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Effects of Silvicultural Practices and Wildfire on Productivity of Forest Soils

ABSTRACT

This chapter reviews the research literature on the effects of timber harvest, site preparation, and cultural treatments on Sierra Nevada forest soils. It is not an assessment of Sierra Nevada soils.

Silvicultural activities alter soil productivity as they alter soil volume, soil porosity, and soil organic matter. Because most of the nutrient capital in Sierra Nevada forest ecosystems is contained in the upper soil layers and in the forest floor, and not in the standing biomass, activities that displace or compact the surface soil have the greatest potential to alter site productivity. The potential for altering the surface soil is greatest during site preparation, and somewhat lower during timber harvest. Intermediate silvicultural treatments generally have low impacts on soil productivity. Wildfire has a much greater impact on soil productivity than prescribed fire, especially during postwildfire salvage and recovery operations. Although there is anecdotal evidence of locally severe losses in soil productivity, the extent of degraded soils in the Sierra Nevada is unknown.

INTRODUCTION

Soil—along with air, water, and sunlight—is a basic building block of ecosystems. Like air, water, and sunlight, soil is so common that it is nearly invisible. Unlike air, water, and sunlight, however, soil is a nonrenewable resource because it accrues so slowly. Soil provides vegetative growth and clean water and buffers the effects of major disturbances. Not including microorganisms, more than 75% of the species in forest ecosystems reside in the soil. Directly or indirectly, all terrestrial forest species, and many aquatic species as well, are dependent on the soil. The health and productivity of Sierra Nevada ecosystems are strongly affected by the potential and condition of their forest soils.

Forest soil processes are commonly misunderstood, even by practicing resource professionals. Many people think that extraction of valuable resources such as timber carries the cost of some soil degradation, without fully understanding the long-term consequences of this degradation or its real costs. Others have the misconception that removal of any biomass from the forest will decrease productivity.

Silvicultural activities and wildfire have the potential to alter significantly the long-term productivity of forest soils. This chapter addresses the effects of timber harvest, silvicultural treatments, and wildfire on forest soils in the Sierra Nevada.

INDICATORS OF SOIL PRODUCTIVITY

Soil Productivity

The productivity of forest soils is difficult to assess directly. Commercial wood growth, net primary productivity (NPP), and soil properties are all indicators of soil productivity. Commercial wood growth is affected by stocking, stand age, genetics, weed competition, and plant pests, and the rate of wood growth changes over time (Powers 1991). Also, the full potential of a site is rarely reached, and yield tables tend to underestimate potential site quality (Powers 1991). NPP, or biomass production, may be a better reflection of inherent productivity, but it is not easily estimated. NPP is usually re-

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ported as above-ground biomass. However, bolewood ranks relatively low in allocation of fixed carbon compared to leaves, roots, and reproductive parts, and as much as 75% of NPP may be allocated below ground (Powers 1990b). Also, NPP can change as stands age. Using soil properties to assess site productivity is not without its problems, either. Soil variables are surrogates for productivity, but they have not been fully calibrated against stand productive potential, much less against NPP (Powers et al. 1990a). Yet changes in soil properties and measurements of tree growth are the only tools currently available, although more rigorous efforts are under way (Powers et al. 1990a). Although imperfect, commercial wood growth remains the best-documented index of productivity and is a useful index of ecosystem health (Powers et al. 1990b). The studies cited in this chapter express changes in soil productivity in terms of tree growth.

The productivity of forest soils is a function of both soil potential and soil condition. Soil potential is defined by physical, chemical, and biological properties such as depth, amount of rock, organic matter content, texture, porosity, clay mineralogy, and temperature and moisture regime. Properties such as texture, clay mineralogy, and temperature and moisture regime are not readily altered. Soil condition is defined by readily altered surface properties such as thickness of surface soils (soil volume), porosity, and soil organic matter. These three properties are also integrators of many soil processes. In this chapter, the effects of silvicultural activities and wildfire on soil productivity will be examined by evaluating how they affect these three indicators of soil condition.

Soil Volume

Soil volume, or soil depth, controls rootable volume, plant-available water, and total nutrient storage, as well as hydrologic function and buffering capacity. A loss of soil depth is nonrenewable because soils form so slowly. Soil volume can be reduced by surface erosion, displacement, and mass wasting.

Soil Porosity

Forest productivity is highly correlated with soil porosity. Rootable soil volume, water infiltration and retention, gas exchange, and biological activity all depend on soil porosity. Forest species are dependent on aerobic mycorrhizal associations. The very high porosity—especially macroporosity—typical of healthy forest soils is the result of biological activity. Coarse, relatively indigestible needles and twigs deposited on the forest floor depend on a succession of macroinvertebrates to break them down to sizes microorganisms can decompose. The large pores created in this process are fragile and readily compressed by heavy equipment.

Organic Matter

The organic matter of forest soils can be grouped into three types: (1) soil organic matter, (2) the forest floor, sometimes referred to as duff and litter, and (3) large woody material, or decaying logs.

Soil Organic Matter

Although it makes up only 5% to 10% of the soil volume, soil organic matter profoundly affects soil properties. Soil organic matter is a storehouse of plant nutrients and is the primary source of plant-available nitrogen, phosphorus, and sulfur. Soil organic matter provides habitat for the diverse soil biota that carries out energy transformations and cycles nutrients and that is responsible for the strong granular structure and high porosity of healthy forest soils. Soil organic matter increases water-holding capacity and infiltration and, by promoting soil structure, protects the soil from erosion. Soil organic matter is composed of two fractions: (1) an active, rapidly recycled labile fraction consisting of plant roots, soil organisms and their feces, and recently dead plant and animal materials; and (2) a recalcitrant humus fraction consisting of the end products of decay, humic acids. Recalcitrant organic matter, the dominant form, may take hundreds to thousands of years to recycle.

The Forest Floor

Litter fall from conifers is highly resistant to decay by soil microbes and thus accumulates under closed forest canopies. Accumulated duff and litter modulate extremes of temperature and moisture, providing an environment favorable for the macroinvertebrates that recycle litter fall. The forest floor is the source of soluble organic ligands that chelate, dissolve, and leach aluminum and iron from mineral soil, thus providing a buffer against metal toxicity, particularly in sites subject to acid deposition (Powers et al. 1990a). The forest floor protects soils from erosion and enhances infiltration and hydrologic function.

Large Woody Material

Large woody material decomposes slowly (Harmon et al. 1986). As it decays, such material provides structural habitat for organisms that fix N nonsymbiotically and acts as refugia for many organisms, particularly the mycorrhizal fungi so critical to the health of forest species. Large woody material provides habitat for small mammals that inoculate openings with the spores of hypogeous fungi (Maser and Trappe 1984).

Much of the research on large woody material and soil wood has been conducted in the Pacific Northwest and Intermountain regions. In the Pacific Northwest decaying logs can persist for two hundred years or more (Sollins et al. 1987). But Harmon and colleagues (1987) found it took only sixty years for large logs to decay in the southern Sierra Nevada. The rate of decay also varies by species. Because sapwood decays rapidly and heartwood decays more slowly, trees with a high heartwood to sapwood ratio persist the longest. These results point out the hazards of extrapolating research information from one ecosystem type to another.

Interactions

Soil porosity, organic matter, and surface soil volume are highly interdependent. For example, soil organic matter and the forest floor foster the biological activity that produces soil structure, increasing porosity. Porosity enhances gas exchange and creates an aerobic environment favorable to soil organisms. Strong structural aggregates increase resistance to erosion and loss of soil volume. Loss of porosity reduces infiltration, increasing erosion and loss of volume. Loss of organic matter reduces soil structure, increasing soil erosion. These effects may be synergistic, not merely additive, and have yet to be quantified.

SOIL PROCESSES

Soil Erosion, Displacement, and Mass Wasting

Soil productivity is reduced by soil loss from erosion, displacement, and mass wasting. Water quality can also be affected by soil erosion and sedimentation from silvicultural activities. It is important not to confuse soil productivity and water quality. For example, displacing topsoil can severely reduce productivity, but if the displaced soil does not reach a watercourse, it has little effect on water quality. In contrast, erosion on roads and skid roads can deliver sediment directly to streams, but this erosion has a minor effect on overall site productivity. The following discussion is on the effects of erosion, displacement, and mass wasting on long-term productivity, not on the impacts of soil erosion on water quality.

Surface Erosion

The effects of erosion on site productivity are difficult to assess. The magnitudes of inputs, outputs, and components are not generally known, and rates of soil formation are not measured directly but are estimated by differences in mass-balance equations (McColl and Powers 1984). It is difficult to measure precisely amounts of soil loss significant to long-term productivity. This is partly because soil loss may not be reflected in sediment measured at the watershed mouth due to considerable on-slope and in-channel storage (Clayton and Kennedy 1985; McColl and Powers 1984), and partly because most erosion occurs during large, episodic events. Where a forest floor has developed under a forest canopy, erosion rates are near zero (McColl and Powers 1984), but rates can increase to ten or more times soil formation rates for short periods following disturbance (Clayton and Kennedy 1985).

Soil productivity will decline if soil is removed at a rate faster than it is replenished, even though reductions may not be measurable over short periods (Alexander 1988). This loss can result from surface erosion, soil displacement, or mass wasting.

Using an elemental balance equation and data from eighteen watersheds with noncarbonate lithology, Alexander (1988) estimated that soils form at a rate of about 0.02 to 1.9 t/ha per year. He suggested loss tolerance limits should be lower than 2.24 t/ha per year (1 ton/acre per year) for shallow and moderately deep soils on plutonic rocks. One ton per acre is equivalent to the thickness of two sheets of paper.

Surface erosion can be caused by overland flow, or it can occur as sheet erosion, rill and gully erosion, or dry ravel. Sheet erosion is the nearly imperceptible loss of soil through the action of falling raindrops. Sheet erosion is greatest on steep slopes because the splash of each raindrop has a greater probability of moving downslope. Overland flow rarely occurs on undisturbed forest soils with surface litter because infiltration is high. Rill and gully erosion results when runoff is concentrated by an impervious surface such as a road, skid trail, landing, or area of rock outcrop or shallow soils. Dry ravel is downslope movement by gravity alone. Dry ravel occurs on very steep slopes, particularly on sandy soils or after intense wildfire. Rill and gully erosion is the most common type of surface erosion on forest soils (Rice 1979).

In the Sierra Nevada, soils developed from granitic bedrock are the most susceptible to rill and gully erosion and to dry ravel; soils developed from metasedimentary bedrock are the most stable. Mature soils with high contents of iron oxides appear to be more resistant to erosion, perhaps because they tend to form stable soil aggregates.

The most effective cover type is a forest canopy with a well-developed forest floor. This cover type not only reduces sheet erosion, but also improves hydrologic function by improving lateral infiltration and movement of water in near-surface soil layers.

The amount of surface erosion approaches zero in undisturbed forests. McColl and Powers (1984) report losses of nitrogen and calcium by erosion in undisturbed forests to be about 100 g/ha per year (.09 lb/acre per year), and about 25 g/ha per year (.02 lb/acre per year) for magnesium and potassium. These losses by surface erosion are significantly less than losses by deep leaching.

Even with extreme disturbance, the loss from surface erosion does not appear large compared to that from mass wasting. In a study of 80% gradient slopes bare of vegetation following slash burning in western Oregon and Washington, Fredriksen and colleagues (1975) report an annual surface erosion rate of 3.6 m^3/ha (1.9 yd^3/acre), and a rate of 21 m^3/ha (11.1 yd^3/acre) from mass wasting. On a helicopter-logged and broadcast-burned clear-cut in the Idaho Batholith, Clayton and Kennedy (1985) reported erosion rates of 1.8, 13, 4, and 4 t/ha per year (0.8, 5.8, 1.8, and 1.8 tons/acre per year) for the first winter, first summer, second winter, and second summer after treatment, respectively. Even at their maximum, these rates are only six times the maximum soil loss tolerance limit suggested by Alexander (1988), and in the second year they were only two times the tolerance limit and decreasing rapidly.

Frequency of disturbance is a major factor in determining how surface erosion affects forest soil productivity. After a major disturbance, erosion rates exceed the rate of soil formation for only a few years, until a new forest floor accumulates and provides effective cover, assuming that reforestation is swift and successful. If the disturbance is not unusually severe, disturbance intervals of eighty to one hundred years—a normal rotation—should not lead to a decline in productivity. In the final analysis, there are many unknowns, and surface erosion effects on long-term productivity can only be inferred (Powers 1991). However, because the loss of surface soil is irreversible, even very small losses should not be taken lightly. Over many rotations even small losses could result in a significant decline in productivity.

Soil Displacement

The biggest threat to soil productivity is direct mechanical displacement of the surface soil. Practices that manipulate the top layer of the soil, and particularly those that remove it, degrade productivity by any standard (Atzet et al. 1989) and inevitably lead to a decline in site quality (Powers and Edmonds 1992).

In the 1950s and 1960s, topsoil was intentionally stripped during site preparation and pushed into windrows to reduce competition by removing sprouting species and dormant weed seeds in the surface soil and litter (McColl and Powers 1984). This is no longer done. The justification for this practice was the overwhelming research results that show early growth and survival of trees is greatest where mineral soils are most disturbed and the most biomass is removed (Morris and Miller 1994). This short-term growth response is due to increased N availability and reduced competition.

Soil may also be displaced unintentionally when slash is machine-piled for burning. More soil is displaced when machines grub out shrubs at the same time. Extensive and relatively “clean” machine piling tends to concentrate nutrients (McNabb and Cromack 1990) and may disrupt the natural decay cycles of large, rotting logs.

Another form of displacement is dusting. When very dry, fine-textured soils—especially soils high in volcanic ash—are subjected to heavy traffic, airborne soil drifts short distances, which can lead to entrenchment of skid roads.

Mechanized removal of slash into piles or windrows has a very high potential to reduce productivity because it can displace large quantities of organic matter, soil, and associated nutrients on much of the site (Morris and Miller 1994; Powers 1991). Productivity is reduced because soil organic matter and readily available nutrients are usually concentrated near the soil surface and decline rapidly with depth (Powers 1990a). In a windrowed slash pine site Morris and colleagues (1983) reported the P, K, Ca, and Mg in windrows represented displacements of between 15% to 40% of the total organic plus soil-extractable nutrient reserves of the ecosystem.

Growth reductions associated with nutrient loss by displacement do not become apparent until after crown closure (Morris and Miller 1994). But when they do finally appear, the growth reductions can be enormous. After only one treatment, the following losses have been reported: a 20% decrease in site index with 25% removal of surface soil (Kittredge 1952); a 30% loss in volume with displacement of about 2 cm (0.8 in) of topsoil (Dyck and Beets 1987); trees within 3 m (10 ft) of windrows produced two times the volume of those farther from windrows (Atzet et al. 1989); and scalped plantations produced three times as much volume after N fertilization as unscalped ones (Powers et al. 1988).

Compared to nutrient export from timber harvest, the N displaced in windrows can be six times that removed by harvest (Morris et al. 1983), and N and P losses can be two to three times those of whole-tree harvesting (Powers et al. 1990b). Nutrients besides N are also affected. Morris and colleagues (1983) report that windrow displacements of P, K, Ca, and Mg can represent displacements of 15%–40% of the total organic plus soil-extractable reserves of the ecosystem.

Forest soils in fir ecosystems are disproportionately vulnerable to productivity loss by displacement, because a much higher proportion of nutrients is in the forest floor (Powers and Edmonds 1992), and nutrients in the underlying mineral soil are typically concentrated in the upper 5–10 cm (2–4 in).

Although productivity losses by displacement can be very high, over many rotations this soil loss may be less serious than the smaller amounts of soil lost by erosion, because displaced soil, if it has not left the site, can be respread. However, respreading soil displaced by dusting may not be an option because the displaced soil is not concentrated.

Mass Wasting

Mass wasting can result from roads, increased pore water pressure, and loss of root strength by decay. Because landslides expose less-fertile subsoils, productivity can be reduced. Miles and colleagues (1984) found that Douglas fir regenerating on landslides in western Oregon averaged 25% less stocking and 62% less height growth than on nearby clearcuts.

Landslides are much more common on steep slopes. Atzet and colleagues (1989) report that landslides on the Siskiyou National Forest are twenty times more likely on slopes steeper than 70% than on slopes with 50% to 70% gradients, and two hundred times more likely than on slopes less than 50% in gradient.

Although mass wasting associated with silvicultural activities occurs locally in the Sierra Nevada, it is not as widespread as in northwestern California or the Pacific Northwest. Where it does occur, mass wasting is usually associated with roads or with geologic contact zones such as the base of the Mehrten formation. Evidence of past shallow debris flows is also common on the steep slopes of canyon inner gorges. The relative lack of widespread mass wasting in the Sierra Nevada may be because the steeper slopes have not been heavily impacted by road building and timber-harvest activities. Rice (1979) reports that about 70% of the forested land in the Sierra Nevada is on slopes with gradients lower than 32%.

Mass wasting has not had a major impact on soil productivity in the Sierra Nevada, but shallow debris flows and other forms of mass wasting could become more common if activity on steeper slopes increases.

Management Strategies to Minimize Soil Loss

Sheet erosion can be effectively mitigated by maintaining effective ground cover. Soil displacement and loss of ground cover can be eliminated by selectively manipulating slash and fuels with special equipment such as small excavators. The careful use of dozers with brush rakes is also effective. Displacement of topsoil into windrows is no longer considered necessary to reforest burns or clear-cut areas. Leaving residual trees or patches of trees can reduce insolation and slow the rate of decomposition of forest litter to protect the site until a needle cast creates a new forest floor. Cool prescribed burns that do not entirely consume the forest duff can reduce fuels and prepare sites for planting without totally removing effective ground cover. Carefully placing and designing roads and maintaining some live trees on unstable sites can reduce the risk of mass wasting. Silvicultural systems that cause minimal disturbance to the forest floor and do not entirely remove the forest canopy will cause little loss of soil to erosion, displacement, or mass wasting.

Soil Compaction

Compaction, Porosity, Density, and Strength

When a force or load is applied, soil will compact until it has enough strength to bear that load or force. As soil compacts, porosity decreases and density increases. Therefore, compaction can be thought of as a decrease in porosity with an increase in density and strength, the result of reduced pore space as air is expelled (Alexander and Poff 1985). Porosity is expressed as a percentage of volume; density as weight per unit volume; and strength as resistance to deformation, usually in kPa of pressure (Alexander and Poff 1985). Soil strength is highly dependent on moisture content.

The natural variability in density of forest soils is quite high (Alexander and Poff 1985). Such variability is not surprising, considering the effects large trees have on the soil in redistributing organic matter and nutrients (Zinke 1962) and the soil mixing that results from windthrows.

Effects on Plant Growth

The penetrating abilities of roots are reduced by poor aeration; oxygen deficiency and excess carbon dioxide both reduce root penetration (Alexander and Poff 1985). Roots do not enter rigid pores smaller than their diameters but, because of their axial pressure, can create their own pores in friable surface soils with low density. Roots are dependent upon extension in dense subsoils. When soil porosity is lost because of compaction, less soil volume is available for roots to occupy, and plant nutrients are relatively immobile. Under such conditions, even water cannot migrate through the soil rapidly enough to supply plant transpiration needs when plants are under extreme moisture stress. Less rootable volume thus equates to less plant growth. This problem is further compounded in forest ecosystems where conifer growth is dependent on mycorrhizal fungi, which are highly aerobic (Harmon et al. 1986). The effects of compaction on tree growth are well documented. Wert and Thomas (1981) found that trees in skid roads produced 74% less bolewood than trees in an adjacent undisturbed area. Because skid roads occupied only part of the area, stand growth was reduced by only 11.8%. On the Foresthill divide, Helms and Hipkin (1986) reported a volume reduction of 59% on soils with the highest amounts of compaction; the volume of an average tree was 21% less on the most compacted soils compared to the least compacted. The decrease in height growth of trees is nearly a linear function of the increase in soil density (Froehlich and McNabb 1984).

Soils are most compactible when moist but not saturated (Baver 1930). Water reduces frictional forces between particles, decreasing the resistance of soil to deformation (Alexander and Poff 1985). Compaction causes a greater reduction in macropores in moist soils than in drier soils (Hatchell et al. 1970). However, when soils are saturated and pores filled with water, which is relatively incompressible, a process called puddling occurs. Puddling destroys soil structure and reduces macroporosity (Alexander and Poff 1985) and can cause a greater loss of porosity and infiltration than compaction, without an increase in density (Hatchell et al. 1970). Soil compaction penetrates deeper under wet conditions than under dry conditions (Froehlich 1974). Because forest vegetation transpires moisture, thereby drying the soil, timing of vegetation removal can be used to manage soil compaction (McNabb 1981).

Soil organic matter has a strong effect on compaction. Free and colleagues (1947) found that soils with the most organic matter were compacted less by a given compactive effort at a given soil moisture content than were soils with the least organic matter. In their study of California forest soils, Howard and colleagues (1981) found a high content of organic matter reduced the effects of soil compaction. Organic matter increases resistance to compaction partly because it increases soil structure (Boyer 1979). Organic matter may also increase resiliency or rebound after cessation of stresses, even though organic matter per se is not considered to be an elastic material (Stone and Larson 1980).

When bare soil is exposed in logging, some soil disturbance and some compaction occurs, but organic litter cushions these effects (Alexander and Poff 1985). Froehlich (1978) found that both the degree and the depth of compaction were reduced by the presence of a litter layer; densities increased with successive trips and as the litter was removed. At the Blodgett Experimental Forest, Miles (1978) attributed the relatively small amounts of compaction on minor skid roads to the presence of 6 to 8 cm (2.4 to 3 in) of organic litter cover, which was no longer present after several trips on primary skid trails. Mace (1970) found that the amount of slash was important in reducing compaction, and Boyer (1979) suggests a surface layer 5 cm (2 in) or greater in thickness will provide protection from compaction at moisture contents approaching field capacity and may support up to two trips with equipment before compaction occurs. Avoiding or minimizing disturbance of the litter layer and surface soil high in organic matter is key to solving soil-compaction problems (McColl and Powers 1984).

Once soil is compacted, it takes decades for porosity to return to natural levels. The length of time to recover from compaction varies with soil type and the degree of compaction (McColl and Powers 1984). Effects of compaction have been reported to persist unchanged for sixteen, eighteen, thirty-two, and fifty years (Froehlich 1979; Hatchell et al. 1970; McColl and Powers 1984; Wert and Thomas 1981). It may take forty to fifty years or more for some soils to recover from compaction (Hatchell et al. 1970; Morris and Miller 1994). If compaction is deep, soils may never return to their original state without major physical disturbance (McColl and Powers 1984). Because the origin of porosity is essentially biological, it follows that recovery from compaction is also biological. Thus, both the depth of the compaction and the amount of organic matter in the compacted soil affect how long it takes to recover. Where compaction occurs in horizons high in organic matter, recovery will be more rapid than that in subsoils lower in organic matter.

Management Strategies to Minimize Compaction

Although the processes associated with soil compaction are complex, management strategies can be developed by thinking of compaction as the result of two opposing forces: a compacting force (or load) applied to the soil and the resistance of the soil (strength) to deformation by that force (Alexander and Poff 1985). Management strategies can then be expressed in terms of manipulating these opposing forces:

- Avoid compactive forces—for example, use aerial yarding systems such as helicopters, balloons, or cables, or yard material by end-lining.
- Reduce compactive forces—for example, use low ground-pressure equipment.
- Absorb compactive forces—for example, operate on a cushion of slash with cut-to-length forwarding equipment, or operate over snow.
- Operate when soil strength is high—for example, when soil moisture is low or when the soil is frozen.
- Confine compactive forces—for example, limit the area compacted by designating skid roads, and either restore porosity by tillage or accept compaction in the skid roads as a cost of resource extraction.

Distribution and Cycling of Mineral Nutrients

Forests are sinks for carbon and nitrogen, and vast amounts are stored above and below ground, especially in the soil. Although varying by biome, amounts of organic carbon in the forest floor plus soil exceed that of the standing forest (Powers and Van Cleve 1991). Globally, soil carbon equals that of vegetation and the atmosphere combined (Johnson 1994).

Tree Biomass Accumulation

A major portion of site productivity is directed below ground, and as much as 75% of net primary productivity can be below ground as fine roots and mycorrhizae (Grier et al. 1981). The proportion of primary productivity directed below ground is much higher in true fir than in mixed conifer forests (Powers and Edmonds 1992).

The rate of nutrient accumulation by forests also changes over time. Early in the life of a stand, crown and bole weights accumulate at similar rates, but after crown closure, crown weight remains constant while bole weight continues to accumulate. Therefore, because most nutrients are in foliage, early in the life of a stand crowns contain the most nutrients, but after crown closure, boles accumulate an increasing proportion of nutrients (Powers 1979). Most nutrients are taken up before crown closure. After crown closure trees internally translocate phloem-mobile nutrients from senescing parts to actively growing sites (Powers and Van Cleve 1991). As much as 30% to 50% of N and 20% to 80% of P may be translocated internally before leaf senescence (Prescott et al. 1989). As a stand reaches maturity, return of nutrients to the soil in litter fall approaches the rate of nutrient uptake (Powers 1979).

Litter Accumulation

In a young stand, the rate of litter accumulation on the forest floor is initially low because open crowns have light litter fall and allow high surface soil temperatures that encourage decomposition. With crown closure, the rate of litter fall increases, decomposition slows, and litter accumulates more rapidly. It may take one hundred years or more to reach an equilibrium between litter accumulation and litter decay (Powers 1979).

Nitrogen

Of all plant nutrients in forest ecosystems, N is often the most limiting—particularly in western forests (Powers and Edmonds 1992). Nitrogen is added to the ecosystem in rainfall, by symbiotic and nonsymbiotic N fixation, and in negligible amounts by rock weathering (Powers 1979). Most N accumulates in soil organic matter and in the forest floor in forms unavailable to plants. In their classic study of a thirty-six-year-old Douglas fir stand, Cole and colleagues (1968) found that 84.8% of total ecosystem N was in the soil, 5.3% in the forest floor, 0.2% in the understory, and 9.7% in the trees. In general, mature mixed conifer stands have about 10% of total ecosystem N in standing biomass, 10% in the forest floor, and 80% in the soil (Powers 1991). Of the standing biomass, at least half of the N is in foliage and branches. In true fir forests, a higher proportion of N is in the forest floor: standing biomass, 13%; forest floor, 40%; soil, 47% (Powers and Edmonds 1992). Although there are significant differences, the distribution of other nutrients generally follows a similar pattern.

Most soil N is unavailable to plants and must be mineralized by bacteria to ammonia or nitrate for plant uptake. Mineralization is regulated by moisture and temperature, with the highest rates occurring at middle elevations in the mixed conifer zone. Cold temperatures limit rates of mineralization at higher elevations; lack of summer moisture limits rates at lower elevations (Powers 1990b). In true fir forests, N is mineralized under cold, moist conditions by cold-loving microbes, although rates are very low, suggesting that increases in mineralization following timber harvest will be less in true fir forests than at lower elevations (Powers and Edmonds 1992).

Management Strategies to Minimize Nutrient Export

Nutrients are lost from forested sites by leaching, biomass removal, volatilization, and soil loss. Because the soil and forest floor hold the vast majority of nutrients on a forest site, they buffer the impacts of ecosystem disturbances such as fire, insects and disease, storm damage, and timber harvest (McColl and Powers 1984). Management practices that maintain the integrity and structure of surface organic matter will have the least impact. Useful strategies to minimize nutrient losses include harvesting boles only, using specialized equipment to selectively manipulate slash without disturbing the forest floor, and using cool prescribed burns that do not consume the lower half of the duff layer.

EFFECTS OF FIRE ON SOILS

Fire can have physical, chemical, or biological effects on soils. Physical effects include loss of soil organic matter, loss of soil structure, hydrophobicity, erosion, and, in extreme cases, destruction of soil clay minerals. Chemical effects include an increase in pH, a loss of cation exchange capacity, and the loss of nutrients by volatilization, in fly ash, or by leaching. Biological effects include direct mortality of soil organisms and loss of their habitat. Fire effects on soil productivity can be either beneficial or devastating, depending on fire intensity, soil type, and site history.

Adverse fire effects on soils increase as burn intensity increases, and the effects are proportional to the amount of surface duff and soil organic matter consumed (DeBano 1979). High amounts of moisture in the soil, particularly in the lower half of the duff layer, reduce organic matter consumption (Sandberg 1980). Maximum temperatures reached, even if only in pulses of short duration, govern the magnitude of effects (DeBano 1979).

Soil temperatures above 50°C are lethal for fungi, and nitrifying bacteria are killed at 100°C (Boyer and Dell 1980). Destructive distillation of organic compounds begins at about 200°C, and organic matter ignites at 260 to 425°C (DeBano 1979). Below 200°C organic matter is not destroyed, but it can be distilled and moved within the soil and affect wettability. Above 200°C, N and S are oxidized rapidly, and at 500°C most N has been volatilized (DeBano 1979). Temperatures of 760°C have been measured at the soil surface during fires in chaparral (DeBano 1979).

Fire may temporarily sterilize soils. Hot burns on moist soils may increase the mortality of soil organisms by driving steam into the soil. Changes in populations of soil organisms usually last only a year or two but vary with fire intensity. After a fire, invertebrates decline, fungi decrease, and bacteria increase. Where fires create very large openings, the loss of host plants for mycorrhizal fungi can lengthen the time it takes to reinoculate the site (Borchers and Perry 1990).

Soil organic matter has a high cation exchange capacity. When organic matter is burned, a flush of cations such as Ca, Mg, Na, and K is released and made more readily available to plants (DeBano 1979). Hotter burns may produce bicarbonate anions, further mobilizing cations in the soil solution (McColl and Powers 1984). Cations released in the ash bed are potentially susceptible to leaching, but revegetation and exchange sites in the soil usually absorb cations quickly, preventing this type of nutrient loss (McNabb and Cromack 1990). Leaching loss could be significant under very intense burns on coarse-textured soils low in organic matter.

Under intense burns, all surface litter may be removed, making soils highly susceptible to erosion. Debris movement and dry ravel may also increase when small organic-debris dams are burned out (DeBano 1979). The formation of hydrophobic layers may accelerate soil erosion. Temperature gradients near the soil surface can be very steep; for example, 760°C at the surface, but 200°C at 5 cm (2 in). Hydrophobic layers form when organic compounds volatilized in the surface litter are driven into the soil and condense on the underlying, cooler soil particles (DeBano 1979). Generally, hydrophobic layers occur deeper, and are more water repellent, in sandy soils because these soils have high macroporosity and low surface area. Strongly hydrophobic layers create an effectively very shallow soil, making the wettable surface soil very vulnerable to erosion. Hydrophobic layers may also form at the surface if soils are moist or clayey, or where fire intensity is low. Surface hydrophobicity protects the soil from erosion but can greatly increase channel scour by causing rapidly accelerated runoff. The formation of hydrophobic layers in forest soils of the Sierra Nevada is quite variable.

As burn intensity increases, increasing amounts of N, and, to a lesser extent, P and S, are volatilized and lost to the atmosphere. In large fires of high intensity, other nutrients may be lost in the smoke plume as convective fly ash (Clayton and Kennedy 1985).

The plant nutrient most affected by fire is nitrogen. Nitrogen loss is almost linearly related to litter consumption, and little N is lost until more than 25% of the litter has been consumed (Dunn and DeBano 1977). McColl and Powers (1984) summarized N losses for different burn intensities. Under severe burns, N losses ranged from 72% to 99%, but under moderate-intensity burns, losses ranged from 11% to 38%. Fire can also increase soil nitrogen. Heating and combustion increase ammonia (Dunn and DeBano 1977), making it readily available for plant uptake. Nitrification is also stimulated by reduction of repressive tannins and by increases in ammonium (Powers 1979).

Losses of sulfur and phosphorus are proportional to nitrogen losses, though smaller—only about 5% to 9% of nitrogen loss. Sulfur is important in decomposition of organic matter and in nitrogen metabolism. Sulfur is of concern because it is not fixed, but is added to the ecosystem abiotically through precipitation and mineral weathering. The origin of atmospheric S includes fossil-fuel consumption, acid deposition, and volcanic eruptions (McNabb and Cromack 1990). Sulfur losses have been detected indirectly in the Pacific Northwest, and as much as 50% of total S may be oxidized at 800°C (Boyer and Dell 1980). Sulfur deficiencies are readily overcome by small amounts of S in fertilizer.

Fire frequency, in the context of a site's natural fire regime, has a major impact on soil productivity (McNabb and Cromack 1990). Frequent, low-intensity fires, on sites where the vegetation has adapted to them, will increase soil productivity over the long term (Klemmendson et al. 1962). On the other hand, frequent high-intensity fires, except on sites adapted to such a fire regime, are likely to reduce nutrient reserves and to initiate long-term productivity decline. Intense fires that consume all the forest floor are particularly damaging to fir forests, where a high proportion of nutrients is contained in the forest floor (Powers and Edmonds 1992).

It is important to distinguish between prescribed fire and wildfire. Wildfires have a far greater potential to affect long-term soil productivity than does prescribed fire (McNabb and Cromack 1990). In contrast to prescribed fires, wildfires are more intense, consume more organic matter, burn longer, occur when soils are drier, and have higher levels of volatilization and convective losses. An intense wildfire may volatilize the equivalent of two hundred years of N input from precipitation (Powers 1979). Soils that are subjected to intense wildfire more frequently than every one hundred years may experience productivity decline (McNabb and Cromack 1990).

An indirect effect of wildfire is the sequence of activities associated with fire suppression, timber salvage, and reforestation that follows major wildfire. The effects of these activities are discussed later in this chapter.

Management strategies to reduce the negative impacts of prescribed fire on soils involve reducing fire intensity (DeBano 1979). They include burning under high humidity, low temperatures, and low wind speeds, and burning smaller areas. Reducing fuel loading before burning, burning when the soil and duff are moist, and burning downslope with a less intense backing fire can also reduce fire intensity.

EFFECTS OF SILVICULTURAL TREATMENTS

In the following discussion, the reader should keep two things in mind. First, silvicultural practices have changed dramatically during the past two or three decades. Site preparation methods of the 1950s, 1960s, and 1970s were especially damaging to soils. Many of the clear-cut and broadcast-burn practices of the 1970s and 1980s were also harsh. From the mid-1980s to the present silvicultural practices have shifted away from large clear-cuts and bare-ground site preparation, to smaller openings and more residual trees. Logging equipment available and wood products considered merchantable have also changed.

Second, because forests grow slowly, most of the citations in the following sections are for retrospective studies on treatments made from the 1950s to 1970s. In spite of these limitations, this research expanded our knowledge of forest soil processes and certainly provides us a historical perspective on the impacts of past treatments. Some effort is needed, however, to interpret these research findings for the issues facing the Sierra Nevada today.

Timber Harvest

Timber harvest can affect soil productivity through erosion, displacement, compaction, biomass export, and leaching. The effects vary with the type of harvest—for example, clear-cutting versus partial removal—and with the degree of disturbance. This section examines only the removal of timber. Site preparation is covered in the following section.

Erosion

The amount of soil erosion caused by timber harvest is directly related to the degree of soil disturbance, which in turn is related to logging method. Percentage of bare soil following logging can range from less than 2% for helicopter yarding to more than 75% for tractor logging (Rice 1979). In clear-cutting, about 6% to 19% of bare soil is exposed using aerial yarding systems, and 15% to 30% or more with ground-based systems. In uneven-aged systems disturbance is less at each entry, but frequency of entry may be higher than in even-aged systems. Although considerable erosion can occur on the skid roads of ground-based systems, surface erosion from just the yarding is typically quite low (McColl and Powers 1984), due in part to surface roughness and to the slash left on the site, which tends to trap sediment and prevent its movement off-site. Most of the erosion during timber harvest operations is related to roads (McColl and Powers 1984).

Compaction

Porosity may be reduced when timber is harvested with ground-based logging systems. The impact on productivity is directly related to the area in skid roads. Uncontrolled skidding in clear-cuts typically results in 20% to 40% of the area in skid trails. Skid-road area may be only 8% to 10% in selection-cutting, but this is per entry. With repeated entries, skid roads under selection-cutting can occupy more than 64% of the harvested area if skid-road locations are not controlled (Dyrness 1965).

Compaction in uneven-aged systems can be difficult to mitigate with tillage. Although specifically designed tillage implements such as the forest cultivator can be used, tillage may damage the roots of residual trees, increasing their susceptibility to disease.

These impacts on soil productivity are not a necessary cost of timber harvest. Modern harvesting equipment, such as cut-to-length processors and forwarders, does not compact soil, even when operating on moist soils. Compaction can also be reduced to acceptable levels using conventional ground-based equipment if designated skid trails and end-lining are used (Froehlich et al. 1981).

Forest Floor

Disturbance of duff and litter during timber harvest may slightly increase the rate of decomposition, but the changes in temperature and moisture resulting from increased insolation and lack of litter fall have the greatest effect on decomposition. In clear-cuts the forest floor disappears in less than a decade; significant losses can also occur under partial cutting (McColl and Powers 1984).

Biomass Export

The amount of nutrients exported through timber harvest depends on nutrient distribution in the ecosystem and utilization standards. About 20% of carbon and 10% of nitrogen are in bolewood in young, mature forests. Even in the most intensive harvests, less than 10% of ecosystem N would be removed (Powers and Edmonds 1992). Actual amounts exported would be considerably less under current practices, even for clear-cutting, because unmerchantable material, snags, and small patches of green trees are typically left. The general consensus is that stem-only harvests of mid-age stands have little impact on nutrient export. Atmospheric inputs of N, P, and probably S exceed harvest export, and soil reserves of K, Ca, and Mg are high, even without weathering inputs (Morris and Miller 1994). However, whole-tree harvesting, where slash and unmerchantable boles are also exported, could be of concern on less productive soils if rotation length is short (Johnson 1983; Zinke et al. 1982).

Nitrogen

Timber harvest can increase ammonification and nitrification by raising summer temperature, increasing moisture, and by adding labile organic matter to the soil (Frazer et al. 1990). On the Challenge Experimental Forest, N mineralization remained elevated for seventeen years after clear-cutting, but the additional N was incorporated into rapidly growing vegetation. Such increases should be considerably less under partial cutting, because forest litter has a strong repressive effect on nitrification (Frazer et al. 1990).

Leaching

During the 1960s there was concern about nutrient loss from leaching following clear-cutting, in part triggered by misinterpretation of the classic Hubbard Brook study (Likens et al. 1969). The current consensus is that, except in extreme cases where vegetation is absent or intentionally suppressed, nutrient losses by leaching are negligible (Johnson 1994; McColl and Powers 1984). In their study of nutrient leaching on a high-porosity, low cation exchange capacity soil, Cole and Gessel (1965) found that nearly all elements released from the forest floor were retained within the rooting zone or taken up by vegetation. Under uneven-aged management, the effects of residual vegetation could be expected to eliminate leaching losses entirely.

Rotation Length in Even-Aged Management

The effects of timber harvest on soil productivity are exaggerated by short rotations, or as frequency of disturbance is increased (Johnson and Todd 1987; Morris and Miller 1994; Powers 1991; Powers et al. 1990b; Switzer et al. 1981). Rate of nutrient uptake is greatest at about the point of crown closure, so short rotations place a greater drain on nutrients than do long rotations (Powers 1990a). Short rotations also forgo the nutrient accretion that occurs in mature stands (Sollins et al. 1980), because of more frequent periods with less crown protection. In general, with normal harvests, rotations greater than sixty to eighty years should not export nutrients faster than they accrue (Powers et al. 1990a). Longer rotations or lighter harvests may be necessary on low-quality sites to avoid productivity decline.

Site Preparation

The potential for impacts on long-term soil productivity is greatest during site preparation. At that time the forest floor and surface soil are most subject to manipulation and most vulnerable to damage (McColl and Powers 1984). The amount of soil and forest floor manipulated varies with type of harvest, clear-felling being the most severe. Partial cutting under uneven-aged systems generates less slash and requires less manipulation of the forest floor and topsoil.

Displacement

The effects of soil displacement on soil productivity are great and well documented. Most research on soil displacement has been conducted on clear-cuts and plantations created from the 1950s to 1970s. Although harsh site-preparation treatments, such as scalping and windrowing, are no longer done, the research on them provides valuable insights on soil processes and the importance of the forest floor and surface soil in soil productivity. The effects of soil displacement, discussed earlier in this chapter, will not be repeated here.

Compaction

Most of the research on soil compaction has been conducted on skid roads. However, the general principles governing soil compaction discussed earlier in this chapter apply to site preparation as well. Conditions during mechanical site preparation make soils highly vulnerable to soil compaction. Typically, soils are moist, bare soil is exposed, and multiple equipment passes are made. Also, a far greater proportion of the treated area can be affected by site preparation. Timing makes a big difference. For example, when mechanical site preparation follows winter logging, subsoils stay moist well into the summer because transpiring trees have not "pumped" moisture out. The compaction that occurs under these conditions is insidious because it goes unnoticed and because it does not readily recover without tillage.

The use of modern equipment drastically reduces, or avoids entirely, soil displacement and compaction during mechanical site preparation. Small excavators equipped with grapple heads, for example, are used to selectively pile logging slash without disturbing the forest floor, without compaction, and even without disturbing decaying logs. The resulting piles contain no soil and few nutrients, and burn clean. Even conventional equipment, used prudently and under the right conditions, can be used to pile slash with minimal soil impacts.

Prescribed Burning

Two general types of prescribed burning are used in site preparation: broadcast burning, and piling and burning. Piling and burning slash concentrates nutrients, and the high temperatures reached under burned piles damage soils. Piling and burning may also cause displacement and compaction as discussed earlier in this chapter.

Broadcast burning has many of the impacts described for fire (see "Effects of Fire on Soils," earlier in this chapter), but the effects are usually less extreme because ignition can be limited to periods when soil moisture is high enough to prevent complete consumption of the duff and litter. Heavy fuels are often removed before burning to reduce the intensity of broadcast burns. Common techniques are yarding unmerchantable material to landings, harvesting material as chips for "hogfuel," or various forms of partial "whole-tree" harvesting, such as yarding and chipping some crowns.

Given these complexities, not to mention weather conditions at the time of burning, it is not surprising there is little published literature on the effects of broadcast burning. Studies that have been done are of complex situations and are often confounded by other factors (Palazzi et al. 1992).

In general, the effects of broadcast burning are related to the condition of duff and litter prior to burning and to what remains afterward. Consumption of the forest floor is a function of its moisture content at the time of burning (Sandberg 1980). Forest floors less than 2 cm (0.8 in) thick generally do not hold enough moisture to withstand a broadcast burn (Boyer and Dell 1980).

The amount of N lost is proportional to duff consumption. Surface erosion is also related to duff consumption, and erosion of the ash bed and surface soil after broadcast burns may be the primary mechanism of nutrient loss (McNabb and Cromack 1990). Accelerated surface erosion is commonly observed after broadcast burns, but surface erosion is difficult to measure, and real data are rare. In the Idaho Batholith, rates of 1.8 to 13 t/ha (0.8 to 5.8 tons/acre) per year were measured the first two years after fire on a broadcast-burned clear-cut (Clayton and Kennedy 1985), about six times the estimated soil formation rate. On many national forests in California, broadcast burning is not allowed, or is severely limited, on soils derived from granitic bedrock because experience has shown that erosion rates are consistently high. The formation of hydrophobic layers under prescribed burning has not been reported and is probably rare.

The effects on soil productivity that have been reported are variable. One severely burned clear-cut had one-third less mineralizable soil N than adjacent unburned areas; but paired burned and unburned units on the Six Rivers National Forest showed no differences in most soil properties (Atzet et al. 1989). Most studies have not found consistent differences in growth between burned and unburned areas, but this result may be confounded because burning can reduce total nutrients while increasing nutrient availability (Morris and Miller 1994).

In summary, the effects of broadcast burning on soil productivity range from minimal, or even beneficial, to extremely severe depending on site conditions. As with timber harvest, the frequency and intensity of biomass removal are probably major factors in determining nutrient loss.

Intermediate Cultural Treatments

After site preparation and planting, a number of treatments can be applied to maintain stocking and growth, and to protect the stand from fire. These treatments have variable effects on soil volume, porosity, and organic matter and nutrient cycling.

Clipping and Hand Grubbing

Weed and brush control is important to stand survival. Treatments are usually applied during the first few years after planting. Clipping, sometimes combined with herbicide applied to sprout stumps, is beneficial to the soil because it increases effective ground cover, protecting the soil from erosion. Grubbing, essentially hoeing brush and weeds around tree seedlings, has variable impacts. The area grubbed is bare and susceptible to erosion. The actual area grubbed depends on stocking level and grubbing radius. For example, grubbing to a 0.8 m (4 ft) radius where stocking is 3 m by 3 m (10 ft by 10 ft), can result in 50% or more of the site in bare soil. On steep slopes, especially on a site that was burned hot, grubbing and the foot traffic associated with it can cause dry ravel and expose the soil to severe erosion, at least for a season or two. In general, treatments that leave the majority of slash in place have little effect on soil productivity (Morris and Miller 1994).

Herbicides

The types and amounts of herbicides normally used in forestry have negligible impacts on long-term soil productivity. Herbicides may be used to control weeds early in the life of a stand. Herbicides may alter biological populations in soil, but very little foliar-applied herbicide reaches the forest floor, and herbicide levels in soils seldom exceed toxic levels for long periods (McColl and Powers 1984). The impacts vary by type of herbicide. Ammonium sulphamate was found harmful to collembola, isopods, and millipedes, affecting the breakdown of litter; asulam reduced nitrate production, reducing N leaching (Norris 1983). Generally, the rate of degradation and mobility in the soil determine the relative hazard of herbicides in the environment (Norris 1983). Because most herbicides are strongly sorbed onto organic particles in the surface soil, the greatest risk of herbicide movement is by erosion. The overall health and condition of the soil—porosity, organic matter, surface duff and litter—control how well the soil will buffer the effects of herbicides.

Grazing

Grazing by cattle or sheep can be used to control brush and weeds early in the life of a stand. The effects are variable, depending on specific site conditions and on how the stock are herded and managed. On gentle slopes, impacts can be negligible. When forced onto steep slopes, grazing cattle can accelerate dry ravel and erosion.

Thinning

Generally the effects of thinning on the soil are minor. Soil compaction in thinning operations is generally insignificant but depends on the type of equipment used. Slash and the forest floor cushion the impact of ground-based equipment, and actively growing trees transpire moisture, creating periods when the soil is dry. Smaller equipment, or equipment with low ground pressures, is often used. Mastication of brush to release young stands, however, has a greater potential for compaction because less duff and litter have accumulated. Equipment used in mastication is highly variable.

Opening the forest canopy can raise soil temperatures, increase biological activity, and accelerate decomposition of the forest floor. Mobile nutrients including N and K contained in foliage and bark can be concentrated in through fall and stem flow, as compared to precipitation in the open, and opening a stand can double the rate of mobile elements leached from the forest floor (McColl and Powers 1984). These nutrients, however, are rapidly absorbed by vegetation or the soil. The foliage added to the forest floor is richer in nutrients than normal needle cast, increasing the substrate needed for ammonification, which may lead to temporary nitrifier activity (McColl and Powers 1984).

If biomass is removed in thinning, the effect will depend on what is removed. If 5% of ecosystem N is bolewood and half the trees are thinned and the boles exported, a maximum of 2.5% of the N would be removed. Because the thinned trees are generally smaller in diameter, the actual removal would be somewhat less. If boles and crowns are removed, however, the impact could be somewhat greater because nutrients are concentrated in actively growing crowns. This loss of nutrients could be of concern on heavily impacted sites, for example, intense wildfires followed by heavy site preparation, such as scalping.

Fertilization

Fertilization with N can restore productivity. In general, soils most responsive to fertilization have more than 10 cm (4 in) of available water-holding capacity and a site index of less than 30 m (95 ft) in fifty years (Miles and Powers 1988). Resources other than N limit growth on sites with lower available water capacity. Nitrogen is not limiting on the more productive sites. The effect of fertilization in increasing stand growth lasts about a decade. Nitrogen fertilization is most effective when combined with other silvicultural treatments such as thinning, and is most effective on stands near crown closure (Powers et al. 1988). Once trees have reached crown closure, N is recycled internally in the crowns and no further nitrogen is necessary. No operational fertilization is being done in the Sierra Nevada.

Fire Protection

Underburning

Prescribed burns are carried out under defined conditions, with high soil and duff moisture. They are much less intense than wildfires, and their effects are quite different. Underburns are also typically less intense than broadcast burns and tend to be more patchy. Because fire intensity is low, nutrient losses to the atmosphere through fly ash are negligible. The pruning and scorching of lower crowns add a needle cast to the forest floor, compensating for the lost duff and providing protection from erosion.

Underburns essentially oxidize the forest floor more rapidly than biological processes, removing organic matter and releasing the more rapidly recycled nutrients (McColl and Powers 1984). Plant growth is stimulated by the nutrients released into the ash layer in forms readily available to plants. Small but measurable gains in soil N occur after light underburns (Klemmendson et al. 1962). Nitrification is stimulated by underburning, possibly by elevated levels of ammonium and the reduced amount of repressive tannins in the duff and litter (Powers 1979).

Manipulation of Fuels

Fuels may be manipulated mechanically to reduce the risk of fire. The effects on soil productivity will depend on site history, the type of equipment used, and whether material is left on-site or exported.

Loss of porosity by soil compaction depends on the type of equipment used, the amount of area affected, and the thickness of slash and litter. Equipment operations could break up decaying logs, interrupting the decay process and forgoing the benefits from it.

If fuels are manipulated and left on-site, as chips for example, the result could be decreased soil temperatures, suppressed nitrification, and increased soil moisture. Bolewood contains phenols that can suppress the activity of microorganisms. Chipped material that is returned to the forest floor is unlikely to alter the C:N ratio of soils unless it is finely divided and well mixed into the soil (McColl and Powers 1984).

If fuels are removed from the site, the result could be increased soil temperatures and, with disturbance, a more rapid oxidation of the forest floor. Export of biomass and nutrients will depend on what material and how much of it is removed: if primarily poles and saplings, the amount will be low, because smaller-diameter materials contain less biomass and nutrients (Zinke et al. 1982).

Fuel Breaks

Shaded fuel breaks can be maintained by underburning or by cultivation. Those maintained by underburning have the same effects as described earlier. Fuel breaks maintained by cultivation have a higher risk of erosion, although generally only from summer precipitation. Cultivation increases oxidation of organic matter, and the benefits of a forest floor are forgone. Compaction may occur, although it is mitigated by cultivation. Considering the small land area involved and the benefits in preventing or controlling a major fire, this dedicated land use benefits soil productivity.

Soil Restoration

Tillage

Implements specially designed for forest soils can be used to recover porosity lost to compaction. Where used correctly and under the right conditions, tillage of compacted forest soils can be quite effective. Tillage breaks compacted soils into smaller aggregates, increasing porosity and surface area, allowing water to penetrate and biological activity to resume, and renewing the natural biological processes that are the source of forest soil porosity.

Tillage must be done with care in residual stands. Where root pathogens are present, damage to the roots of trees in stands can lead to root diseases such as black stain or annosus (Kliejunas 1995). Mechanisms of infection differ, so the type of tillage implement used is important.

Respreading Topsoil

Where surface soils have been scalped and piled into windrows, practices common in the 1950s and 1960s but no longer done, lost productivity can be recaptured by respreading the topsoil. Five-year productivity gains of 37% have been reported from respreading topsoil (R. F. Powers, U.S. Forest Service, letter to the author, June 16, 1995).

Forest Roads

Although forest roads are essential for forest management, they also have both direct and indirect effects on soil productivity. The direct effect is removal of land area from the growing base. Indirect effects include landslides, gullies, and side-cast material. Roads can also disrupt the subsurface flow of water, drying out sites downslope or ponding water upslope, thus changing soil moisture regime and productivity. Roads can be restored only with difficulty and at great expense, but restoration efforts have been successful in Redwood National Park (Steensen and Spreiter 1992).

POSTWILDFIRE SALVAGE AND REFORESTATION

Loss of protective ground cover and deterioration in soil structure following wildfire increase the risk of soil loss through erosion. The use of prescribed fire to reduce fuel loading after salvage logging operations carries a high risk of increased erosion through deterioration of soil structure and further reductions in cover.

Periods following wildfire are especially critical for soil compaction. Intense wildfires can remove all surface duff and litter and may even consume surface-soil organic matter. Because trees that would normally transpire moisture are dead or removed, soil moisture levels remain critically high for several seasons following the fire. Soil moisture often is high in the subsoil, creating a situation ideal for compaction during salvage logging and subsequent site preparation activities.

Where biomass in the forest floor, crowns, and fine fuels has already been consumed by wildfire, the amount of biomass and nutrients removed in postfire salvage operations can be relatively low. The value of leaving large amounts of severely charred large woody material is questionable. It may provide some wildlife habitat, but such material adds little to soil productivity. Charring disrupts the normal decay processes of large woody material, which adds nitrogen by nonsymbiotic fixation. Burned logs potentially can trap sediment, but unless they have good soil contact and are aligned on the contour, they may actually accelerate gully erosion.

Salvage logging can generate slash, adding ground cover to reduce erosion. In some cases, salvage operations can be used to break up hydrophobic soil layers near the surface, further reducing erosion (Poff 1988). However, this benefit may be offset by other soil disturbance associated with salvage logging. Depending on the site history, soil disturbance during salvage logging may stimulate brush species by bringing viable seeds to the surface, which can have either desirable or undesirable consequences for soil productivity.

Large openings created by wildfires may create opportunities for soil restoration. Topsoil piled into windrows can be respread, and tillage can be used to restore porosity.

There is a common misperception that allowing natural succession to reforest areas following major wildfire builds soil. This idea assumes that the intense wildfires the Sierra Nevada has experienced recently are natural phenomena, and not the result of fuel buildup as a consequence of fire protection and fire exclusion. It also assumes that the soils on these burns contain sproutable roots or a seed bank of desirable species that will revegetate the site.

Ceanothus species and western mountain mahogany have root nodules with nitrogen-fixing capability (Biswell 1974). However, not all shrubs fix nitrogen, nor do they provide the same degree of soil protection. For example, Zinke (1969) has shown that soil nitrogen decreases over time under chamise. Biswell (1974) reports that chamise has extremely poor soil-protecting qualities. Research from southern California chaparral ecosystems is not transferable to forest ecosystems of the Sierra Nevada, but it does show that the ecology of shrub communities is complex and that generalizations are risky.

Erosion rates are substantially higher under shrub vegetation than under forest cover, due in part to the lack of stable soil aggregates (Perry et al. 1987) under most shrub species, and in part to the lack of effective soil cover. Runoff is more rapid under shrubs, and sheet flow is more common than where a forest floor is present. Shrub species differ in their ability to protect soil from accelerated erosion. Manzanita, for example, does not form a surface mulch that protects soils from erosion.

Nutrient retention by herbaceous communities is low in early successional stages, because little biomass is accumulated (Johnson and Swank 1973). In contrast, young vigorous forests accumulate biomass and immobilize large quantities of nutrients. Rapid reinvasion by shrubs and herbs after a fire may be important in preventing leaching of nutrients released into the ash bed. However, its importance will depend on how well buffered the soil is. For example, deep, clayey soils, high in organic matter, will allow less nutrient leaching than will shallow, coarse-textured soils, low in organic matter.

Another argument for natural succession is that reforestation with one species, commonly pine, will lead to a monoculture with low diversity. This situation rarely occurs, even when attempted in plantations, because it is difficult to exclude invading shrubs and shade-tolerant species. In a study of California plantations McDonald and Fiddler (1993) found considerable diversity, particularly in shrub species. Natural succession after fire may lead to a thick fir stand, a cover type even less resistant to fire.

The more quickly a site reaches crown closure and the more quickly a forest floor develops, the sooner soil productivity will be stabilized. However, that does not justify the severe activities used in the past such as windrowing, scalping, and intensive grubbing on steep slopes. These kinds of activities are likely to cause more degradation of soil productivity than allowing an extended period of shrub cover.

The multiple successional pathways following a wildfire will vary with ecological type, site history, burn intensity, soil type, and soil condition. Which pathway to follow will depend on resource objectives, but maintaining long-term soil productivity must be an objective common to all choices. In terms of lost site productivity, the true cost of allowing a previously forested site to remain in brush for decades could be unacceptably high.

NEEDS FOR RESEARCH AND INVENTORY

Although a great deal is known about the effects of silvicultural activities on forest soils in the Sierra Nevada, much remains to be done. Some of the published research on basic processes was done in other regions and must be extrapolated; older studies were often done on practices no longer used, and existing information is not organized into forms readily accessible to land managers.

Research Needs

Basic Productivity

There is need for basic research on how changes in soil porosity and soil organic matter affect long-term soil productivity, and on how they interact. The U.S. Forest Service studies on long-term soil productivity (Powers et al. 1990a) are noteworthy in pursuing this goal. Eight long-term soil productivity (LTSP) installations now are operating in the Sierra Nevada mixed conifer forest and are part of the world's leading research effort on the subject (R. F. Powers, U.S. Forest Service, letter to the author, June 16, 1995).

Large Woody Material

Much emphasis is being placed on preserving large woody material in Sierra Nevada forests. Although decaying logs do provide wildlife habitat, little is known of their significance to long-term soil productivity in Sierra Nevada ecosystems. Most research on large woody material has been done in the Pacific Northwest and Intermountain regions, which have ecosystems quite different from those of the Sierra Nevada. However, research has been under way since 1993 at Blacks Mountain Experimental Forest (R. F. Powers, U.S. Forest Service, letter to the author, June 16, 1995).

Postwildfire Plant Succession

There is a common misperception that after a major wildfire the best treatment is to allow sites to reforest by natural plant succession. The true costs in terms of soil productivity gains or losses under such a strategy are not known. Much work has been done on natural succession in chaparral in southern California, but knowledge from these ecosystems may not apply to forested ecosystems of the Sierra Nevada. Similarly, little is known about the use of native versus non-native plants to control erosion in postfire emergency watershed treatments.

Soil Biology

Very little is known about the soil macrofaunal populations of the Sierra Nevada and their role in soil processes. Most of the research on soil biology has been done in the Pacific Northwest and is not readily extrapolated to the Sierra Nevada. Research specific to the Sierra Nevada has just begun (Moldenke 1992).

Soil Erosion and Rates of Soil Formation

Soil erosion and formation rates are not well documented for the Sierra Nevada. Although rates of erosion are typically low after timber harvest, they could be potentially serious after intense wildfire or severe site preparation. More knowledge about soil erosion and formation rates would assist in determining appropriate postfire strategies for reforestation and for emergency treatments for burned areas. Limited work is under way at the LTSP installations.

Alternative Fuel Treatments

The effects of the mechanical treatment of fuels on forest soil processes are not well understood. Fine surface organic matter and large woody material both have structural functions that affect soil biology beyond their nutrient content. Limited work on the effects of chipping has been done on the Foresthill Divide (Lanini and Radosevich 1986), and research on chipping, fungal inoculation, and N fixation has begun.

Riparian-Terrestrial Ecosystem Linkages

With the current focus on protection of riparian ecosystems, a better understanding of the linkages between terrestrial and aquatic ecosystems is needed. Geomorphologic relationships suggest that the linkages vary considerably from site to site.

Forest Soils Extension

There is a wealth of information on Sierra Nevada forest soils in research, inventory, and practical experience that is not being fully used in planning, modeling, or designing and implementating projects. Better technology transfer is needed between researchers and practicing land managers in the field. Researchers have many insights into forest soil processes that should be shared with field resource specialists and resource managers. Although the experiences of resource managers and field specialists are often anecdotal and unverified, these resource specialists have years of field observations and experience that are of much value. If the results of research are to be implemented, there must be a stronger link from researcher, to field specialist, to interdisciplinary team member, to decision maker and implementer.

Inventory Needs

Soil Survey

Except for a few isolated foothill areas, soil inventories have been completed for all of the Sierra Nevada at Order 3 or Order 2 levels (Order 4 in wilderness areas). Soils have been classified using Keys to Soil Taxonomy (Soil Survey Staff 1992). This information is adequate for small watershed and regional planning but should be verified in the field for project-level work. Only portions of this soil information are in a geographic information system (GIS) database that can be readily accessed and utilized.

Soil Analysis

Comprehensive laboratory analyses have been conducted on Sierra Nevada forest soils (Zinke et al. 1982). However, the soils analyzed have not been correlated and classified using Keys to Soil Taxonomy, making extrapolation of the results difficult. These laboratory data should also be correlated with newly developed ecological plant associations.

Inventory of Soil Condition

A comprehensive inventory of the condition of Sierra Nevada forest soils is needed. Such an inventory is essential to assess watershed condition, to identify areas needing restoration, and to identify areas at risk. This inventory could be carried out using information on the history of land treatments that is already available. History of past land disturbances could help identify areas most likely to have lost surface soil by erosion or displacement, and where soil compaction is most likely. Soil condition has been altered most severely on old burns of the 1950s that were subjected to timber salvage and severe site preparation, usually scalping to remove the topsoil and its content of weed seeds.

Soils most at risk would be soils with initially low resiliency that had been subjected to the most disturbance. Sites with more robust soils that had received modest levels of disturbance would be less at risk; sites with high-potential soils with high levels of disturbance would be candidates for restoration because there is more opportunity for recovery.

A model predicting soil condition could be quickly developed and field-tested with random sampling. After initial field-testing, predictions could be made and checked in the field to evaluate the accuracy of the model.

Stand-Record Card System

The U.S. Forest Service has a system of stand-record cards that contains nearly fifty years of detailed historical information on timber stands and their treatments. This information should be captured in an electronic database to prevent its being lost and to facilitate its use. It could be invaluable in assessing the condition of Sierra Nevada forest soils, discussed earlier in this chapter.

Soil Interpretations

Interpretations of how Sierra Nevada forest soils respond to management treatments are inconsistent. Except for the Soil Erosion Hazard Rating system—an interdisciplinary effort sponsored by several state and federal agencies and universities—there is no unified system for interpreting the response of Sierra Nevada soils to use and management. Many good soil interpretations are available, but they are scattered and occur in many forms.

Soil Erosion in the Mediterranean Region

The destruction of forests and extensive erosion in the Mediterranean region is frequently cited as an example of what not to allow in the Sierra Nevada. The lessons of the Mediterranean should not be taken lightly. It took several thousand years and hundreds of harvests to reach the level of destruction in the Mediterranean (Thirgood 1981), whereas there are already areas of serious soil erosion in the Sierra Nevada after barely 150 years of activity. We have developed machinery capable of major soil impacts much more rapidly than we have acquired knowledge of what these impacts mean (Powers et al. 1990b).

The Sierra Nevada and the Mediterranean have similarities in climate, soils, and ecosystems. Yet, there are also important differences. The destruction of the Mediterranean forest has been well documented by Thirgood (1981). Although there were large wildfires and periods of heavy harvest for shipbuilding, much of the forest destruction and soil erosion occurred incrementally as a result of overgrazing, especially by nomadic herds of goats. Destruction was accelerated during periods of political instability. Intensive agriculture was also practiced. Although heavy grazing has occurred in the Sierra Nevada, the area is not subject to nomadic grazing, agricultural impacts have been relatively minor, and much of the land base is in highly regulated public ownership. Private forest lands are managed under some of the most restrictive forest practice rules in the world, although it could be argued that soil-management issues have not received enough emphasis under these rules. Most aspects of forest management in the Sierra Nevada receive a high level of public scrutiny.

Although the lessons of the Mediterranean are sobering, it is unlikely that these sequences of soil degradation will be repeated in the Sierra Nevada. Perhaps the most important lesson from the Mediterranean experience is that soil losses too small to observe or measure can, if allowed to continue for a long time, result in a severe decline in forest soil productivity.

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APPENDIX 16.1

Forest Soils of the Sierra Nevada

Figure 16.A1 is a generalized soil map showing the distribution of Sierra Nevada forest soils. The map was made using a November 1, 1994, 1:650,000 map of Cal-Veg types, and a 1:650,000 map of soil associations from the STATSGO soils data base for California as reference. A transparency of the STATSGO soil associations was placed over the Cal-Veg map, and soil areas were hand-drawn for small scale reproduction. A map of California soil temperature regimes and personal knowledge of the Sierra Nevada provided additional guidance in making the soil groupings.

The map is intended to show the distribution of forest soils in the Sierra Nevada. Forest soils occur primarily in map areas 1–8 and 12–13. No attempt was made to differentiate soils in areas 9–11 and 14. These latter areas are either outside the Sierra Nevada proper or contain relatively few forest soils. Dominant soil types, Cal-Veg types, parent material, and soil temperature regime are listed for each soil area in table 16.A1. Soils are classified according to soil taxonomy (Soil Survey Staff 1992).

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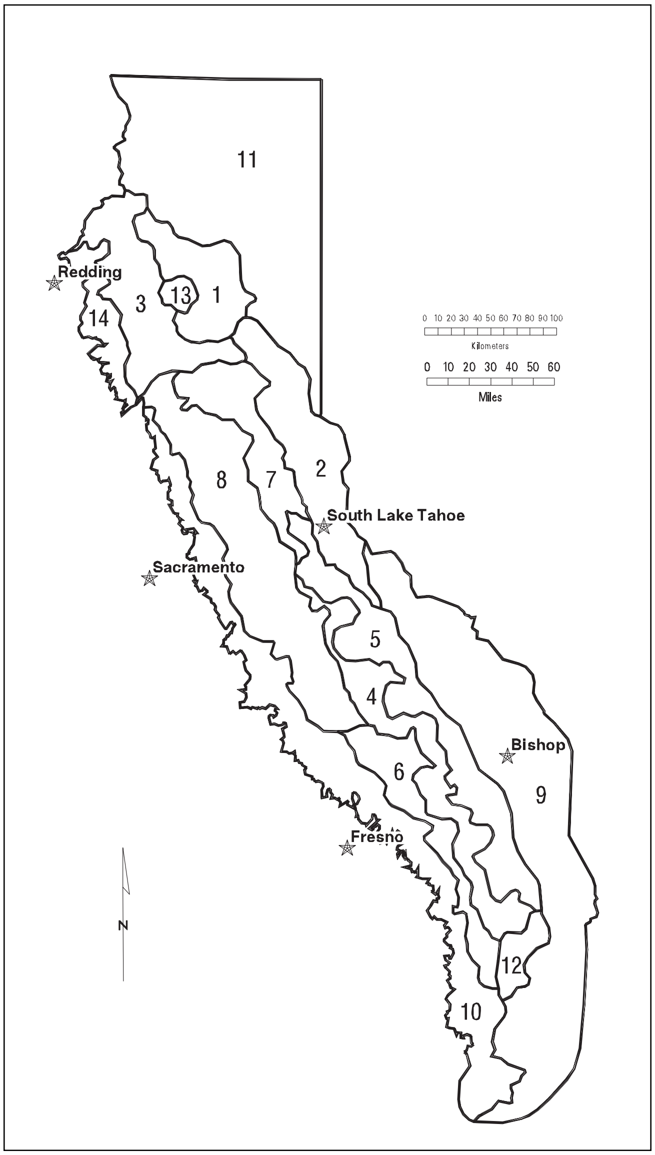

FIGURE 16.A1

Soils areas within the SNEP study area.

Errata

February 10, 1997

Correction to Volume II. **This table replaced Table 16A1 on page 495.**

Table 3. Forest Soil Areas Within the SNEP Study Area

Map Area	Parent Material	Cal-Veg Type	Dominant Soils	Soil Temperature	Comments
1	Volcanic	Mixed Conifer-Fir Jeffrey Pine Basin Sagebrush	Ultic Haploxeralfs Ultic Argixerolls Andic Haploxeralfs Andic Xerochrepts	Frigid	
2	Volcanic Granitic	Mixed Conifer-Fir Jeffrey Pine Basin Sagebrush	Ultic Argixerolls Ultic Haploxeralfs Typic Xeropsamments	Frigid	
3	Volcanic	Mixed Conifer-Fir Mixed Conifer-Pine Manzanita	Ultic Haploxeralfs Andic Xerumbrepts Xeric Haplohumults	Mesic	Eastside mountains and foothills
4	Granitic	Red Fir	Typic Xerumbrepts Dystric Xeropsamments Andic Haplumbrepts Andic and Lithic Cryumbrepts	Frigid	
5	Granitic Glacical drift	Red Fir Lodgepole Pine Mountain Hemlock Barren/Cushion Plant	Andic Cryumbrepts Andic Haplumbrepts Dystric Xeropsamments Typic Xerumbrepts	Frigid Cryic	Crest of Sierra Nevada
6	Granitic	Ponderosa Pine Mixed Conifer-Fir Chamise	Ultic Haploxeralfs Dystric Xerochrepts Dystric Xeropsamments	Mesic	
7	Volcanic Glacial drift Metasediments	Red Fir Mixed Conifer-Fir	Andic Xerumbrepts Typic Xerumbrepts Ultic Haploxeralfs	Frigid	
8	Medisediments Volcanic Granitic	Mixed Conifer-Pine	Typic Haploxerults Ultic Haploxeralfs Xeric Haplohumults Andic Xerumbrepts	Mesic	Mountains of western slope of Sierra Nevada
9	(not mapped)	Basin Sagebrush Pinyon-Juniper Creosote	(not mapped)	Hyperhermic to Cryic	Eastern Sierra Nevada foothills and Basin and Range
10	(not mapped)	Blue Oak Annual Grassland Interior Live Oak Chamise	(not mapped)	Thermic Mesic	Western foothills and edge of Great Central Valley
11	(not mapped)	Basin Sagebrush Ponderosa Pine Western Juniper	(not mapped)	Mesic Frigid	Modoc Plateau
12	Granitic	Jeffrey Pine Chamise	Dystric Xeropsamments Typic Xerothents Entic Haploxerolls	Mesic Frigid	
13	Granitic	Red Fir Ceanothus	Andic Xerumbrepts Ultic Haploxeralfs	Frigid	
14	Mixed	Blue Oak Manzanita Mixed Conifer-Pine	Lithic-Ruptic-Xerorthentic Xerochrepts Pachic Argixerolls Typic Rhodoxeralfs	Thermic Mesic	Foothills and valleys

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