Jennifer D. Knoepp
Leonard F. DeBano
Daniel G. Neary

Chapter 3:
Soil Chemistry

Introduction

The chemical properties of the soil that are affected by fire include individual chemical characteristics, chemical reactions, and chemical processes (DeBano and others 1998). The soil chemical characteristics most commonly affected by fire are organic matter, carbon (C), nitrogen (N), phosphorus (P), sulfur (S), cations, cation exchange capacity, pH, and buffer power. Some purely chemical reactions occur in soils. These include the exchange of cations adsorbed on the surface of mineral soil particles and humus with their surrounding solutions. Another predominately chemical reaction is the chemical weathering of rocks and their eventual transformation into secondary clay minerals during soil formation. During the chemical decomposition of rock material, the soil and its surrounding solution become enriched with several cations. Associated with the chemical interactions during weathering and soil formation are physical forces (freezing and thawing, wetting and drying) and biological activities (production of organic acids during the decomposition of humus) that also accelerate soil development. The most common chemical processes occurring in soils that are affected by fire, however, are those mechanisms that are involved in nutrient availability and the losses and additions of nutrients to the soil.

Soil Chemical Characteristics

The chemical characteristics of soils range from the inorganic *cations*—for example, calcium (Ca), sodium (Na), magnesium (Mg), potassium (K), and so forth—that are adsorbed on the surface of clay materials to those contained mainly within the organic matrix of the soil—for example, organic matter, C, N, P, S. All chemical characteristics are affected by fire, although the temperatures at which changes occur can vary widely. The best estimates available in the literature for the threshold temperatures of individual soil chemical characteristics are given in table 3.1.

The published information describing the effects of fire on changes in individual chemical constituents of soils and organic matter are contradictory and have often led to differing conclusions about the magnitude and importance of the chemical changes that actually occur during a fire. Different studies have concluded that soil chemical constituents increase, decrease, or remain the same (DeBano and others 1998). This has been particularly true for studies reporting changes in N and other nutrients that can volatilize readily during a fire (for example, organic matter, sulfur, and phosphorus). Differing conclusions arise primarily because of the method used for

Table 3.1—Temperature thresholds for several soil chemical characteristics of soil.

Soil characteristic	Threshold temperature		Source
	°F	*°C*	
Organic matter	212	100	Hosking 1938
Nitrogen	414	200	White and others 1973
Sulfur	707	375	Tiedemann 1987
Phosphorus and potassium	1,425	774	Raison and others 1985a,b
Magnesium	2,025	1,107	DeBano 1991
Calcium	2,703	1,484	Raison and others 1985a,b
Manganese	3,564	1,962	Raison and others 1985a,b

calculating the chemical constituents. Chemical changes can be expressed in either percentages (or some other expression of concentrations, for example, ppm or mg/kg) or be based on the actual changes in total amounts of the constituent (for example, pounds/acre or kg/ha). Before fire, the percent of a given chemical constituent is usually based on the amount contained in a prefire sample that can contain variable amounts of organic matter. In contrast, following the fire the percent of the same chemical constituent is based on the weight of a burned sample that contains varying amounts of ash along with charred and unburned organic matter. Thus, the confusion in nutrient changes arises because different bases are used for calculating the change in a particular chemical constituent (that is, based on mainly organic matter before combustion as compared to ashy and unburned materials following a fire). This confusion between percentages and total amounts was first reported in a study on the effect of fire on N loss during heating (Knight 1966). This study indicated that the differences between percent N and total amount of N started at 212 °F (100 °C) and became greater until about 932 °F (500 °C). Because of these difficulties in interpreting concentration and percentage data, the following discussion on the fire-related changes in chemical constituents will first focus on the more fundamental changes in chemical constituents in wildland ecosystems.

As a general rule, the total amounts of chemical elements are never increased by fire. The total amounts of different chemical elements on a particular burned site most likely decrease, although in some cases may remain the same (for example, elements with high temperature thresholds such as Mg, Ca, and others listed in table 3.1). The fire, however, does change the form of different elements and in many cases makes them more available for plants and other biological organisms. A classic example of this is total N contained in the ecosystem organic matter (table 3.2). When organic matter is combusted, total N on the site is always decreased, although increases in the available forms of N are likely to occur as is discussed in a later section, "Nitrogen." Therefore, managers must be alert when interpreting the significance of the sometimes contradictory changes in different nutrients during a fire that are reported in the literature. The following sections focus on describing these changes in terms of the underlying chemical processes and to indicate the management implications of these changes in terms of soil and ecosystem productivity and postfire management.

Table 3.2—Effect of burning at low, medium, and high severities on organic matter and mineralizable N in forest soils in northern Idaho. (Adapted from Niehoff 1985, and Harvey and others 1981).

	Organic matter		Mineralizable N		
Treatment depths =	Mineral soil 2.5-7.5 cm		Mineral 2.5-7.5 cm	Organic 0-2.5 cm	Total N
	Percent	*Change (%)*	*ppm (mg/kg)*	*ppm (mg/kg)*	*Change (%)*
Undisturbed	3.6	0	9.4	68	0
Clearcut					
No burn	3.9	+8	9.7	97	+22
Low	4.1	+12	9.5	75	+8
Medium	2.8	–22	9.3	5	–82
High	0.6	–83	0.7	0	–99

Organic Matter and Carbon

Many chemical properties and processes occurring in soils depend upon the presence of organic matter. Not only does it play a key role in the chemistry of the soil, but it also affects the physical properties (see chapter 2) and the biological properties (see chapter 4) of soils as well. Soil organic matter is particularly important for nutrient supply, cation exchange capacity, and water retention. However, burning consumes aboveground organic material (future soil organic matter, including large logs), and soil heating can consume soil organic matter (fig. 3.1). The purpose of the following discussion is to focus as much as possible on the purely chemical properties of organic matter and on changes that occur as the result of soil heating. Because organic C is one of the major constituents of organic matter, the changes in organic matter and organic C during soil heating are considered to be similar for all practical purposes.

Location of Organic Matter in Different Ecosystems—Organic compounds are found in both aboveground and belowground biomass where they make up the standing dead and live plants and dead organic debris (that is, leaves, stems, twigs, and logs) that accumulate on the soil surface and throughout the soil profile (DeBano and others 1998). Organic matter found in the soil consists of at least seven components, namely:

- The L-layer, (oi) which is made up of readily identifiable plant materials.
- The F-layer, (oe) which contains partially decomposed organic matter but can still be identified as different plant parts (needles, leaves, stems, twigs, bark, and so forth).
- The H-layer, (oa) which is made up of completely decayed and disintegrated organic materials, some of which is usually mixed with the upper mineral soil layers.
- Coarse woody debris that is eventually decayed but can remain on the soil surface or buried in the mineral soil for long periods.
- Charcoal or other charred materials that become mixed with the forest floor and uppermost layers of the mineral soil.
- The uppermost part of the A-horizon, which is composed mainly of a mixture of humus and mineral soil particles.
- A mixture of mineral soil, plant roots, and biomass (live and dead) that is concentrated primarily in the A-horizon but may extend downward into the B-horizon or deeper depending upon the type of vegetation growing on the site.

The amount of aboveground and belowground organic matter varies widely between different vegetation types depending upon on the temperature and moisture conditions prevailing in a particular area (DeBano and others 1998). In almost all ecosystems throughout the world, greater quantities of C (a measure of organic matter) are found belowground than aboveground (fig. 3.2). In grasslands, savannas, and tundra-covered areas, much greater quantities of organic C are found in the underground plant parts than aboveground (less than 10 percent of the total C in these herbaceous vegetation ecosystems is found

Figure 3.1—Large logs combusting in a prescribed fire in a ponderosa pine stand. (Photo by Daniel Neary).

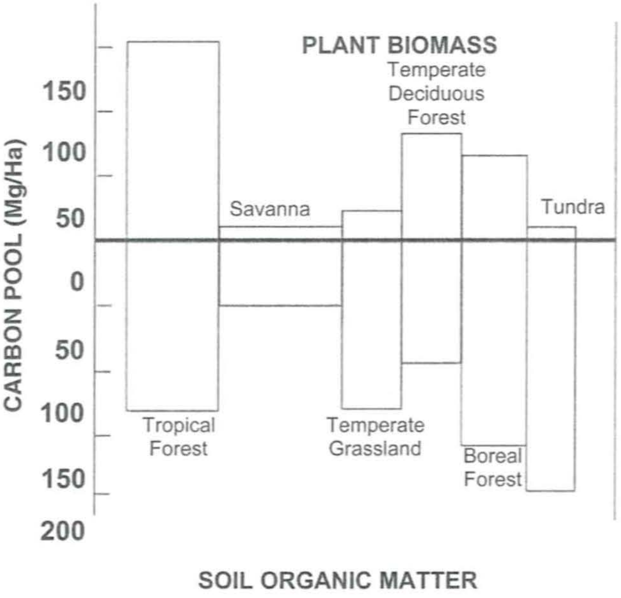

Figure 3.2—Distribution of C and soil organic matter (including litter) in major ecosystem types of the world. (Adapted from J. M. Anderson, 1991. The effects of climate change on decomposition processes in grassland and coniferous forest. Ecological Applications. 1: 326-347. Copyright © 1991 Ecological Society of America.)

aboveground). Tundra ecosystems are unique in that large amounts of organic matter accumulate on the soil surface because the low year-long temperatures severely limit decomposition. In forest ecosystems, C is more evenly distributed aboveground and belowground (for example, temperate deciduous and boreal forests). In general, soils with larger proportions of organic matter in the aboveground biomass and on their forest floors are more prone to disturbances (including fire) in their nutrient and C regimes than those in which most of the C in the ecosystem is located belowground.

Dynamics of Organic Matter Accumulation—In forests, the dynamics of the forest floor are responsible for the accumulation of organic matter, and the forest floor provides a major storage reservoir for nutrients that are cycled within natural ecosystems (fig. 3.3). An aggrading forest ecosystem sequesters nutrients and C aboveground in both the biomass and the forest floor (Knoepp and Swank 1994). Over many years this material forms the forest floor or the organic soil horizons (designated as Oi, Oe, and Oa horizons in part A, fig A.1). Depending on the soil type, organic matter may be concentrated in the forest floor or spread in decreasing amounts downward through the soil profile (fig. 3.4 and A.2).

The forest floor increases during forest development and aggradation when the rate of addition is greater than the rate of decomposition. For example, Knoepp and Swank (1994) found that forest floor mass increased by 28 and 45 percent over a 10-year period in an aggrading mixed oak (*Quercus* spp.) forest and white pine (*Pinus strobus*) plantation, respectively. In Arizona, Covington and Sackett (1992) examined forest floor accumulation in a ponderosa pine (*P. ponderosa*) stand having several different age "substands" within it and found several significant differences in forest floor mass among the substands. In general, the younger sapling areas had the smallest accumulations of forest floor materials compared to old growth pine substands that had the greatest. Over long periods the inputs and outputs of forest floor materials, coarse woody debris, fine woody debris, and leaf litter eventually reach a dynamic equilibrium depending upon the stand type (for example, coniferous versus hardwood) and forest management practices used (for example, uncut versus cut, log only versus whole-tree harvest).

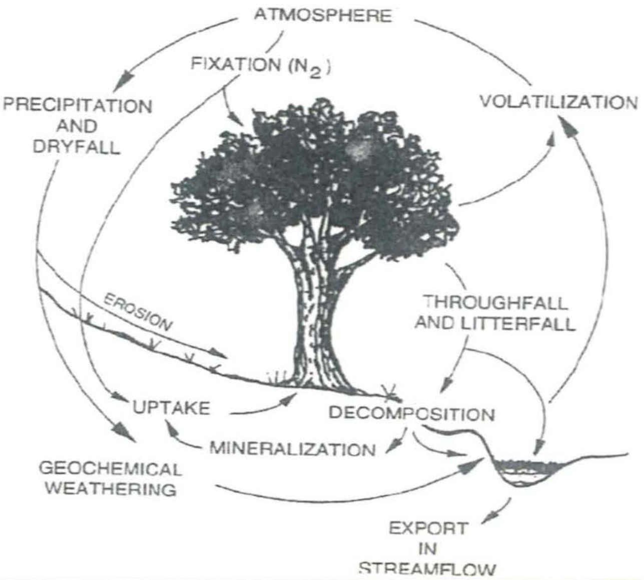

Figure 3.3—Nutrient cycling in natural environments. (Adapted from Brown 1980.)

Figure 3.4—Burn out of high organic matter soil in the Barca Slough, Vandenburg Air Force Base, California. (Photo by U.S. Air Force).

Coarse Woody Debris—*Coarse woody debris* (including slash piles) is an important component of the organic matter pools found in forested ecosystems (fig. 3.5). In many cases it is partially or totally covered by soil and humus layers, and it has been found to comprise more than 50 percent of the total surface organic matter (this can amount to 16.5 to 22.3 tons/acre or 37 to 50 Mg/ha) in old growth forests in the Inland Northwest (Page-Dumroese and others 1991, Jurgensen and others 1997). Coarse woody debris, along with smaller organic matter, enhances the physical, chemical, and biological properties of the soil and thereby contributes directly to site productivity (Brooks and others 2003). It also provides a favorable microenvironment for the establishment

Figure 3.5—Coarse woody debris: (A) slash pile from pinyon-juniper thinning operation, Apache-Sitgreaves National Forest, Arizona; (B) logging slash in a Douglas-fir and mixed conifer, Mt. Baker-Snoqualmie National Forest, Cascade Mountains, Washington. (Photos by Malchus Baker and Kevin Ryan, respectively).

of seedlings and plant growth. The microbiological role of coarse woody debris is discussed further in chapter 4.

Fire Effects—Fire not only affects the organic matter by directly affecting its chemical composition but it also indirectly affects the subsequent decomposition rates. The magnitude of changes is related to the severity of the burn (for example, low, moderate, or high).

Chemical Changes: The low temperature threshold of organic matter makes it especially sensitive to soil heating during fire (table 3.1). Also, a major portion of the organic matter is located in the uppermost part of the soil profile (surface litter and humus layers) where it is exposed directly to the heat radiated downward during a fire (see part A). The changes in organic matter during the course of heating have been of interest to scientists for more than 60 years (Hosking 1938), and the changes reported by these earlier studies showed that:

- Losses of organic matter can occur at temperatures below 212 °F (100 °C).
- Volatile constituents in organic matter are lost at temperatures up to 392 °F (200 °C).
- Destructive distillation destroys about 85 percent of the soil organic matter at temperatures between 392 and 572 °F (200 and 300 °C).
- Above 572 °F (300 °C), the greater part of the residual organic matter consists of carbonaceous material, which is finally lost upon ignition.
- Heating the soil to 842 °F (450 °C) for 2 hours, or to 932 °F (500 °C) for 1/2 hour, destroys about 99 percent of the organic matter.

Recent studies on the detailed heat-induced changes in organic matter have improved our understanding of the specific chemical changes that occur in organic matter during the course of heating (DeBano and others 1998). At low temperatures, the changes in organic matter affect the more sensitive functional groups; at higher temperatures the thermal decomposition of nuclei occurs (Schnitzer and Hoffman 1964). At lower temperatures between 482 and 752 °F (250 and 400 °C) both phenolic OH and carboxyl (COOH) groups are lost, although phenolic groups are the more stable of the two. Another study of the thermal changes occurring in the H-layer under an evergreen oak forest in Spain showed that oxygen-containing functional groups found in humic and fulvic acids were altered (Almendros and others 1990). Humic acids were converted into alkali-insoluble substances that contributed to soil humus, while fulvic acids were transformed into acid-insoluble polymers. Biomass that was not completely burned contained both alkali-soluble lignin materials and brown products formed by dehydration of carbohydrates. The lignin compounds formed were more resistant to further chemical and biological change.

In a separate study, Ross and others (1997) found a decrease in total soil C and potassium sulfate extractable C at 1.5 and 2.5 years after burning. Sands (1983) found that 24 years after an intense site preparation burn on sandy soils, soil C was still lower than on adjacent unburned sites. This was generally the case for all soil C components he examined, including total organic C, extractable C, water-soluble C, humic acids, and carbohydrates.

Decomposition rates: In unburned ecosystems, natural decomposition processes (most biologically mediated) slowly release nutrients to tree and plant roots growing within the forest floor and to the mineral soil below. These biological processes add organic matter and nutrients to soils in forest environments under moderate temperatures through the activity of insects and microbes (DeBano 1991). Burning, however, acts as an instantaneous physical decomposition process that not only volatilizes nutrients, such as N, from the site but also alters the remaining organic materials (St. John and Rundel 1976).

Burning not only rapidly accelerates the rates of organic matter decomposition during the fire itself but can also indirectly affect postfire decomposition rates. For example, Schoch and Binkley (1986) and Raison and others (1990) studied loblolly pine (*P. taeda*) and radiata pine (*P. radiata*) plantations following fire. They found that decomposition rates of the remaining forest floor increased after burning, releasing ammonium (NH_4) and other nutrients. Observed changes in nutrient release and availability may be due to the alteration of organic matter solubility as a result of soil heating during a fire. The change in nutrient release and availability along with increased soil temperature and moisture content may also increase biological activity. This response may be short lived, however, because this readily available organic matter often diminishes rapidly and decomposition rates decrease (Raison and others 1990). Conversely, some studies have noted decreases in the rates of organic matter decomposition following burning. Monleon and Cromack (1996) measured decreased rates of decomposition in ponderosa pine forests immediately following burning and for up to 12 years. They concluded that the lower decomposition rates may be due to the combination of increased temperature and decreased moisture in the postfire forest floor. Springett (1976) also measured slower decomposition in Australian plantations and native forests caused by the changes in soil temperature and moisture as well as a decrease in the diversity and density of soil fauna following burning. This suggested that burning on a frequent rotation could simplify the litter fauna and flora, but these changes may permanently alter patterns of organic matter decomposition and nutrient release.

Both fire severity and frequency of burning affect the amount of organic matter that is lost as a result of burning. These are two characteristics of fire effects that fire management specialists can alter within the context of a prescribed burning program.

Fire severity: The effect of severity of burning on the amount of organic matter burned was reported for a 350 acre (142 ha) wildfire that burned a table mountain pine stand in the Shenandoah Valley (Groeschl and others 1990, 1992, 1993). This wildfire left a mosaic pattern of areas that were burned at different severities. They reported that on areas burned by a low-severity fire, the forest floor Oi and Oe layers were completely combusted, but the Oa layer remained. High-severity burning also consumed the Oa layer. Of the 10.1 tons/acre (22.6 Mg/ha) of C present in the forest floor in the unburned areas, no C remained in the high-severity burned areas compared to 9.3 tons/acre (20.8 Mg/ha) C that was left on the burned areas at low severities.

The effect of prescribed burning on the C and N content of the forest floor on an area supporting a mixed pine-oak overstory with a ericaceous shrub layer was studied in the Southern Appalachian Mountains (Vose and Swank 1993, Clinton and others 1996). The study areas were treated with felling-and-burning of existing trees to stimulate pine regeneration. Carbon and N content of the forest floor in these systems was examined after felling, prior to burning, and it was found that the forest floor contained between 15 and 22 percent of the total aboveground C on the site and 44 to 55 percent of the total aboveground N. Prescribed burning of these sites consumed the entire Oi layer, but 75 to 116 percent of the total forest floor C and 65 to 97 percent of the N remained in the combined Oe and Oa layers. On these sites, about half of the total aboveground N pool was contained in the forest floor. Total aboveground N losses ranged from 0.086 tons/acre (0.193 Mg/ha) for the lowest severity fire to 0.214 tons/acre (0.480 Mg/ha) on the most severe burn. Under prescribed burning conditions it is frequently possible to select appropriate weather conditions prior to burning (for example, time since last rain, humidity, temperature) to minimize the effects of fire on the consumption of organic matter. Therefore, it has been recommended that weather conditions prior to burning (for example, time since rainfall) could be used as a predictor of forest floor consumption (Fyles and others 1991).

Responses of total C and N are variable and depend on site conditions and fire characteristics. For example, Grove and others (1986) found no change in organic C in the surface 0 to 1.2 inch (0-3 cm) of soil immediately following burning; percent total N, however, increased. Knoepp and Swank (1993a,b) found no consistent response in total N in the upper soil layer, but did find increases in NH_4 concentrations and N mineralization on areas where a burning treatment followed felling.

Fire frequency: As would be expected, frequency of burning can affect C accumulations. A study was carried out on tropical savanna sites in Africa having both clay and sandy soils that were burned repeatedly every 1, 3, or 5 years (Bird and others 2000). While sites with clay soils had greater total C than did the sandy soils, they responded similarly to burning. All unburned sites had 40 to 50 percent greater C than burned sites. Low frequency burning (every 5 years) resulted in an increase in soil C of about 10 percent compared to the mean of all burned areas. High frequency burning (every year) decreased C about 10 percent. In another study, Wells and others (1979) reported the results of a 20-year burning study in a pine plantation in South Carolina. They found that periodic burning over 20-year period removed 27 percent of the forest floor. Annual burning conducted in the summer removed 29 percent of the forest floor as compared to a 54 percent loss resulting from winter burning. The total organic matter content of the surface soil (0 to 2 inches or 0 to 5 cm) increased in all cases, but there was no effect on the 2 to 3.9 inches (5-10 cm) soil layer. Interestingly, when they summed the organic matter in the forest floor and in the surface 0 to 3.9 inches (0-10 cm) of soil they found that these low-severity periodic burns sites had not reduced but only redistributed the organic matter.

The incidence of fire has been found to also affect the organic matter composition of savannahlike vegetation (referred to as "cerrado") in central Brazil (Roscoe and others 2000). On plots exposed to more frequent fires (burned 10 times in 21 years) C and N were decreased in the litter by 1.652 and 0.046 tons/acre (3.703 and 0.104 Mg/ha), respectively, although no significant differences were noted in the upper 3 feet (1 meter) of the underlying soil. Interestingly, the increase in fire incidence replaced the C_3-C with C_4-C by about 35 percent throughout the soil profile. This suggested that a more rapid rate of soil organic matter turnover occurred in areas burned by frequent fires, and as a result the soil would not be able to replace sufficient C to maintain long-term productivity of the site.

Prescribed fire was returned into overstocked ponderosa pine stands on the Mogollon Rim of Arizona for the purpose of restoring fire into the ecosystem and removing fuel buildups (Neary and others 2003). Prescribed fires were ignited at intervals of 1, 2, 4, 6, 8, and 10 years to determine the best fire return interval for Southwest ponderosa pine ecosystems (Sackett 1980, Sackett and others 1996). Two sites were treated—one on volcanic-derived soils and the other on sedimentary-derived soils near Flagstaff, AZ. Soil total C and total N levels were highly variable and exhibited an increasing, but inconsistent, concentration trend related to burn interval. They ranged from 2.9 to more than 6.0 percent total C and 0.19 to 0.40 percent total N (fig. 3.6). High spatial variability was measured within treatments, probably due to microsite differences (location of samples in the open, under large old-growth trees, in small-diameter thickets, in pole-sized stands, next to downed logs, and so forth). Stratification of samples by microsite differences could possibly reduce the within-plot variability but add complexity to any sampling design. Although there were statistically significant differences between the total C levels in soils of the unburned plots and the 8-year burning interval, there were no differences between burning intervals. There also was a statistically significant difference between unburned and 2-year burning interval and the 8-year burning interval in total soil N. This study determined that burning increased mineral soil C and N, which conflicted with Wright and Hart's (1997) contention that the 2-year burning interval could deplete soil N and C pools. This study did not examine the mineral fractions of the soil N pool, NH_4-N, and NO_3-N. Although the mineral forms of N are small (less than 2 percent of the total soil N pool), they are important for plant nutrition and microorganism population functions

Soil organic matter: Summary reports have described the effect of different management activities (including the effect of fire) on the organic matter and N found in the mineral portion of forest soils (D.W. Johnson 1992, Johnson and Curtis 2001). A metaanalysis on the results of 13 studies completed between 1975 and 1997 (table 3.3) show that the C and N contents of both the A-horizon and the underlying mineral soil layers change only a small amount (less than 10 percent) in the long term (fig. 3.7 and 3.8). These results agreed with the conclusions of another review (E. A. Johnson 1992) that indicated the overall effect of fire was not significant, although there was a significant effect of time since fire. It must be remembered, however, that although small changes in soil organic matter and C occurred in the soils during these studies, that substantial amounts of both organic litter and duff were most likely consumed during these fires. Organic matter and N losses from the forest floor could have a lasting effect on the long-term productivity and sustainability of forest sites, particularly when they occur on nutrient-deficient sites (see the later discussions in this chapter on N loss and ecosystem productivity).

Cation Exchange Capacity

Cation exchange is the interchange between cations in solution and different cations adsorbed on the surface of any negatively charged materials such as a clay or organic colloids (humus). *Cation exchange capacity* is the sum of the exchangeable cations found on organic and inorganic soil colloids (fig. 3.9). It arises from the negatively charged particles found on clay particles and colloidal organic matter in the soil. Cation exchange capacity sites are important storage places for soluble cations found in the soil. The adsorption of cations prevents the loss of these cations from the soils by leaching following fire. Although most of the exchange sites in soils are negative and attract cations, there are some positively charged sites that can attract anions (anion exchange has been reported to occur on clay particles).

The relative contribution of clay particles and organic matter to the cation exchange capacity of the soil depends largely upon the proportion of the two components and the total quantities of each present (Tate 1987). Cation exchange capacity also depends upon the type of clay and organic matter present. Clay materials such as montmorillonites have large exchange capacities, and other clays such as kaolinite are much lower. Other mineral particles such as silt and sand contain few adsorption sites for cations. In organic matter, the degree of humification affects the cation exchange capacity, and the more extensive the decomposition of organic material, the greater the exchange capacity.

Soil heating during a fire can affect cation exchange capacity in at least two ways. The most common change is the destruction of humus compounds. The location of the humus layer at, or near, the soil surface

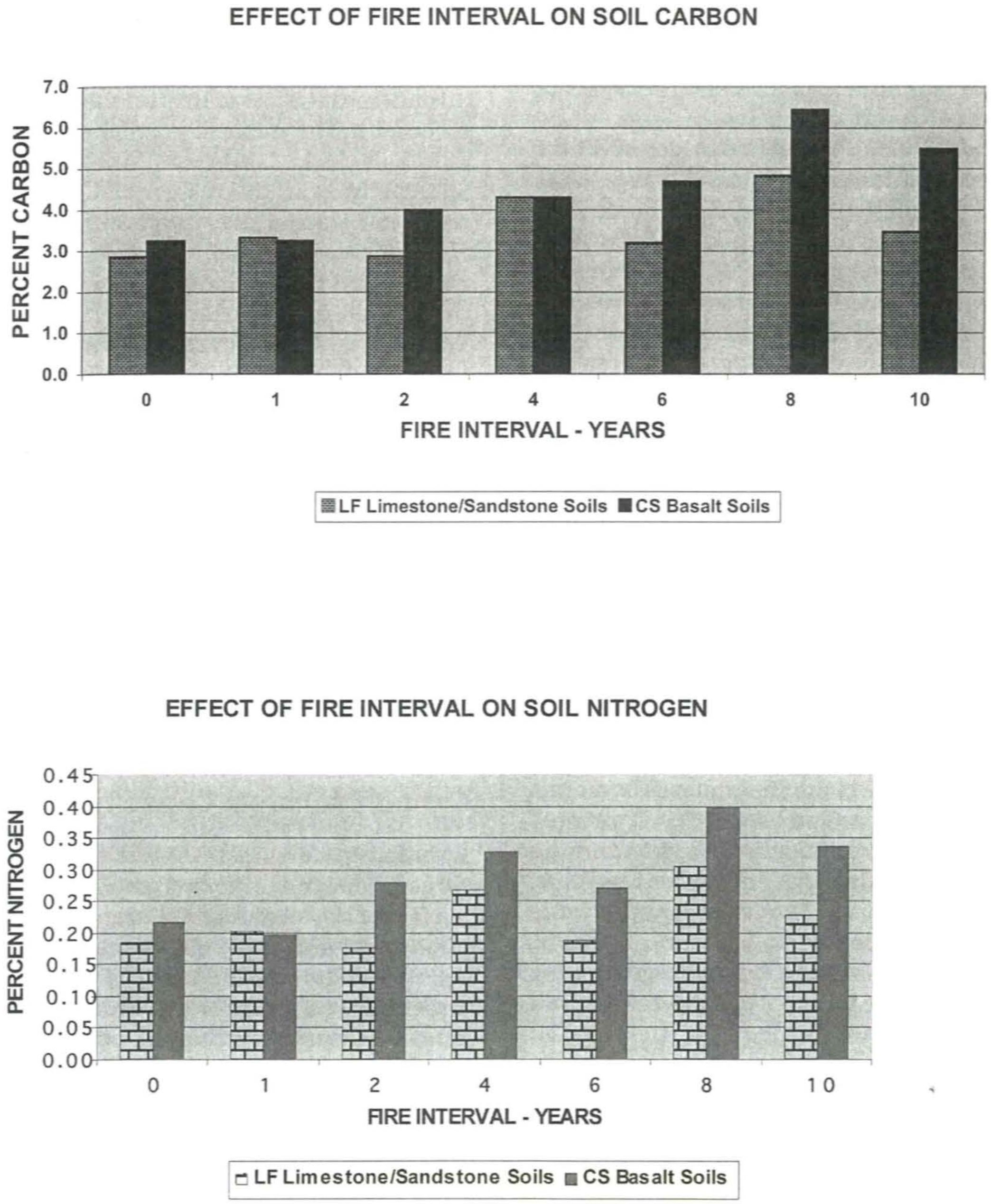

Figure 3.6—Effect of fire interval on (A) 0 to 2 inch (0-5 cm) soil total carbon, and (B) 0 to 2 inch (0-5 cm) soil nitrogen, Limestone Flats and Chimney Springs burning interval study, Arizona. (From Neary and others 2003).

makes it especially vulnerable to partial or total destruction during a fire because organic and humic materials start decomposing at about 212 °F (100 °C) and are almost completely destroyed at 932 °F (500 °C). These temperatures are easily reached during brushland and forest fires (see chapter 2 discussion on soil temperatures). In contrast, the cation exchange capacity of the clay materials is more resistant to change because heating and temperatures of 752 °F (400 °C) must be reached before dehydration occurs. The complete destruction of clay materials does not occur until temperatures of 1,292 to 1,472 °F (700 to 800 °C) are reached. In addition, clay material is seldom located on the soil surface but instead is located at least several centimeters below the soil surface in the B-horizon where it is well protected from

Table 3.3—References for the Johnson and Curtis (2001) meta-analysis of the effects of forest fires on soil C and N contents.

Location	Species	Fire type	Reference
Southern U.S.A.			
SC	Longleaf pine	PF[1]	Binkley and others 1992
SC, AL, FL, LA	Loblolly and other pines	PF	McKee 1982
Southwest U.S.A.			
AZ	Ponderosa pine	PF	Covington and Sackett 1986
AZ	Pinyon-juniper	PF	Klopatek and others 1991
Northwest U.S.A.			
WA	Mixed conifer	WF	Grier 1975
WA, OR	Douglas-fir, conifer mix	BB	Kraemer and Hermann 1979
OR	Ponderosa pine	PF	Monleon and others 1997
MT	Mixed conifer	PF	Jurgenson and others 1981
Alaska and Canada			
AL	Mixed spruce and birch	WF	Dyrness and others 1989
BC	Sub-boreal spruce	BB	Macadam 1987
World			
Australia	Eucalyptus	BB	Rab 1996
Algeria	Oak	WF	Rashid 1987
Sardinia	Chaparral	PF	Giovannini and others 1987

[1] PF: prescribed fire; WF: wildfire; BB: cut and broadcast burn.

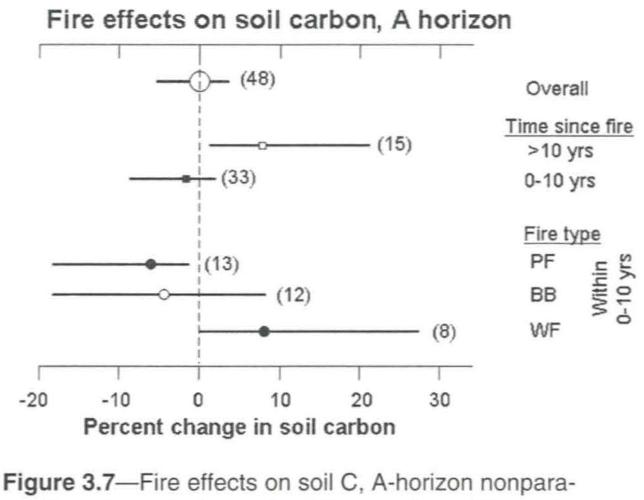

Figure 3.7—Fire effects on soil C, A-horizon nonparametric metaanalysis results; 99 percent confidence intervals (bars) and number of studies (in parentheses); PF = prescribed fire, WF = wildfire, and BB = broadcast burning of slash after harvest) (After Johnson and Curtis 2001, Forest Ecology and Management, Copyright © 2001, Elsevier B.V. All rights reserved).

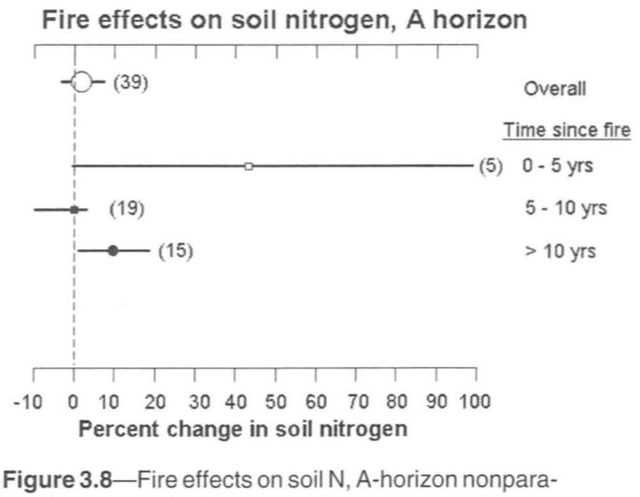

Figure 3.8—Fire effects on soil N, A-horizon nonparametric metaanalysis results; 99 percent confidence intervals (bars) and number of studies (in parentheses). (After Johnson and Curtis 2001).

Figure 3.9—Cation exchange capacity in soil is provided by both organic matter (humus) found in the forest floor and upper soil horizons as well as inorganic mineral particles such as silts and clays found lower in the profile. (Soil profile from Appalachian Mountains, Nantahala National Forest; photo by Daniel Neary).

surface heating. In general, the reduction in exchange capacity as the result of a fire is proportional to the amount of the total cation capacity that is provided by the organic component (DeBano and others 1998). The amount of cation exchange capacity remaining after a fire affects the leaching losses of soluble nutrients released during the fire. For example, the prefire cation exchange capacity of sandy soils may consist mainly of exchange sites found on the humus portion of the soil. If large amounts of humus are destroyed in these sandy soils during burning, then no mechanisms are available to prevent large losses of soluble nutrients by leaching.

The loss of cation exchange capacity, as the result of organic matter destroyed by fire, has been reported on by several authors. Soto and Diaz-Fierros (1993) intensively monitored changes in soil cation exchange capacity for one of the six soils they exposed to increasing temperatures. They found that cation exchange capacity decreased from 28.4 meq/100 g (28.4 cmol/kg) at 77 °F (25 °C) down to 1 meq/100 g (1 cmol/kg) when exposed to 1,292 °F (700 °C). The largest decrease occurred between 338 and 716 °F (170 and 380 °C), dropping from 28.1 to 6.9 meq/100 g (28.1 to 6.9 cmol/kg). Sands (1983) examined two adjacent radiata pine sites on sandy soils in Southeastern Australia 24 years after cutting. He found that the sites that received an intense site preparation burning before planting had decreased cation exchange capacity downward in soils to 20 cm compared to no changes on unburned naturally regenerated sites.

A stand replacement fire in the Southern Appalachians that resulted in a mosaic burn pattern similar to a wildfire produced a slight but significant decrease in cation exchange capacity 3 months after burning (Vose and others 1999). Also associated with the change in cation exchange capacity on midslope areas (medium-severity burn) was a decrease in exchangeable K and Mg, along with an increase in soil pH.

Cations

Cations found in the soil that are affected by fire include Ca, Mg, Na, K, and ammonia (NH_4), although these cations are not usually deficient in most wildland soils (DeBano 1991). In many studies, a significant increase in soil cation concentration following either prescribed burning or a wildfire has been reported (Grove and others 1986, Raison and others 1990, Soto and Diaz-Fierros 1993). The NH_4 cation, which is an important component of N cycling and soil productivity, responds differently from the other cations. With the exception of NH_4, cations have high temperature thresholds and, as a result, are not easily volatilized and lost from burned areas. The ash deposited on the soil surface during a fire contains high concentrations of cations, and their availability is increased, including NH_4 (Marion and others 1991, DeBano and others 1998; fig. 1.4). The amount of NH_4 released by burning depends upon fuel loading and the quantity of fuel combusted (Tomkins and others 1991). Some of the cations can be lost through particulate transfer in the smoke (Clayton 1976).

Monovalent cations, such as Na and K, are present largely as chlorides and carbonates that are readily mobilized (Soto and Diaz-Fierros 1993). Divalent ions, such as Ca and Mg, are less mobile and are commonly present as oxides and carbonates. The formation of insoluble calcium carbonate can occur, which limits the availability of P following fire. Although these readily available monovalent and divalent cations probably do not materially affect plant growth directly, their amount and composition determines base saturation, which plays an important role in controlling the pH regimes in soils (DeBano and others 1998).

Soil pH and Buffer Capacity

Soil *pH* is a measure of the hydrogen ion activity in the soil and is determined at specified moisture contents. Neutral soils have a pH of 7, acidic soils have a pH less than 7, and basic soils are those with a pH greater than 7. *Buffer capacity* is the ability of ions associated with the solid phase to buffer changes in ion concentration of the soil solution.

The combustion of organic matter during a fire and the subsequent release of soluble cations tend to increase pH slightly because basic cations are released during combustion and deposited on the soil surface. The increase in soil pH, however, is usually temporary depending upon the original soil pH, amount of ash released, chemical composition of the ash, and wetness of the climate (Wells and others 1979). The ash-bed effect discussed later in this chapter is an example of these factors in which large amounts of nutrients are deposited, with pH values being measurably changed by fire.

The pH of the soil is an important factor affecting the availability of plant nutrients (fig. 3.10). The nutrients released during a fire that are most likely to be affected are P, iron, and copper. P is particularly important because it is a macronutrient that is frequently limiting in wildland ecosystems, and it can also become insoluble at both high or low pHs (see part A). At low pH, P forms insoluble compounds with iron and at high pH, Ca compounds tend to immobilize it.

Nitrogen

Nitrogen is considered the most limiting nutrient in wildland ecosystems and as such it requires special consideration when managing fire, particularly in N-deficient ecosystems (Maars and others 1983). Nitrogen is unique because it is the only soil nutrient that is not supplied to the soil by chemical weathering of parent rock material. Almost all N found in the vegetation, water, and soil of wildland systems has to be added to the system from the atmosphere. A rare exception is the addition of some synthetic N-fertilizers that have been produced industrially and used for fertilizing forested areas. The cycling of N involves a series of interrelated complex chemical and biological processes (also see chapter 4). Only those cycling processes affecting chemical changes in N are discussed in this chapter (that is, N volatilization). Biologically mediated processes affecting N are discussed in more detail as part of chapter 4. The changes in N availability produced during fire are discussed later in this chapter in a section describing the effect of fire on nutrient availability

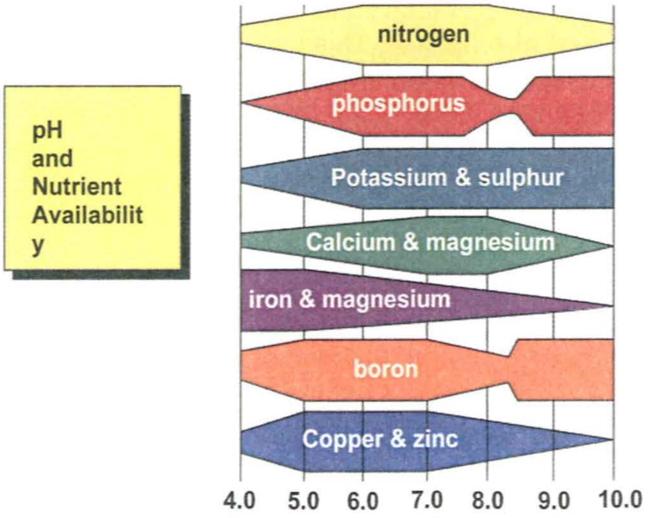

Figure 3.10—The availability of some common soil nutrients at different soil pH. (Figure courtesy of the USDA Forest Service, National Advanced Fire and Resource Institute, Tucson, AZ).

Responses to Soil Heating—Volatilization is the chemically driven process most responsible for N losses during fire. There is a gradual increase in N loss by volatilization as temperature increases (Knight 1966, White and others 1973). The amount of loss at different temperatures has established the following sequence of N losses upon heating:

- Complete loss (100 percent) of N occurs at temperatures above 932 °F (500 °C).
- Between 75 and 100 percent of the N is lost at temperatures of 752 to 932 °F (400 to 500 °C).
- Between 50 and 75 percent of the N is lost at temperatures of 572 to 752 °F (300 to 400 °C).
- Between 25 and 50 percent of the N is lost at temperatures of 392 to 572 °F (200 to 300 °C).
- No N losses occur at temperatures below 392 °F (200 °C).

As a general rule the amount of total N that is volatilized during combustion is directly proportional to the amount of organic matter destroyed (Raison and others 1985a). It has been estimated that almost 99 percent of the volatilized N is converted to N_2 gas (DeBell and Ralston 1970). At lower temperatures, N_2 can be produced during organic matter decomposition without the volatilization of N compounds (Grier 1975). The N that is not completely volatilized either remains as part of the unburned fuels or it is converted to highly available NH_4-N that remains in the soil (DeBano and others 1979, Covington and Sackett 1986, Kutiel and Naveh 1987, DeBano 1991).

Estimates of the total N losses during prescribed fire must be based on both fire behavior and total fuel consumption because irregular burning patterns are common. As a result, combustion is not complete at all locations on the landscape (DeBano and others 1998). For example, during a prescribed burn in southern California, total N loss only amounted to 10 percent of the total N contained in the plant, litter, and upper soil layers before burning (DeBano and Conrad 1978). The greatest loss of N occurred in aboveground fuels and litter on the soil surface. In another study of N loss during a prescribed fire over dry and moist soils, about two-thirds of the total N was lost during burns over dry soils compared to only 25 percent when the litter and soil were moist (DeBano and others 1979). Although these losses were relatively small, it should be remembered that even small losses can adversely affect the long-term productivity of N- deficient ecosystems. The importance of N losses from ecosystems having different pools of N is considered in more detail below.

Monleon and others (1997) conducted understory burns on ponderosa pine sites burned 4 months, 5 years, and 12 years previously. The surface soils, 0 to 2 inches (0 to 5 cm), showed the only significant response. The 4-month sites had increased total C and inorganic N following burning and an increased C/N ratio. Burning the 5-year-old sites resulted in a decrease in total soil C and N and a decrease in the C/N ratio. Total soil C and N in the surface soils did not respond to burning on the 12-year-old site.

Nitrogen Losses—An Enigma— It has been conclusively established by numerous studies that total N is decreased as a result of combustion (DeBano and others 1998). The amount of N lost is generally proportional to the amount of organic matter combusted during the fire. The temperatures at which N is lost are discussed above. In contrast, available N is usually increased as a result of fire, particularly NH_4-N (Christensen 1973, DeBano and others 1979, Carballas and others 1993). This increased N availability enhances postfire plant growth, and gives the impression that more total N is present after fire. This increase in fertility, however, is misleading and can be short-lived. Any temporary increase in available N following fire is usually quickly utilized by plants within the first few years after burning.

Nitrogen Losses and Ecosystem Productivity— The consequences of N losses during fire on ecosystem productivity depend on the proportion of total N lost for a given ecosystem (Barnett 1989, DeBano and others 1998). In N-limited ecosystems even small losses of N by volatilization can impact long-term productivity (fig. 3.11).

The changes in site productivity are related to the proportion of total N in the system that is lost. For example, the left portion of figure 3.11 represents a situation where large quantities of N are presented on a site having high productivity. Moving to the right side of the graph, both total N capital and productivity decrease. This decrease is not linear because there are likely to be greater losses in productivity per unit loss of N capital on sites having lower productivity (right side of fig. 3.11) than on sites having higher site productivity (left side of fig. 3.11). As a result, the losses in site productivity per unit N loss (a_h to b_h) from sites of high productivity (l_h) are less than losses in site productivity per unit N loss (a_i to b_i) from sites having low productivity (l_i). This relationship points to the importance of somehow replenishing N lost during a fire on low productivity sites or when using prescribed fire in these situations, taking special care not to consume large amounts of the organic matter present.

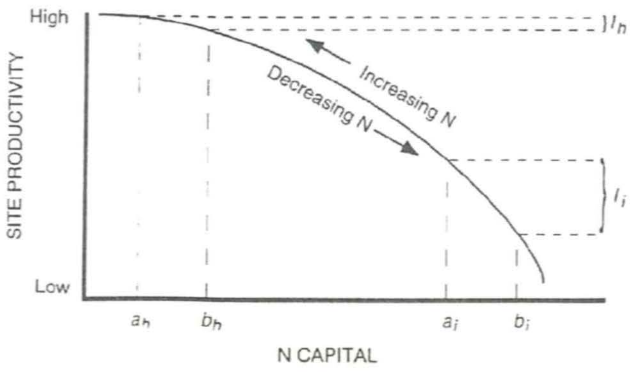

Figure 3.11—Relative importance of nitrogen low at different levels of site productivity. (After Barnett 1989).

Phosphorus

Phosphorus is probably the second most limited nutrient found in natural ecosystems. Deficiencies of P have been reported in P-fixing soils (Vlamis and others 1955) and as a result from N fertilization applications (Heilman and Gessel 1963). Phosphorus uptake and availability to plants is complicated by the relationship between mycorrhizae and organic matter and in most cases does not involve a simple absorption from the soil solution (Trappe and Bollen 1979). Phosphorus is lost at a higher temperature during soil heating than N, and only about 60 percent of the total P is lost by nonparticulate transfer when organic matter is totally combusted (Raison and others 1985a). The combustion of organic matter leaves a relatively large amount of highly available P in the surface ash found on the soil surface immediately following fire (see discussion on nutrient availability later in this chapter; also fig. 1.4). This highly available P, however, can be quickly immobilized if calcareous substances are present in the ash and thus can become unavailable for plant growth.

Sulfur

The role of S in ecosystem productivity is not well understood although its fluctuation in the soil is generally parallel to that of inorganic N (DeBano and others 1998). Sulfur has been reported as limiting in some coastal forest soils of the Pacific Northwest, particularly after forest stands have been fertilized with N (Barnett 1989). The loss of S by volatilization occurs at temperatures intermediate to that of N and P (Tiedemann 1987), and losses of 20 to 40 percent of the S in aboveground biomass have been reported during fires (Barnett 1989). Sulfur is similar to P (and unlike N) in that it cannot be fixed by biological processes, but instead is added primarily by burning fossil fuels (a source of acid rain), as fallout from volcanic eruptions, or by the weathering of rocks during soil development (DeBano and others 1998).

Soil Chemical Processes

Nutrient Cycling

Nutrients undergo a series of changes and transformations as they are cycled through wildland ecosystems. The sustained productivity of natural ecosystems depends on a regular and consistent cycling of nutrients that are essential for plant growth (DeBano and others 1998). Nutrient cycling in nonfire environments involves a number of complex pathways and includes both chemical and biological processes (fig. 3.3). Nutrients are added to the soil by precipitation, dry fall, N- fixation, and the geochemical weathering of rocks. Nutrients found in the soil organic matter are transformed by decomposition and mineralization into forms that are available to plants (see chapter 4). In nonfire environments, nutrient availability is regulated biologically by decomposition processes. As a result, the rate of decomposition varies widely depending on moisture, temperature, and type of organic matter. The decomposition process is sustained by litter fall (that is, leaf, wood, and other debris that falls to the forest floor). Through the process of decomposition, this material breaks down, releases nutrients, and moves into the soil as soil organic matter. Forest and other wildland soils, unlike agricultural soils where nutrients from external sources are applied as needed, rely on this internal cycling of nutrients to maintain plant growth (Perala and Alban 1982). As a result, nutrient losses from unburned ecosystems are usually low, although some losses can occur by volatilization, erosion, leaching, and denitrification. This pattern of tightly controlled nutrient cycling minimizes the loss of nutrients from these wildland systems in the absence of any major disturbance such as fire.

Fire, however, alters the nutrient cycling processes in wildland systems and dramatically replaces long-term biological decomposition rates with that of instantaneous thermal decomposition that occurs during the combustion of organic fuels (St John and Rundel 1976). The magnitude of these fire-related changes depends largely on fire severity (DeBano and others 1998). For example, high severity fires occurring during slash burning not only volatilize nutrients both in vegetation and from surface organic soil horizons, but heat is transferred into the soil, which further affects natural biological processes such as decomposition and mineralization (fig. 3.12; see also chapter 4). The effects of fire on soil have both short- and long-term consequences (that is, direct and indirect effects) on soil and site productivity because of the changes that occur in both the quantity and quality of organic matter.

In summary, many nutrients essential for plant growth including N, P, S, and some cations described earlier are all affected to some extent by fire. Nitrogen is likely the most limiting nutrient in natural systems (Maars and others 1983), followed by P and S. Cations released by burning may affect soil pH and result in the immobilization of P. The role of micronutrients in ecosystem productivity and their relationship to soil heating during fire is for the most part unclear. One study, however, did show that over half of the selenium in burned laboratory samples was recovered in the ash residue (King and others 1977).

Nutrient Loss Mechanisms

Nutrient losses during and following fire mainly involve chemical processes. The disposition of nutrients contained in plant biomass and soil organic matter during and following a fire generally occurs in one of the following ways:

- *Direct gaseous volatilization into the atmosphere takes place during fire.* Nitrogen can be transformed into N_2 along with other nitrogenous gases (DeBell and Ralston 1970).
- *Particulates are lost in smoke.* Phosphorus and cations are frequently lost into the atmosphere as particulate matter during combustion (Clayton 1976, Raison and others 1985a,b).
- *Nutrients remain in the ash deposited on the soil surface.* These highly available nutrients are vulnerable to postfire leaching into and through the soil, or they can also be lost during wind erosion (Christensen 1973, Grier 1975, Kauffman and others 1993).

Figure 3.12—Pinyon-juniper slash fire, Apache-Sitgreaves National Forest, Arizona. (Photo by Malchus Baker).

- *Substantial losses of nutrients deposited in the surface ash layer can occur during surface runoff and erosion.* These losses are amplified by the creation of a water-repellent layer during the fire (see chapter 2; DeBano and Conrad 1976, and Raison and others 1993).
- *Some of the nutrients remain in a stable condition.* Nutrients can remain onsite as part of the incompletely combusted postfire vegetation and detritus (Boerner 1982).

Although the direct soil heating effect is probably limited to the surface (1 inch or 2.5 cm), the burning effect can be measured to a greater depth due to the leaching or movement of the highly mobile nutrients out of the surface layers. For example, leaching losses from the forest floor of a Southern pine forest understory burn increased from 2.3 times that of unburned litter for monovalent cations Na and K to 10 to 20 times for divalent cations Mg and Ca (Lewis 1974). Raison and others (1990) noted that while K, Na, and Mg are relatively soluble and can leach into and possibly through the soil, Ca is most likely retained on the cation exchange sites. Soil Ca levels may show a response in the surface soils for many years following burning. However, some cations more readily leached and as a result are easily lost from the site. For example, Prevost (1994) found that burning *Kalmia* spp. litter in the greenhouse increased the leaching of Mg but none of the other cations. Although ash and forest floor cations were released due to burning, there was no change in surface soil cation concentrations (0-2 inches or 0-5 cm). Soto and Diaz-Fierros (1993) measured changes in the pattern of cation leaching at differing temperatures for the six soils that represented six different parent materials. Leaching patterns were similar for all soil types. Leaching of divalent cations, Ca, and Mg, increased as the temperatures reached during heating increased, with a peak at 860 °F (460 °C). Monovalent cations, K, and Na, differed in that initially leaching decreased as temperature increased, reaching a minimum at 716 °F (380 °C). Then, leaching increased up to 1,292 °F (700 °C). The nutrients leached from the forest floor and the ash were adsorbed in the mineral soil. Surface soils were found to retain 89 to 98 percent of the nutrients leached from the plant ash (Soto and Diaz-Fierros 1993). As the leachates moved through the mineral soil, the pH of the solution decreased.

Nutrient Availability

The increased nutrient availability following fire results from the addition of ash, forest floor leachates, and soil organic matter oxidation products as the result of fire. The instantaneous combustion of organic matter described earlier directly changes the availability of all nutrients from that of being stored and slowly becoming available during the decomposition of the forest floor organic matter to that of being highly available as an inorganic form present in the ash layer after fire. Both short- and long-term availability of nutrients are affected by fire.

Extractable Ions—Chemical ions generally become more available in the surface soil as a result of fire. Grove and others (1986) found that immediately after fire, extractable nutrients increased in the 0 to 1.2 inch (0-3 cm) depth. Concentrations of S, NH_4, P, K, Na, zinc (Zn), Ca, and Mg increased. Everything except Zn and organic C increased in terms of total nutrients. At the lower depths sampled, 1.2 to 3.9 inches and 3.9 to 7.9 inches (3-10 and 10-20 cm), only extractable P and K were increased by burning. One year later nutrient levels were still greater than preburn concentrations, but had decreased. A study on an area of pine forest burned by a wildfire reported that in the soil, concentrations of P, Ca, and Mg, aluminum (Al), iron (Fe) had increased in response to different levels of fire severity (Groeschl and others 1993). In the areas exposed to a high-severity fire, C and N were significantly lower and soil pH was greater. In another study the soil and plant composition changes were studied in a jack pine (*P. banksiana*) stand whose understory had been burned 10 years earlier (Lynham and others 1998). In this study the soil pH increased in all soil layers following burn—O horizon, 0-2 inches (0-5 cm), and 2-3.9 inches (5-10 cm)—and remained 0.5 units greater than preburn 10 years later in the O horizon. Phosphorus, K, Ca, and Mg all increased in the mineral soil; P and K were still greater than preburn levels 10 years later. A stand replacement fire in the Southern Appalachians that resulted in a mosaic burn pattern affected exchangeable ions (Vose and others 1999). The midslope areas of this fire burned at a moderate severity, and a decrease in exchangeable K and Mg along with an increase in soil pH was measured. Soil Ca, total C and N did not respond in any of the burned areas. There are other studies that have also shown no effect or decreases of soil nutrients following burning (Sands 1983, Carreira and Niell 1992, Vose and others 1999).

Nitrogen—The two most abundant forms of available N in the soil are available NH_4- and $N0_3$-N. Both forms are affected by fire. Burning rapidly oxidizes the soil organic matter and volatilizes the organic N contained in the forest floor and soil organic matter, thereby releasing NH_4-N (Christensen 1973, Jurgensen and others 1981, Kovacic and others 1986, Kutiel and Naveh 1987, Marion and others 1991, Knoepp and Swank 1993a,b). The release of NH_4-N has been found by more detailed chemical analysis to involve the thermal decomposition of proteins and other nitrogen-rich organic matter. Specifically, the production of

NH_4-N is related to the decomposition of secondary amide groups and amino acids. These secondary amide groups are particularly sensitive to decomposition during heating and decompose when heated above 212 °F (100 °C) to yield NH_4-N (Russell and others 1974). The volatilization of more heat-resistant N compounds can occur up to 752 °F (400 °C). The temperatures required to volatilize nitrogen compounds are increased by the presence of clay particles in the soil (Juste and Dureau 1967).

Most NH_4-N that is volatilized is lost into the atmosphere, but significant amounts can move downward and condense in the mineral soil as exchange N. The ash produced by the fire can also contain substantial amounts of NH_4-N. As a result of these two processes, the inorganic N in the soil increases during fire (Kovacic and others 1986, Raison and others 1990, Knoepp and Swank 1993a,b). In contrast, $N0_3$-N is usually low immediately following fire and increases rapidly during the nitrification of NH_4 (see chapter 4). These $N0_3$-N concentrations may remain elevated for several years following fire (fig. 3.13).

The production of $N0_3$-and NH_4-N by fire depends on several factors. These include fire severity, forest type, and the use of fire in combination with other postharvesting activities.

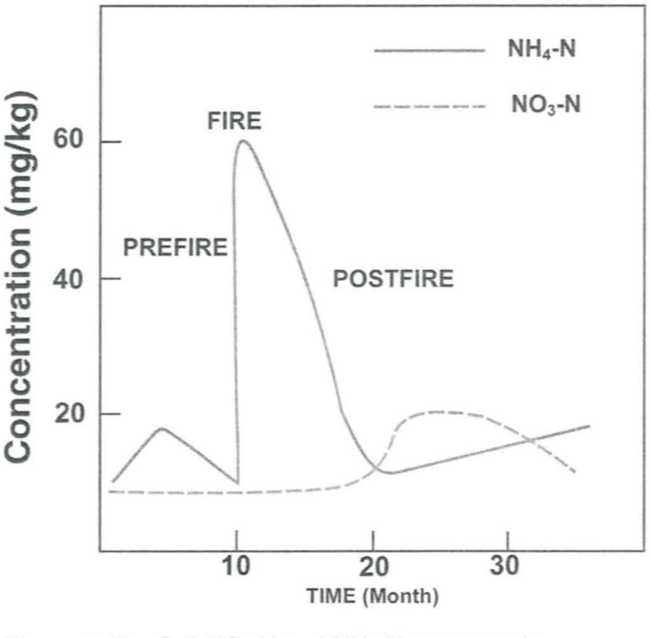

Figure 3.13—Soil NO_3-N and NH_4-N concentrations before, immediately following, and for several months following fire in Arizona chaparral. (Adapted from DeBano and others 1998. Fire's Effects on Ecosystems. Copyright © 1998 John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.).

Effect of fire severity: The amounts of NH_4-N that are produced as a result of fire generally increase with the severity and duration of the fire and the associated soil heating (fig. 3.13, 3.14, 3.15). Although large amounts of the total N in the aboveground fuels, litter, duff, and upper soil layers are lost into the atmosphere by volatilization, highly available NH_4-N still remains in the ash or in the upper mineral soil layers following fire (fig. 3.13). During both high and low severity fires, increase occurs in the amounts of NH_4-N that can be found both in the ash remaining on the soil surface following fire and in the upper mineral soil layers (Groeschl and others 1990, Covington and Sackett 1992). The

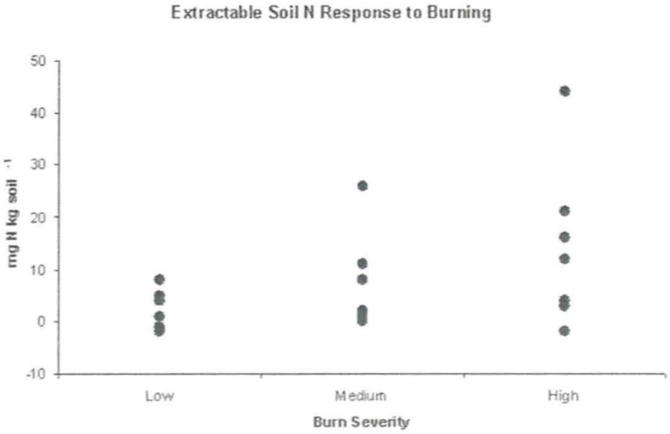

Figure 3.14—Extractable soil N in response to burn severity measured on eight studies.

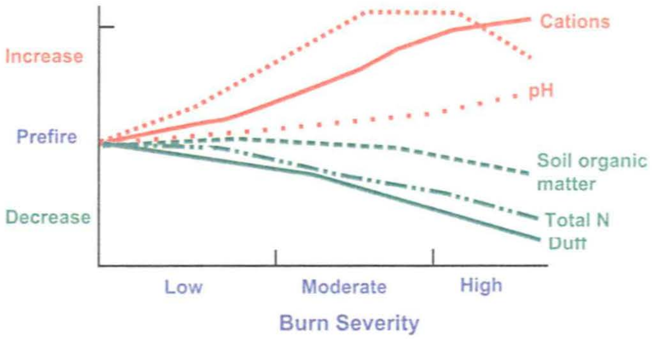

Figure 3.15—Generalized patterns of decreases in the forest floor (duff), total N, and organic matter, and increases in soil pH, cations, and NH_4 associated with increasing levels of fire severity. (Figure courtesy of the USDA Forest Service, National Advanced Fire and Resource Institute, Tucson, AZ).

concentrations of NH_4-N found in the ash depend on the severity of the fire and amount of forest floor consumed, which in turn reflects stand age. During low severity fires, less of the forest floor is consumed and correspondingly less amounts of NH_4-N are produced (fig. 3.15). The amounts of NH_4-N produced during a fire may vary from increases of less than 10 ppm (10mg/kg) during low severity fires to 16 and 43 ppm (16 mg/kg and 43 mg/kg) during medium and high severity fires, respectively. The variability in the amounts of NH_4-N produced also increases with fire severity. The NH_4-N concentrations following burning are short lived (fig. 3.13), although Covington and Sackett (1992) reported that NH_4-N levels remained elevated for at least 1 year following a prescribed burn in ponderosa pine stands in northern Arizona.

The direct effects of fire on $N0_3$-N concentrations are less predictable. For example, the results of a study in the Shenandoah National Park showed that although total extractable inorganic N was elevated for 1 year following the fire, the $N0_3$-N on areas burned by either high or low severity fires increased only slightly (Groeschl and others 1990). A more common scenario for $N0_3$-N changes following fire results from the increased nitrification of the highly available N produced directly during the fire (for example, NH_4-N). The end result being that NH_4-N produced directly during fire is rapidly nitrified, and $N0_3$-N begins to increase following fire, depending on temperature and moisture conditions (fig. 3.13)

The effects of these increased levels of highly available N during and following fire are often beneficial to the recovering plants by providing a temporary increase in site fertility. However, these short-term benefits must be carefully weighed against the overall and long-term effect that the loss of total N during a fire has on the sustained productivity of the site (see the previous discussion on Nitrogen Losses –An Enigma).

Effect of forest type: Forest type can also affect the amount of NH_4-N produced by fire. This occurs mainly as a result of nature of the fire behavior and the amounts of litter that accumulate under different forest types. Such was the case in a study conducted in Idaho on pine/hemlock sites compared to sites occupied by a Douglas-fir/western larch forest (Mroz and others 1980). In this study the NH_4-N did not increase following burning of the pine/hemlock forest in contrast to the Douglas-fir/western larch forest site where it did increase. Within 3 to 7 days, however, mineralization and/or nitrification had begun on most sites.

Frequency of burning: Repeated burning and its frequency are often-asked questions by fire managers when conducting prescribed burns. In terms of N availability, the effects of burning frequency depends largely upon the ecosystem, its inherent fertility (in terms of total and available N), total amounts of organic matter destroyed, and its ability to replenish the N lost by volatilization (DeBano and others 1998).

Several studies have focused on the effect of different frequencies of prescribed burning on changes in total and concentrations of total and available nitrogen. For example, a study on the effect of repeated burn low-intensity burning in Australian eucalypt forests (*Eucalyptus* spp.)showed that fire-free periods of about 10 or more years were required to allow natural processes time to replace the amount of N lost during the burning, assuming that about 50 percent of the total N in the fuel was volatilized (Raison and others 1993). In contrast, a study of repeated burning at 1-, 2-, and 5-year intervals in ponderosa pine forests in northern Arizona showed no significant differences in total N among the different burning frequencies, but available N (NH_4- and $N0_3$-N) was higher on the sites that repeatedly burned in comparison to the unburned controls (Covington and Sackett 1986). Researchers concluded from this Arizona study that frequent periodic burning can be used to enhance N availability in Southwestern ponderosa pine forests.

Studies on the effects of burning frequency on grasslands and shrubs have been reported to have less desirable outcomes. For example, the annual burning of tall grass prairies in the Great Plains of the Central United States resulted in greater inputs of lower quality plant residues, causing a significant reduction in soil organic N, lower microbial biomass, lower N availability, and higher C:N rations in soil organic matter (Ojima and others 1994). Likewise, increases in available N may have adverse effects on some nutrient-deficient shrub ecosystems as has been reported by a study in a shrubland (fynbos) in South Africa. In a study of lowland fynbos, a twofold increase in soil nutrient concentrations produced by fire were detrimental to the survival of indigenous species that had evolved on these nutrient-impoverished landscapes (Musil and Midgley 1990).

Phosphorus—Responses of available soil P to burning are variable and more difficult to predict than those of other nutrients (Raison and others 1990). Phosphorus volatilizes at temperatures of about 1,418 °F (770 °C). The fate of this volatilized P is not well understood. One study indicated that the only response was on the surface soil, and P did not appear to move downward in the soil via volatilization and condensation, as N does (DeBano 1991). Grove and others (1986) found the opposite. They measured responses in all major cations, S, $NH_{4,}$ and Zn following burning in the surface 0 to 1.2 inches (0-3 cm) of soil. In their study, only P and K concentrations also responded in the lower soil depths (1.2-3.9 inches and 3.9-7.9 inches; 3-10 cm and 10-20 cm).

As in the case of N, fire severity affects changes in extractable P. During high-severity fires, 50 to 60 percent of the total fuel P might be lost to volatilization (Raison and others 1990, DeBano 1991). Part of this volatilized P ends up as increased available P in both the soil and ash following burning. An extensive study of P responses to different burning severities was reported for eucalypt forests (Romanya and others 1994). The study sites included unburned, burned, and in an ash bed found under a burned slash pile. The greatest effects occurred in the surface soil (0-1 inch; 0-2.5 cm), and the response was dependent on fire severity. Extractable P concentrations increased with increasing fire severity, but the response decreased with depth. Organic P on the other hand reacted oppositely; concentrations were lower in the intensively burned areas and greater in the unburned and low-severity burned sites.

Fire affects the enzymatic activity and mineralization of P. One study compared these P responses in a controlled burn versus a wildfire (Saa and others 1993). When temperatures reached in the forest floor of the controlled burn were less than 329 °F (50 °C), extractable P concentrations (ortho-phosphate) showed no significant response. In contrast, a wildfire that produced higher soil temperatures reduced phosphatase activity and increased the mineralization of organic P, which increased ortho-phosphate P and decreased organic P. Laboratory experiments showed that phosphatase activity can be significantly reduced when heating dry soils but was absent in wet soils (DeBano and Klopatek 1988). In the pinyon-juniper soils being studied, bicarbonate extractable P was increased although the increases were short lived.

Ash-Bed Effect

Following fire, variable amounts of ash are left remaining on the soil surface until the ash is either blown away or is leached into the soil by precipitation (fig. 1.4). On severely burned sites, large layers of ash can be present (up to several centimeters thick). These thick accumulations of ash are conspicuously present after piling and burning (for example, burning slash piles). Ash deposits are usually greatest after the burning of concentrated fuels (piled slash and windrows) and least following low-severity fires.

The accumulation of thick layers of ashy residue remaining on the soil surface after a fire is referred to as the "ash bed effect" (Hatch 1960, Pryor 1963, Humphreys and Lambert 1965, Renbuss and others 1972). The severe burning conditions necessary to create these thick beds of ash affect most of the physical, chemical, and biological soil properties. Soil changes associated with ash beds can occur as a result of a fire itself (soil heating), the residual effect of the ash deposited on the soil surface (that is, the ash bed), or a combination of both (Raison 1979).

The amount and type of ash remaining after fire depend upon the characteristics of the fuels that are combusted, such as fuel densities (packing ratios), fuel moisture content, total amount of the fuel load consumed, and severity of the fire (Gillon and others 1995). As a result of the fire, the ash remaining after a fire can range from small amounts of charred dark-colored fuel residues to thick layers of white ash that are several centimeters thick (DeBano and others 1998). When densely packed fuels are completely combusted, large amounts of residual white ash are usually in one place on the soil surface following burning (such as after piling and burning slash). The severe heating during the fire will change the color of the soil mineral particles to a reddish color, and where extreme soil heating has occurred, the mineral soil particles may be physically fused together. Silicon melts at temperatures of 2,577 °F (1,414 °C; see chapter 2).

Chemically, fire consumption of aboveground material determines the amount of ash produced. Ash consists mostly of carbonates and oxides of metals and silica along with small amounts of P, S, and N (Raison and others 1990). Calcium is usually the dominant cation found in these ash accumulations. Most of the cations are leached into the soil where they are retained on the cation exchange sites located on clay or humus particles and increase the mineral soil cation content (fig. 3.15). The pH may exceed 12. However, the composition of the preburn material and the temperature or severity of the fire determines the chemical properties of ash. Johnston and Elliott (1998) found that ash on uncut forest plots generally had the highest pH and the lowest P concentrations.

Physical changes associated with the ash bed effect mainly include changes in soil structure and permeability to water. The combustion of organic matter in the upper part of the soil profile can totally destroy soil structure, and the ashy material produced often seals the soil to water entry.

The biological impact of the ash bed effect is twofold. During the fire the severe soil heating can directly affect the long-term functioning of microbial populations because the high temperature essentially sterilizes the upper part of the soil. Plant roots and seeds are also destroyed so that the revegetation of these sites depends on long-term ecological succession to return to its former vegetative cover. Indirectly, the large amounts of ash can affect soil microbial populations. A study of the effects of ash, soil heating, and the ash-heat interaction on soil respiration in two Australian soils showed that large amounts of ash slightly decreased respiration, but small amounts had no effect (Raison and McGarity 1980). Additions of ash to sterilized soil produced no effect, indicating that ash acted via its influence on active soil biological populations. The chemical nature of ash was hypothesized to affect soil respiration by its effect on:

- Increasing pH.
- Changing the solubility of organic matter and associated minerals in water.
- Adding available nutrients for microbial populations.

Management Implications

Understanding the effects of fire on soil chemical properties is important when managing fire on all ecosystems, and particularly in fire-dependent systems. Fire and associated soil heating combusts organic matter and releases an abundant supply of highly soluble and available nutrients. The amount of change in the soil chemical properties is proportional to the amount of the organic matter combusted on the soil surface and in the underlying mineral soil. Not only are nutrients released from organic matter during combustion, but there can also be a corresponding loss of the cation exchange capacity of the organic humus materials. The loss of cation exchange capacity of the humus may be an important factor when burning over coarse-textured sandy soils because only a small exchange capacity of the remaining mineral particles is available to capture the highly mobile cations released during the fire. Excessive leaching and loss can thus result, which may be detrimental to maintaining site fertility on nutrient-limiting sandy soil.

An important chemical function of organic matter is its role in the cycling of nutrients, especially N. Nitrogen is most limiting in wildland ecosystems, and its losses by volatilization need to be evaluated before conducting prescribed burning programs. Nitrogen deficiencies often limit growth in some forest ecosystems. Xeric and pine dominated sites, which are typically prone to burning, often exhibit low N availability, with low inorganic N concentrations and low rates of potential mineralization measured on these sites (White 1996, Knoepp and Swank 1998). Forest disturbance, through natural or human-caused means, frequently results in an increase of both soil inorganic N concentrations and rates of potential N mineralization and nitrification. The N increases resulting from a combination of changes in soil moisture and temperature and the decreased plant uptake of N make more N available for sustaining microbial populations in the soil.

Historically, some wildland ecosystems have been exposed to frequent fire intervals. Many of these ecosystems are low in available N and other nutrients such as P and cations. The cycling of nutrients, especially N, may be slow, and the exclusion of fire from these systems often results in low N mineralization and nitrification rates. Frequent fire, however, can accelerate these biological rates of N mineralization because it destroys the inhibiting substances that hinder these processes. For example, in ponderosa pine forests in the Southwest, monoterpenes have been found to inhibit nitrification (White 1991). These monoterpenes are highly flammable and as a result are combusted during a fire. As a result, the removal of this inhibition by fire allows N mineralization and nitrification to proceed. It is hypothesized that these inhibitory compounds build up over time after a fire and decrease N mineralization. Significant differences in monoterpenes concentrations have been established between early and late successional stages, although specific changes over time have not been detectable because of the large variability between sites (White 1996).

Another study has shown that the xeric pine-hardwood sites in the Southern Appalachians are disappearing because of past land use, drought, insects, and the lack of regeneration by the fire-dependent pine species (Vose 2000). This information was used to develop an ecological model that could be used as a forest management tool to rejuvenate these *Pinus rigida* stands (fig. 3.16). This model specifies that a cycle of disturbance due to drought and insect

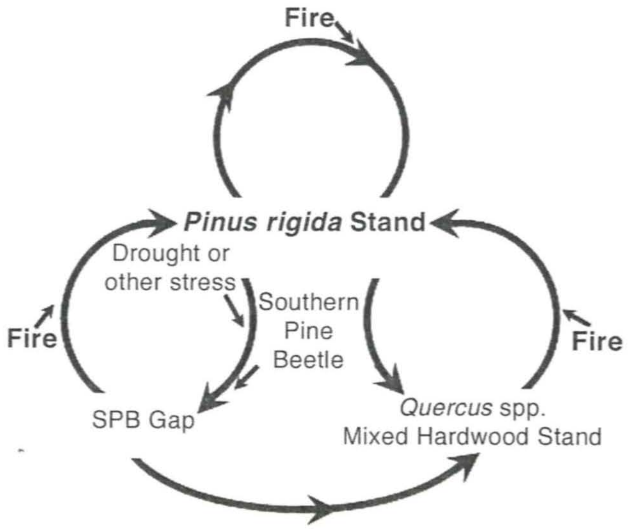

Figure 3.16—Effect of fire on nutrient cycling processes in *Pinus ridgida* stands. (Adapted from Vose 2000).

outbreaks followed by fire is necessary to maintain the pine component of these ecosystems. Without fire, mixed hardwood vegetation dominates the stand. Therefore, prescribed burning is proving to be an effective tool for enhancing ecosystem health and for sustaining, preserving, and restoring these unique habitats.

Fire severity is probably the one most important feature of a fire that affects the chemical soil properties. Generalized relationships for several soil properties at different severities are presented in figure 3.15. Nitrogen, organic matter, and duff decrease as fire severity increases. Available NH_4-N and cations increase. The pH of the soil generally increases because of the loss of organic matter and its associated organic acids, which are replaced with an abundance of basic cations in the ash.

Summary

The most basic soil chemical property affected by soil heating during fires is organic matter. Organic matter not only plays a key role in the chemistry of the soil, but it also affects the physical properties (see chapter 2) and the biological properties (see chapter 4) of soils as well. Soil organic matter plays a key role in nutrient cycling, cation exchange, and water retention in soils. When organic matter is combusted, the stored nutrients are either volatilized or are changed into highly available forms that can be taken up readily by microbial organisms and vegetation. Those available nutrients not immobilized are easily lost by leaching or surface runoff and erosion. Nitrogen is the most important nutrient affected by fire, and it is easily volatilized and lost from the site at relatively low temperatures. The amount of change in organic matter and N is directly related to the magnitude of soil heating and the severity of the fire. High- and moderate-severity fires cause the greatest losses. Nitrogen loss by volatilization during fires is of particular concern on low-fertility sites because N can only be replaced by N-fixing organisms. Cations are not easily volatilized and usually remain on the site in a highly available form. An abundance of cations can be found in the thick ash layers (or ash-bed) remaining on the soil surface following high-severity fires.

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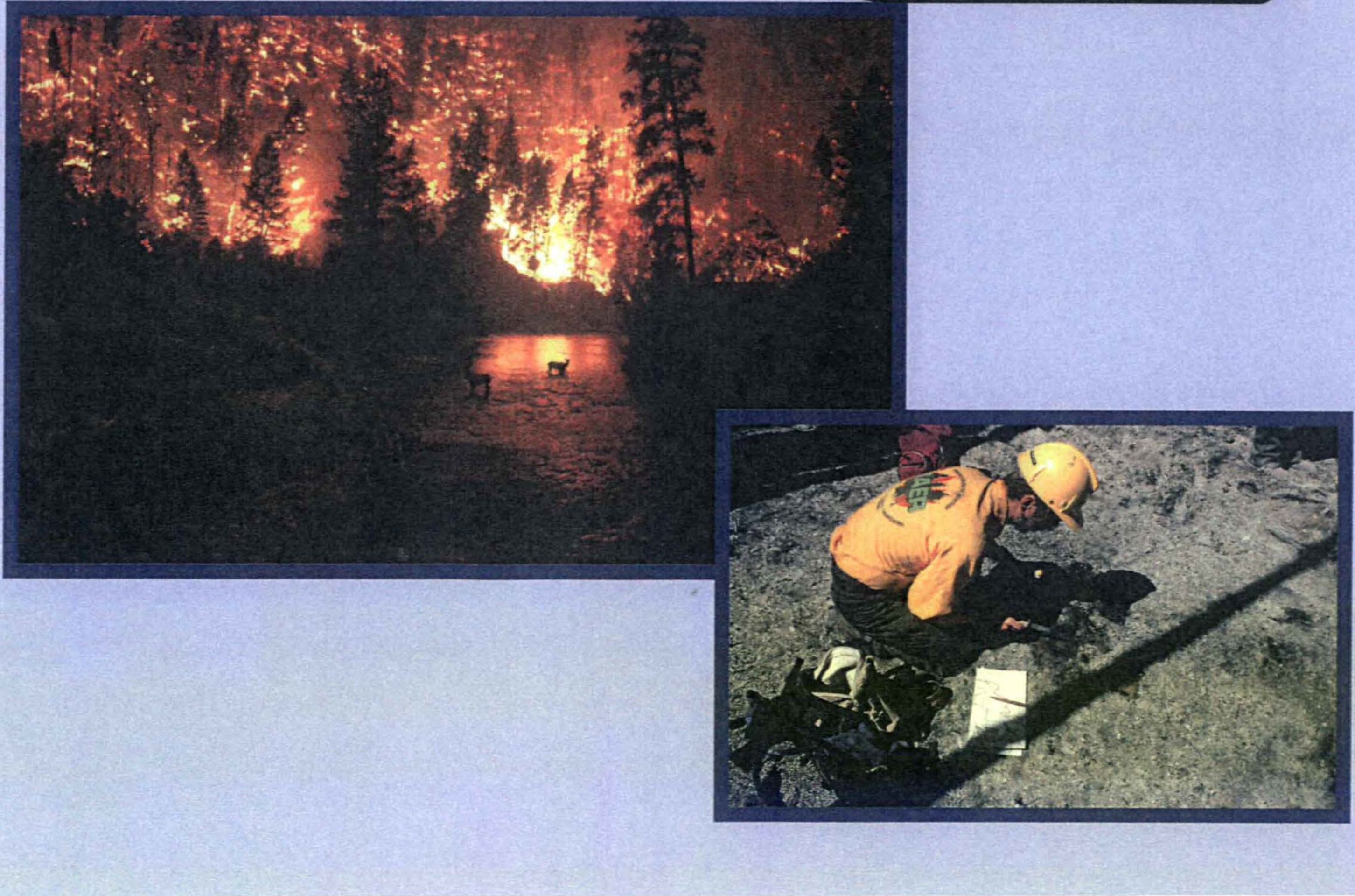
Wildland Fire in Ecosystems

Effects of Fire on Soil and Water



Abstract

Neary, Daniel G.; Ryan, Kevin C.; DeBano, Leonard F., eds. 2005. **Wildland fire in ecosystems: effects of fire on soils and water**. Gen. Tech. Rep. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

This state-of-knowledge review about the effects of fire on soils and water can assist land and fire managers with information on the physical, chemical, and biological effects of fire needed to successfully conduct ecosystem management, and effectively inform others about the role and impacts of wildland fire. Chapter topics include the soil resource, soil physical properties and fire, soil chemistry effects, soil biology responses, the hydrologic cycle and water resources, water quality, aquatic biology, fire effects on wetland and riparian systems, fire effects models, and watershed rehabilitation.

Keywords: ecosystem, fire effects, fire regime, fire severity, soil, water, watersheds, rehabilitation, soil properties, hydrology, hydrologic cycle, soil chemistry, soil biology, fire effects models

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Cover photo—Left photo: Wildfire encroaching on a riparian area, Montana, 2002. (Photo courtesy of the Bureau of Land Management, National Interagency Fire Center, Image Portal); Right photo: BAER team member, Norm Ambos, Tonto National Forest, testing for water repellancy, Coon Creek Fire 2002, Sierra Ancha Experimental Forest, Arizona.

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