sheets are useful to compare nutrient inputs, outputs, and on-site reserves (Smith 1986). Forest managers can estimate the amount of nutrients removed during whole-tree fuels reduction by first taking stock of what is held in tree crowns and boles and then determining how much material will be removed during treatment. For example, canopy fuels in a dense, mid-elevation west slope Sierra Nevada stand with high fire hazard conditions were estimated at 17 Mg/ha (8 t/ac) (Reinhardt et al. 2006). Estimates from other similar studies in the Western United States found crown fuel loads between 9 and 21 Mg/ha (4 to 9 tons/ac) (Cruz et al. 2003, Fulé et al. 2001). Assuming that half the crown volume of a stand is removed and that its foliar N content is 1.4 percent (Carter 1992, Garrison et al. 2000), approximately 65 to 150 kg N/ha (0.029 to 0.067 t N/ac) might be removed as crown material during fuels treatments. Assuming that an equal portion of N is stored in the wood, 65 to 150 kg N/ha (0.029 to 0.067 t N/ac) may also be removed as bole material. For many Sierra Nevada sites, 130 to 300 kg N/ha (0.058 to 0.130 t N/ac) represents only a small percentage of the N stored in the soil (Zinke and Stangenberger 2000) and an even smaller proportion of total ecosystem N on site. Furthermore, the actual amount of N removed will vary by stand and thinning treatment. At their east-side Jeffrey pine site, Johnson et al. (2008) reported N removal of 50 and 162 kg N/ha (0.022 and 0.072 t N/ac) in areas treated with cut-to-length and whole-tree thinning, respectively. It is important to remember that N is chronically added to forest stands by deposition and lost by leaching, and these processes vary by geographic region. By estimating local deposition and leaching rates, one can consider harvest N removals in the context of how quickly they will be replenished (table 2). Although useful as a simple tool to gain perspective on long-term nutrient changes, this nutrient budget approach cannot account for complex and unpredictable changes in nutrient cycling or rates of availability (Powers et al. 1990).

For particularly sensitive sites, there are a number of options to minimize or compensate for nutrient losses from whole-tree harvesting. More nutrients can be kept on site by harvesting in the fall or winter. Wood becomes more brittle during

Table 2—Example of soil nutrient capital and nutrient balance accounts for a site thinned with a whole-tree harvest approach

Credit/debit	Nutrient balance	Explanation
	Kilograms N per hectare	
Soil pool	9800	The soil acts as a large reservoir to store N. Most soil N occurs in organic form, which is not readily available for plant uptake and cannot be easily leached. Plant-available inorganic N is slowly released through decomposition and mineralization pathways.
Harvest export	-200	Whole-tree thinning removes some of the N capital from the site. The time required to replenish lost N depends on rates of inputs and outputs. Harvesting alters soil microclimate, which can increase or decrease the amount of N available for plant uptake by altering rates of decomposition and N mineralization.
Annual deposition	6	Nitrogen is continually added to terrestrial systems as both dry and wet deposition.
Annual leaching	-1	Nitrogen leaching losses typically occur as plant-available nitrate.

Nitrogen (N) removal from whole-tree harvest is equal to less than 3 percent of the total soil pool of N. Assuming that deposition and leaching rates remain constant, N is added at a rate of 5 kg $\cdot$ ha^{-1} $\cdot$ yr^{-1}. At that rate, the N removed from the thinning treatment would be replenished after approximately 40 years, or sooner, if the abundance of N-fixing vegetation increased after treatment.

this time and is more likely to break during thinning activities. Leaving broken branches or tops in the stand will reduce the nutrients exported off site. Harvesting trees during their dormant period may also reduce nutrient exports, as leaves translocate their nutrients to the roots and other components at senescence (Nambiar and Fife 1991). Thinning deciduous trees after leaf drop can also reduce foliar export out of the stand. Marking guidelines that account for species nutrient requirements can also help offset nutrient removals; thinning trees with high nutritional needs while retaining more frugal species may export a relatively larger amount of nutrients, but the overall nutrient demand in the residual stand will be reduced. Where species exhibit great differences in nutrient needs, these nutrient requirements could become a consideration in marking guidelines for fuels reduction, in addition to crown spacing, shade tolerance, and fire behavior characteristics. Five years after whole-tree thinning to reduce fuels and restore stand structure, units where large trees were preferentially retained, regardless of species, had greater levels of soil N, and thus greater short-term potential for increased growth and productivity, than units where pine species were preferentially retained. However, the pine-retention stands had higher levels of forest floor N, suggesting greater potential for nutrient availability in the future (Miesel et al. 2008).

In many cases, whole trees are skidded to a landing where processors, such as delimbers, remove the nonmerchantable material from the bole. Rather than chipping or burning the slash, skidders could backhaul some or all of it into the unit

to redistribute the nutrients on site. This would allow efficient harvesting equipment (e.g., feller-bunchers) to fell trees while reducing nutrient losses. Rich (2001) addressed some operational constraints and practices to help make backhauling of slash a feasible option. However, fuel loading should be a consideration in plans that include redistribution of slash.

Prescribed Fire Treatments

Prescribed fire operations designed to reduce ground and surface fuel loads are common in the Sierra Nevada, and many basic prescribed fire effects on soils have been well described in review or meta-analysis publications that use references from around the globe (e.g., see Carter and Foster 2004; Certini 2005; Johnson and Curtis 2001; Nave et al. 2011; Neary et al. 1999, 2005; Raison 1979; Wan et al. 2001). Like mechanical vegetation removal, fire reduces the nutrient capital on site, but through a very different mechanism. Whereas harvests physically remove nutrients contained in biomass, fires volatilize and transform nutrients through heating and combustion. Similar effects are generally found regardless of whether or not sites are thinned prior to burning, but the magnitude of those effects can vary. Management practices that alter the forest floor will similarly alter fire behavior and effects. Conditions that lead to greater fuel consumption have the potential to increase impacts on soils. Slashmats left in yarding trails during cut-to-length harvests create continuous fuelbeds that burn more than adjacent areas, whereas skid trails tend to disrupt fuel continuity and burn less than adjacent areas.

Recent research has focused on comparing the individual and combined effects of thinning and burning treatments on soil. Boerner et al. (2008a, 2008b, 2008c, 2009) have conducted soil meta-analyses for 12 North American forest sites in which the same study design was used to examine forest thinning, burning, and combination treatments. A number of similar forest restoration or fuels reduction studies using prescribed fire have been implemented across and near the Sierra Nevada, and these form the basis for this section. They include treatments in mixed-conifer stands in the Goosenest Adaptive Management Area in the southern Cascade Range, Blodgett Forest Research Station in the central Sierra Nevada (fig. 1), Teakettle Experimental Forest and Sequoia National Park in the southern Sierra Nevada, and a Jeffrey pine forest east of the Sierra crest.

One of the most significant changes to the soil system caused by fire is the loss of mass and nutrients from the forest floor. Fuel consumption typically varies across a burned area owing to microsite differences in fuel moisture, loading, and continuity. In unharvested stands, Knapp and Keeley (2006) found that 70 percent of the treatment area burned during early season prescribed fires when fuels and soil were

Scott Stephens

Scott Stephens

Figure 1—(A) Before (2001) and (B) after (2003) photos of a Fire and Fire Surrogate Study site at the University of California's Blodgett Forest Research Station that was thinned and burned.

moist, whereas 88 percent burned during late-season fires when conditions were substantially drier. Prefire harvests can both increase and decrease fuel continuity and burn extent. Cut-to-length harvesting, in which activity slash is placed in the yarding trail, can result in higher levels of fuel consumption within slash mat features; in one study, fire covered 60 percent of the area outside slashmat features, while 70 percent of the area burned within the slashmat trails (Murphy et al. 2006a). In contrast, skid trails typically expose large amounts of bare soil, reducing the percentage of area burned. Following whole-tree harvest, Murphy et al. (2006a) found that fire covered 77 percent of areas outside skid trails, but only 30 percent of the area within them. Similarly, Moghaddas and Stephens (2007) found that, in thinning units where both logging slash and masticated debris were left on site, 95 percent of areas outside skid trails burned, but only 48 percent of the area within skid trails burned. Where skidders were used, the combination of thinning and burning exposed more bare soil than either one alone (Moghaddas and Stephens 2007, Wayman and North 2007).

When litter and duff layers burn, most of the N they contain is lost to the atmosphere in gaseous form. The amount of N lost during fires is positively correlated to the amount of material burned, which can vary tremendously across the Sierra Nevada. For example, prescribed fire in a highly productive mixed-conifer forest reduced the forest floor mass by 87 percent, causing N losses of 725 to 750 kg/ha (0.32 to 0.33 t/ac) (Moghaddas and Stephens 2007), which represents well under 10 percent of the ecosystem N on site (Boerner et al. 2008c). But burning in east-side Jeffrey pine forests reduced the forest floor mass by 60 to 75 percent, with concomitant N losses of only 100 to 250 kg/ha (0.04 to 0.11 t/ac) (Murphy et al. 2006a), equivalent to less than 5 percent of ecosystem N there (Johnson et al. 2008). At each locale, the greater losses occurred in stands where logging slash was present. The forest floor was reduced by more than half at both sites, causing a substantial relative reduction in surface N capital. Carbon losses from the forest floor follow similar patterns to N, with proportionately more C lost as more forest floor is combusted.

Despite huge changes in the forest floor, total C and N pools in mineral soil often remain unchanged following prescribed fire.

Despite huge changes in the forest floor, total C and N pools in mineral soil often remain unchanged following prescribed fire, though both decreases and increases have been observed. Total soil C and N were unchanged following burning in both examples described above (Johnson et al. 2008, Moghaddas and Stephens 2007). Similarly, burning and thin-burn treatments in a southern Sierra Nevada site did not alter soil C pools (North et al. 2009) or C and N concentrations relative to control plots (Wayman and North 2007). Soil pools may remain largely unaffected, because so much nutrient capital exists in the soil that fire-induced

changes are relatively small by comparison (Wan et al. 2001), and because prescribed burns do not often reach temperatures high enough to combust soil organic matter beyond shallow surface layers (Johnson et al. 2009). At another southern Sierra Nevada mixed-conifer site, 74 percent of the forest floor mass was consumed during early-season burns (Knapp et al. 2005), with no change in soil total C or N pools (Hamman et al. 2008). In contrast, late-season burns at the same site consumed 94 percent of the forest floor (Knapp et al. 2005), reducing soil C levels for at least 3 years, but causing no change in total N. The drier fuel and soil conditions during late-season burns can contribute to greater burn severity and a more

Box 5.1-3

Putting Nutrient Removals in Perspective

Because of fire suppression, accumulations of litter and duff in many Sierra Nevada forests that evolved with frequent fires may exceed levels that occurred historically and may now represent novel conditions. As a result, proportionately higher pools of nutrients may exist aboveground than in the past. Both forest thinning (harvest) and prescribed fire cause nutrient losses, although through very different mechanisms. Whereas nutrients are directly exported in boles (and tops and limbs, in the case of whole-tree harvest) during thinning, fires remove carbon and nitrogen (N) largely through combustion and volatilization. Cumulatively, harvest and burning treatments will remove more nutrients than either treatment alone. It is a good idea to assess the scale of nutrient removal relative to existing pools in order to evaluate potential risks to forest productivity and consider soil resilience to nutrient losses. Soils are widely variable in space, and knowing if a specific soil has vast reserves of N and other nutrients or is shallow and nutrient poor can be critical in assessing the consequences of nutrient removal. This is especially true if repeat or cumulative treatments are being considered. Management goals may not seek to replenish these nutrients if they are removed through harvest or fire, but understanding the magnitude of change and rate of recovery can provide important ecological perspective. Balance sheets can provide ballpark estimates of nutrient inputs and outputs and give managers a sense of the scale of impact different treatment alternatives may carry (see table 2). After treatments, periodic site visits can be used to assess the cover and type of nitrogen-fixing shrubs; these visits can further refine estimates of N replenishment over time.

prolonged soil effect (Hamman et al. 2008). In the southern Cascade Range, Miesel et al. (2007) reported reduced concentrations of soil C in unthinned, burned stands, but no change in areas that had been whole-tree harvested prior to burning. The decrease was attributed to greater soil heating and organic matter combustion in the unthinned areas. In some cases, soil C can increase following prescribed fire owing to the incorporation of charcoal (Johnson and Curtis 2001), but no examples of this have been documented in the Sierra Nevada.

A short-term increase in soil pH is often, though not universally, observed following prescribed fire as a result of deposition of ash rich in base cations (Raison 1979). Studies in the Sierra Nevada that measured pH show that thinning and burning treatments elicit the same soil response as burn-only treatments, whether that response is an increase in pH (Moghaddas and Stephens 2007, Ryu et al. 2009) or no change in pH (Murphy et al. 2006a). Fire also tends to increase inorganic N levels in the soil (Miesel et al. 2007, Moghaddas and Stephens 2007). In both the southern Cascade Range and the central Sierra Nevada, thinning before burning resulted in greater inorganic N increases. At the latter location, the increase was due primarily to large increases in ammonium, which can result from oxidation of organic matter during burning and increased N mineralization. Presumably, the organic matter and N source was the combusted forest floor, as volatilized N can condense and move down into the mineral soil. The increase in inorganic N, however, represented only 5 percent of the N lost from the forest floor (Moghaddas and Stephens 2007). Nitrogen-fixing plants, which occur at both of these study sites, can also contribute inorganic N to the soil. Despite increases in mineral N, no changes in mineralization rates were detected following burning in the southern Cascade Range (Miesel et al. 2007) or in central Sierra Nevada (Moghaddas and Stephens 2007) or southern Sierra Nevada (Hamman et al. 2008) sites, and changes in nitrification rates were variable. Although N turnover rates often increase following fire, microbial activity is strongly linked to substrate availability, organic matter quality, and microclimate—factors that will vary under different site and burn conditions. When changes do occur following prescribed fire, they tend to diminish within several years (Wan et al. 2001).

Woody fuels are piled and burned in some areas because of infeasibility or restrictions against underburning or mechanical operations. Burn piles concentrate soil heating effects into relatively small, confined areas beneath the pile footprint. Soil heating during pile burning can be extreme. In southern Colorado, Massman and Frank (2004) measured soil temperatures of 400 °C (752 °F) beneath a large slash pile, and temperatures remained elevated for several days. Significant changes in the physical, chemical, and biological properties of soil are likely under

these conditions, but not all pile burns result in extreme soil temperatures or soil damage (Busse et al. 2014). The severity of an individual burn plays a large role in subsequent soil impacts, which may include changes in organic C and N, available nutrients, water repellency, microbial activity, soil texture, mineralogy, bulk density, and porosity. Pile burning is also responsible for the so-called "ash-bed effect," in which the release of nutrients (particularly N, calcium, magnesium, and potassium) from organic materials can temporarily augment soil fertility. In the Sierra Nevada, York et al. (2009) found that 10-year height and diameter growth of conifer seedlings was up to 50 percent greater within pile burn perimeters than on adjacent, unburned ground.

Fuels managers face decisions about the appropriate size and density of piles for given treatment units. Although larger piles will generate more heat overall, they do not necessarily increase the degree of soil heating. For example, Busse et al. (2013) found no significant relationship between pile size and maximum soil temperature or heat duration for piles ranging from 1.8 to 6.1 m (6 to 20 ft) in diameter in the Lake Tahoe basin. Rather, fuel composition was the key factor in soil heating at these sites. Piles containing high levels of large-diameter bole wood reached greater soil temperatures for longer durations than piles containing smaller diameter materials and limbs. Under all piles, the most extreme heating was limited to the surface 5 to 10 cm (2.0 to 3.9 in) of mineral soil below the pile. Extreme soil heating may be of little concern if it occurs beneath widely spaced piles that occupy little of the total land surface. The greater the density or total ground coverage of piles, the greater the potential to affect soil quality as a result of extreme soil heating. Across 71 sites in the Lake Tahoe basin, ground coverage by piles averaged 8 percent, but reached as high as 35 percent where larger diameter insect-killed trees were bucked and piled (Busse et al. 2014). These findings suggest that, in most cases, decisions regarding the optimal size and number of piles per treatment unit can be based on operational factors, including cost effectiveness, fire risk, and operator safety, rather than potential soil effects.

In most cases, decisions regarding the optimal size and number of piles per treatment unit can be based on operational factors, including cost effectiveness, fire risk, and operator safety, rather than potential soil effects.

Soil resilience and repeat burning: fire as a restoration tool—
Most terrestrial areas in the Sierra Nevada evolved with some periodic influence of fire, including the changes in nutrients and soil processes that fire causes. The reintroduction of fire is often recommended as a restoration and maintenance tool. There are very few data available about repeat burning effects on soils in the Sierra Nevada. Perhaps the most extensive research on the soil impacts of long-term, frequent prescribed fire programs has come from the Southeastern United States. Soil studies in southern pine forests have examined impacts following decades of annual burning and made comparisons to less frequently burned or unburned

stands. As with single-entry prescribed fires, repeat burning results in reductions in the forest floor and the nutrients contained therein. The more frequent the burns, the greater the reduction in forest floor N content. For example, following 30 years of prescribed fire treatments in the coastal plain of South Carolina, forest floor N mass was reduced by 29, 60, 60, and 85 percent following fires every 4, 3, 2, and 1 years, respectively, relative to the 480 kg N/ha (0.21 t N/ac) in the control stand (Binkley et al. 1992). Similarly, annual burning at another South Carolina site reduced forest floor N by 68 percent, and a fire return interval of 7 years resulted in a 32-percent loss of N relative to the 408 kg N/ha (0.18 t N/ac) in the control (McKee 1982). Although climate, soils, and forest type differ between the Sierra Nevada and the Southeast, the concept that more frequent fire results in greater cumulative forest floor N losses transcends these differences. Johnson et al. (1998) developed a nutrient cycling model to predict N changes following frequent prescribed fire at a site in the eastern Sierra Nevada. Using local litterfall rates, N concentration, and litter decay rates, they simulated the forest floor biomass and N content under varying fire frequencies and levels of fuel consumption. They showed that, over a 100-year period, prescribed fires every 10 years would result in 35 percent more N loss than fires every 20 years, assuming half the forest floor is consumed. Allowing litter to accumulate for 100 years before it is completely consumed by wildfire would result in less than half the N loss modeled for a 10-year prescribed fire interval (Johnson et al. 2009).

Over time, repeated fires can lead to a gradual reduction in the N capital of a site. This does not suggest, however, that infrequent fire is the most desirable management strategy. Although more N is conserved under infrequent fire regimes, that scenario places overall soil resilience at risk. In that case, the forest floor N pool slowly swings between extreme states—unprecedented accumulation in thick duff and litter layers, then complete loss following wildfire. Furthermore, fires that completely consume the forest floor leave the mineral soil vulnerable to erosion and associated losses of nutrients and organic matter. Rather than broadly excluding fire to preserve on-site N pools, managers may choose to consider local N replenishment mechanisms following periodic fire and factor that into planning efforts. Soil resilience to N loss depends on the rate of N recovery. Predominant N input sources include atmospheric deposition and N fixation. Levels of N deposition depend largely on air pollution and weather patterns, which vary across the Sierra Nevada (see chapter 8.1, “Air Quality”). The National Atmospheric Deposition Program maintains a long-term record of wet deposition chemistry and may be a useful starting point for managers to approximate deposition levels. In relatively unpolluted areas, N fixation is the most important N input source. Johnson et al. (2004) studied nutrient changes following the stand-replacing Little Valley Fire in the

eastern Sierra Nevada. Although 71 percent of aboveground N was consumed in the 1981 fire, additions from the N-fixing shrub snowbrush (*Ceanothus velutinus* Douglas ex. Hook) had more than made up for the losses 16 years later. If inputs were limited to deposition alone, the lost N would not be replaced for more than 1,000 years at this relatively unpolluted site (Johnson et al. 2004). Other N-fixing species contribute far less to ecosystem N recovery. Slow-growing N-fixing shrubs in northeastern California and central Oregon, including bitterbrush (*Purshia tridentada* (Pursh) DC.) and mahala mat (*Ceanothus prostratus* Benth.), probably fix enough N to meet their own needs, but are unlikely to contribute enough to compensate for N losses following disturbances such as fire (Busse 2000). Johnson et al. (2009) suggested that frequent prescribed burning (with intervals less than 10 to 20 years) has potential to result in substantial N losses over time. It follows that historical frequent fire regimes would have also caused cumulative N losses, potentially reducing productivity over time. Similar losses from frequent prescribed fire might raise concerns about contemporary site productivity, but they may also be a desirable outcome, especially in watersheds with nutrient-sensitive water bodies, such as Lake Tahoe, and areas with heavy N pollution. Where cumulative N loss from repeat prescribed burns is a concern, techniques to increase burn heterogeneity, in which areas of the forest floor remain unburned, may be useful. In general, research on the effects of frequent prescribed burning in the Sierra Nevada is needed, as the effects of long-term fire suppression on forest soils in this region are not well understood (Miesel et al. 2011).

Effects of Wildfire

Wildfires can cause a number of important effects on soils, including increased runoff and erosion, potential changes in soil structure and biota, and loss of the forest floor and associated C and N. Postfire effects and recovery, hydrologic response, and the magnitude of erosion events are highly variable depending on fire severity and extent, postfire rainfall amount and intensity (especially in the first three years following wildfire), and geology and topography (Miller et al. 2011, Moody et al. 2008, Robichaud et al. 2008). A recent synthesis on soils (Busse et al. 2014) provided a more detailed consideration of the effects of fire. That report cautions that severe burns induce losses of organic matter, alter surface physical and chemical properties, and can increase soil erosion and reduce long-term soil productivity. Three important advances in understanding of fire effects on soils are considered briefly here: the importance of plant and litter cover in limiting erosion, the issue of "sterilization" by intense fire, and the issue of fire-induced water repellency. Effects of wildfire on streams are discussed in chapter 6.1, "Watershed and Stream Ecosystems," and strategies for treating postfire impacts are discussed in chapter 4.3, "Post-Wildfire Management."

Postfire impacts on physical and biological properties— Research has shown that plant and litter cover play an overwhelming role in controlling postfire erosion (Larsen et al. 2009). Loss of forest floor cover during wildfire exposes bare mineral soil to raindrop impact and decreases surface roughness, leading to greater velocity of overland flow and potential sheetwash, rill, and gully erosion. Patterns of fire severity help dictate the nature and extent of these impacts. Wildfires generally burn in mosaics of low, moderate, and high severity, leaving a patchy distribution of litter and duff across the landscape. Generally, the degree of patchiness of forest floor cover determines its effectiveness in intercepting rainfall and surface flow and preventing surface runoff and erosion (Pannkuk and Robichaud 2003, Robichaud 2000). Recovery of vegetation cover is also site specific yet can be rapid depending on timing and amount of rainfall or snowmelt. Erosion control is considered "partially effective" once plant cover exceeds 30 percent, and it is considered "effectively" controlled, even during high-intensity rain events, when plant cover approaches 60 percent (Quinton et al. 1997, Robichaud et al. 2000). In the Sierra Nevada, postfire erosion decreases with time through the first several years following fire (Berg and Azuma 2010, Pierson et al. 2008) as vegetation becomes reestablished and cover increases (Keeley et al. 2003).

A common perception has been that high-severity wildfires sterilize soils, but research indicates that severely burned "red" soils are not sterile, although such burning does greatly reduce soil nutrients and microbial abundance (Hebel et al. 2009). These impacts can be particularly acute where there are concentrations of large wood debris that burn for extended periods, as reported from studies of burn piles. Although these patches can be recolonized from less severely burned areas, recovery of plant communities may be much slower than recovery of the microbial community (Busse et al. 2014, Fornwalt and Rhoades 2011, Korb et al. 2004).

The formation of water repellent layers following burning is another fire-related soil process that has received attention from researchers. Soil water repellency (or hydrophobicity) causes soils to resist wetting for extended periods, which can result in increased runoff from the hydrophobic patches and accelerated soil erosion (Doerr et al. 2000). Studies have shown that soil water repellency is a common feature of many Sierra Nevada soils not only after fire but also in areas that have not been burned (see Busse et al. 2014). Burning can volatilize hydrophobic organic compounds present in the soil and litter, which then condense onto soil particles. However, burning can also break down repellent layers in soils, especially at high temperatures (>400 °C), although such effects are not necessarily consistently associated with burn severity (Doerr et al. 2000). Most wildfires result in a mosaic of repellency from zero to high levels that is influenced by the distribution of plants

on the landscape, nonuniformity of fire temperature and duration, litter depth and moisture content, and differences in soil moisture and soil texture (Hubbert et al. 2006, MacDonald and Huffman 2004). Most research has inferred rather than demonstrated a direct causal link between water repellency and erosion, and few studies have succeeded in isolating the erosional effects of water repellency from other related causes (Doerr et al. 2000). Because water repellency is greatest in dry soils, it is probable that reduced infiltration rates leading to overland flow and subsequent erosion events would be most likely to occur after prolonged dry periods (Rice and Grismer 2010). Therefore, one would expect fire-caused repellency to play a minimal role in the middle of a Sierra Nevada winter, but its effect would be much more pronounced during summer thunderstorms or the first rain events of the fall. Presence of soil cracks, burned root holes, and patches of hydrophilic soils can prevent hydrophobic patches from having significant effects (Shakesby and Doerr 2000). As a result, other fire effects, such as reduced infiltration resulting from sealing of surface pores by ash and fine soil particles, may be more important determinants of postfire runoff and erosion than water repellency (Martin and Moody 2001, Robichaud et al. 2013).

Effects on soil nutrients—

There are very few studies of wildfire effects on soils that include comparisons of pre- and postfire data. Only one such study exists in the Sierra Nevada; it took place on the southeast side of Lake Tahoe, where soil research plots burned in the 2002 Gondola Fire (Johnson et al. 2007, Murphy et al. 2006b). That fire resulted in a 20-percent reduction in ecosystem C and a 15-percent reduction in ecosystem N, owing primarily to combustion of vegetation, the organic soil horizon, and large woody debris. Although the wildfire had no statistically significant effect on soil C and N, about one-fifth of the N lost was from mineral soil (Johnson et al. 2007). This is in contrast to most prescribed fires, which do not typically reach temperatures high enough to volatilize N in the soil. Unfortunately, no data on the intensity of the Gondola Fire were reported. Some of the C and N losses may have been caused by erosion. A few weeks after the fire, a high-intensity precipitation event (up to 15 mm; 0.59 in within 3 to 5 hours) led to runoff and erosion of up to 1.4 cm (0.55 in) of soil from the study area (Murphy et al. 2006b). The ecosystem C is unlikely to be replenished until a mature forest is established at this site, whereas lost N may recover within a few decades if N-fixing shrubs, such as snowbrush ceanothus (*Ceanothus velutinus*), colonize the site (Johnson et al. 2007).

A similar study of pre- and postfire soil conditions was conducted in southwestern Oregon in the area that burned in the 2002 Biscuit Fire. However, the Biscuit Fire burned at high intensity, reaching temperatures >700 °C (>1,292 °F),

Box 5.1-4

Heavy Metals and Mercury

Heavy metal accumulation is a nationwide environmental health hazard. Even relatively remote forest ecosystems are not immune from this problem—in fact, extensive fire suppression in the Sierra Nevada is suspected to have led to a buildup of heavy metals, particularly mercury, in forest litter (Obrist et al. 2009). Of immediate concern is the potential for redistribution of litter and sediment-bound metals during fire, leading to unwanted pollution of lakes and reservoirs and, ultimately, heavy metal bioaccumulation in fish (Obrist 2012).

The environmental fate of mercury is reasonably well studied in Sierra Nevada soils and offers insight to the fates of other heavy metals such as lead, chromium, cadmium, nickel, and zinc. Mercury accumulation has resulted largely from human activity, coinciding with the start of the industrial revolution. For example, Drevnick et al. (2010) reported estimates of mercury flux to Lake Tahoe at 2 $\mu g/m^2$/year for preindustrial sediments and 15-20 $\mu g/m^2$/year for modern sediments. Key points relevant to the fate of mercury in Sierra Nevada forests are:

- Ninety to 98 percent of the total mercury in Sierra Nevada forests is found in mineral soil (Engle et al. 2006; Obrist et al. 2009, 2011).
- Mercury is essentially inert in mineral soil and unaffected by wildfire or prescribed fire (Engle et al. 2006, Schroeder and Munthe 1998). Large postfire erosional events that transport sediment-bound mercury to streams, lakes, and reservoirs may be of concern (Burke et al. 2010, Caldwell 2000, Driscoll et al. 2007).
- Carbon and nitrogen rich soils (highly fertile) typically contain the highest concentrations of mercury (Obrist et al. 2009, 2011). The corollary is that **many low-fertility Sierra Nevada soils are at low risk for mercury contamination.**
- Combustion of forest litter is the primary source of mercury transport during fire (Engle et al. 2006, Obrist et al. 2009). Thus, **severe burning with complete combustion of the forest floor represents the greatest risk for mercury redistribution and potential bioaccumulation in Sierra Nevada waters.**

as evidenced by melted aluminum tags in the research area (Bormann et al. 2008). This study represents the first direct evidence of significant mineral soil C and N losses from wildfire. Unlike the Gondola Fire, which did not affect mineral soil C pools, 60 percent of C lost from the organic and mineral horizons in the Biscuit Fire came from mineral soil. Similarly, 57 percent of the N lost from the organic and mineral horizons in the Biscuit Fire came from mineral soil. The Biscuit Fire caused substantial losses of fine soil, totaling up to 127 Mg/ha (57 t/ac). This loss was likely caused by water erosion as well as convective transport in the fire's smoke plume (Bormann et al. 2008). The loss of soil organic matter may affect soil bulk density, structure, water-holding capacity, and nutrient content, contributing to declines in soil resilience. As a general conclusion regarding effects of wildfire, management strategies that reduce the potential for uncharacteristically severe wildfires in Sierra Nevada forests will help limit erosional losses and conserve essential soil functions.

Management strategies that reduce the potential for uncharacteristically severe wildfires in Sierra Nevada forests will help limit erosional losses and conserve essential soil functions.

Knowledge Gaps

Mastication is a technique used across the Sierra Nevada to thin forested stands and plantations and rearrange woody fuels. Mastication produces a layer of woody residue on the forest floor that has no natural analog. Debris size, depth, and density depend on the characteristics of the mastication equipment and masticated materials, as well as the time since treatment. Residues effectively serve as a mulch layer, reducing soil heating caused by solar radiation and retaining soil moisture by reducing evaporation. But few studies have examined the effects of mastication on soils, particularly long-term responses as the debris settles and decays. Soil scientists have concerns about deep residues, and how they may affect rates of nutrient cycling, N availability, or soil aeration. Depending on the depth, density, and continuity of masticated debris, fire treatments in masticated stands may result in more severe effects to soils. No long-term studies exist to address these issues.

Many ground-based mechanical operations in the Sierra Nevada are limited to slopes of less than 35 percent, but there is an increasing desire to treat steeper slopes. Operational knowledge is needed to effectively treat steep ground without substantially increasing the risk of soil loss, erosion, and sedimentation into streams. Existing equipment innovations may render the 35-percent slope restriction obsolete, and field-based trials and studies are needed to inform and enhance managers' options in this sensitive terrain.

The topic of coarse woody debris has received much attention as a habitat component for wildlife and a structural attribute of aquatic systems. Less is known about the importance of large wood for overall soil resilience, or what levels and

Box 5.1-5

Dynamic Soils, Dynamic Data?

Soil survey data is a tremendous asset to land managers. However, soil resource inventories provide only a single snapshot in the life of a soil. Soils change over time, and long-term monitoring can inform adaptive management strategies to achieve sustainable, resilient forests. To this end, the Forest Service's Forest Inventory and Analysis (FIA) and Forest Health Monitoring programs have incorporated soil measurements into their national assessment scheme. On a very coarse spatial scale (1 soil plot per 38 450 ha [95,012 ac]), soil data are collected to monitor erosion, surface disturbance, and chemical and physical properties (O'Neill et al. 2005). Plots are to be remeasured every 5 years to capture changes in soil characteristics and condition. Over time, this ambitious undertaking will provide a wealth of data to conduct trend assessments and provide broad insights for management strategies and on long-term climatic influences. Already, the data have allowed a national assessment of forest floor C stocks (Woodall et al. 2012). One legitimate criticism of the FIA protocol is its focus on the upper soil, which neglects material greater than 20 cm deep (Harrison et al. 2011).

types of woody material are desirable for Sierra Nevada ecosystems. Woody debris acts as a barrier against soil erosion, provides water to plants and microbes during summer drought, and contributes to nutrient cycling processes. However, actual ground cover of down wood is typically so low that the importance of these services may either be viewed as trivial or as highly valuable owing to their relatively rare occurrence. Evaluations of the contribution of woody debris to soil ecosystems in the Sierra Nevada is needed to help establish desirable woody debris conditions, including size, quantity, and decay class distributions.

Soil biotas are essential to many basic soil processes, but our understanding of soil biodiversity—both composition and function—is limited. However, healthy soils are an important component of forest health, and further research in this area would complement management efforts in the synthesis region.

Management Implications

Preventing soil loss—

- Maintaining soil in place is paramount to current and future soil quality, resilience, and health. Recovery of severe erosion is beyond human time scales.
- With proper design and BMPs, mechanical treatments and prescribed fires can be implemented with low risk of soil erosion.
- Severe wildfire, particularly at large scales, poses a high risk of postfire soil loss through erosion.

Minimizing physical disturbance—

- Bare soil exposure can be minimal following mechanical treatments, but compacted skid trails can contribute to decreased soil function and to downstream sedimentation.
- Compaction may have beneficial soil impacts in sandy soils. In other cases, operational restrictions, such as soil moisture guidelines or equipment specifications, can be tailored to the specific soil type to limit compaction.
- Prescribed fire can greatly reduce the mass and depth of the forest floor. Needlecast from scorched trees can quickly replace lost soil cover.
- Combined thinning and prescribed fire treatments typically expose more bare soil than either practice alone.
- In most cases, the size and density of burn piles can be based on operational factors rather than potential soil heating effects.
- Severe wildfire can remove the forest floor and woody debris, expose bare soil, and alter soil structure and bulk density.

Evaluating changes in nutrient capital and turnover—

- Whole-tree harvest techniques transport more nutrients off site than bole-only methods, but many Sierra Nevada sites have large soil N reservoirs and are fairly resistant to N loss regardless of thinning method.
- Prescribed fire removes C and N by combusting the forest floor, but C and N pools in the mineral soil typically remain unchanged.
- Nutrient cycling models show that frequent, low-severity fire will cause greater overall nutrient loss than infrequent, high-severity fire where fuels have accumulated over many decades. At face value, reduced nutrient loss seems beneficial to soils, but extensive high-severity fire in fact poses far greater risks to long-term soil quality and resilience.
- Design repeat burns to produce patchy fuel consumption to temper nutrient losses from frequent fires.

- Simple balance sheets are useful to gain perspective on nutrient losses relative to existing pools and inputs or outputs over time.

Recognizing effects on organic matter and soil biota—

- Because of fire suppression, accumulations of litter and duff in many Sierra Nevada forests that evolved with frequent fires may exceed levels that occurred historically.
- Biologically healthy soil is critical to sustaining resilient forests, but predicting and quantifying management effects on soil organisms is generally beyond the reach of forest managers.
- Severe wildfires consume soil organic matter. This loss can affect soil bulk density, structure, water-holding capacity, and nutrient content, ultimately contributing to declines in soil resilience.

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