2 Soil

Along with changes in the characteristics of ground vegetation, soil impacts are the most frequently mentioned of all the effects of outdoor recreation activities. An understanding of ecological impacts presupposes that the reader has had exposure to soil science concepts and terminology. A brief overview of soil characteristics and properties is given and must be understood to appreciate the major impacts of outdoor recreation on soils. Foremost among these characteristics are soil texture, structure, pore space, bulk density, and profile development. For additional information on soils, the following references are suggested: Wilde (1958), Foth (1978), and Brady (1990).

BASIC SOIL ECOLOGY

What Is Soil?

Soil, the basis of all terrestrial life, is commonly misunderstood. Much more than just inert dirt, soil is alive—produced and maintained by interactions between living organisms, rock, air, water, and sunlight (Dasmann 1972). Soils consist of four major components. Minerals and organic matter, both dead and alive, make up the solid portion; the soil solution, water and dissolved substances, and air occupy the pore spaces between solids. Although all of these components are present in all soils, usually so intimately mixed that separation is rather difficult, their relative abundance and distribution vary greatly. These differences affect both the soil's capacity as a medium for supporting life and its response to recreational use.

Soil Texture and Structure

The mineral fraction of soils has been divided into classes based on the size of particles. *Sand* particles are 2.0 to 0.02 mm in diameter, *silt* particles are between 0.02 and 0.002 mm, and *clay* particles are less than 0.002 mm. Particles larger than sand are called coarse fragments. *Texture* describes the proportion of these various particle sizes in a soil. A sandy soil contains a large proportion (at least 70 percent) of the relatively large sand particles; a clay soil contains at least 35 to 40 percent submicroscopic clay particles. Soils with about equal proportions of sand, clay, and silt particles are called loams. Many intermediate classes have also been defined (e.g., silty clay loam).

Sandy soils are *coarse* textured. The relatively large particles do not pack together tightly; consequently, pore spaces are large. Except when soils have recently been wetted, water occupies only small (*capillary*) pores, where it is held by absorption to the soil particles; air occupies the larger pores. Consequently, sandy soils hold more air and less water than soils with smaller pores (Fig. 1). Such soils drain readily and are apt to be excessively dry.

Clay and silt soils are *fine* textured. They hold more water but less air than sand soils. Clay soils can remain waterlogged for long periods of time, providing poor aeration for plant growth. Moreover, despite large quantities of water, much water is held so tightly by the soil particles that it may be unavailable for use by plants. Soils containing equal amounts of sand, silt, and clay such as loam and silt loam soils generally have the best balance of water availability, drainage, and aeration.

Structure refers to how the individual soil particles of different sizes combine into aggregates. Clay particles and organic matter, in particular, promote the aggregation of many individual soil particles into clumps of various shapes and sizes. Thus, a fine textured soil may appear coarse and may function in many ways as a coarse soil, because the fine particles coalesce into large granules with large pores between them (Spurr and Barnes 1980). Soil structure is particularly important in fine-textured soils where aeration can be a problem. Large pores around aggregates provide good water movement and aeration despite relatively small pores around individual particles. Organic matter can improve the structure in soils of various textures. In coarse-textured soils, organic matter can improve the water-holding capacity of the soil because of its capacity to absorb and hold water.

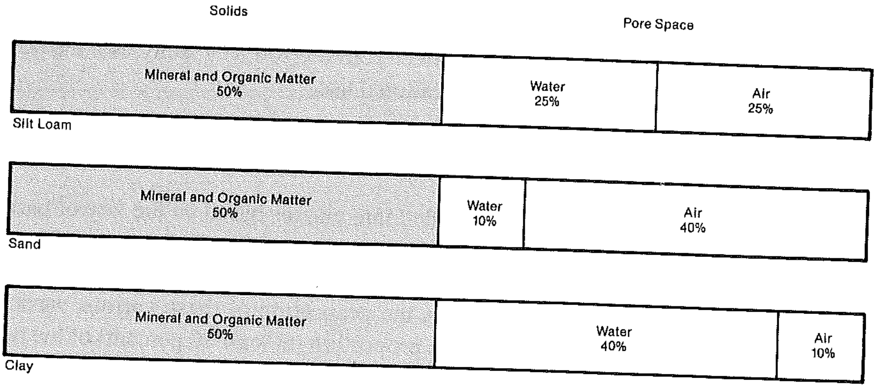

FIGURE 1. Difference in the relative proportion of solid particles, water, and air in representative silt loam, sand, and clay soils.

Favorable soil structure developed under forest conditions may be destroyed by removing the forest vegetation and exposing the soil surface directly to rainfall. The direct impact of rainfall can detach soil particles from aggregates. The detached particles clog spaces between aggregates, forming a crust that is relatively impervious to water. Less water entering the soil means that more is running across the surface, and this increases erosion. The effects of recreational trampling on soil structure can be even more profound. Destruction of leaf litter by trampling eliminates the possibility of its incorporation into the surface soil horizon, decreasing the amount of organic matter that is so important to promoting good soil structure. More will be said about this and the serious effects of soil compaction later.

Pore Space

As was previously mentioned, the pore space is determined largely by the texture and structure of soils. Soils with a large proportion of large particles, such as sands, or with a compacted structure in which particles lie close together have a low *total porosity*. Soils that are medium-textured, high in organic matter, and uncompacted have a high total porosity. Soil pores have been divided into two size classes—*macro* and *micro*. The larger macropores allow the ready movement of air and percolating water, but they retain little water. In contrast, water is retained in micropores, but air and water movement is impeded. Sandy soils have low total porosity, but a large proportion of that porosity consists of macropores. Consequently, the movement of air and water is rapid (Brady 1990).

Despite a large total pore space, movement of air and water in fine-textured soils is relatively slow. Porosity is dominated by micropores, which are often full of water, leaving little pore space for air. In addition, the water occupying the capillary micropores is held tightly to clay particles by tension forces, contributing to the slow movement of water. The significant point here is that the size of individual pore spaces (macro or micro) is more important to the movement of air and water than total pore space.

Bulk Density

Bulk density is a soil weight measurement, defined as the mass (weight) of a unit volume of soil. It is determined primarily by the quantity of pore space within a given volume of soil. Thus, it is closely related to porosity. It is affected by the compactness of the soil and by the soil's composition, particularly its texture, structure, and organic matter content. Soils that are loose and porous will have low weights per unit volume (bulk densities), and those that are compact will have high values. Soils high in fine-textured material and organic matter will have lower bulk densities than soils high in sand and low in organic matter. The bulk densities of clay, clay loam, and silt loam surface soils normally range from 1.00 to as high as 1.60 g/cm^3 whereas sands and sandy loams vary from 1.20 to 1.80 g/cm^3 (Brady 1990). These differences, present under undisturbed conditions, should be kept in mind when using bulk density as a measure of compaction.

Variation in the relationships between soil texture, compaction, and bulk density is illustrated in Fig. 2. The increase in bulk density with compaction is more pronounced in fine-textured soils. Uncompacted, fine-textured soils have low bulk densities because the soil particles can be packed together more tightly than large particles. Consequently, fine-textured soils can be compacted to a greater density than coarse-textured soils.

Moreover, bulk density tends to increase with profile depth. This apparently results from a lower content of organic matter, less aggregation and root penetration, and compaction caused by pressure from the weight of overlying horizons. Compact subsoils may have bulk densities greater than 2.0 g/cm^3 (Brady 1990). Bulk density also increases in campsites as one moves from the periphery to the intermediate and the core zones of sites (Stohlgren and Parsons 1986).

Although bulk density is the common measure of compaction in soil sciences, soil penetration resistance is commonly used in recreation field studies. Soil penetration resistance refers to the force necessary to drive a rod of known length into the ground, recorded on an instrument called a penetrometer. Campsite penetrometer readings in wilderness areas have ranged from 70 to 300 percent.

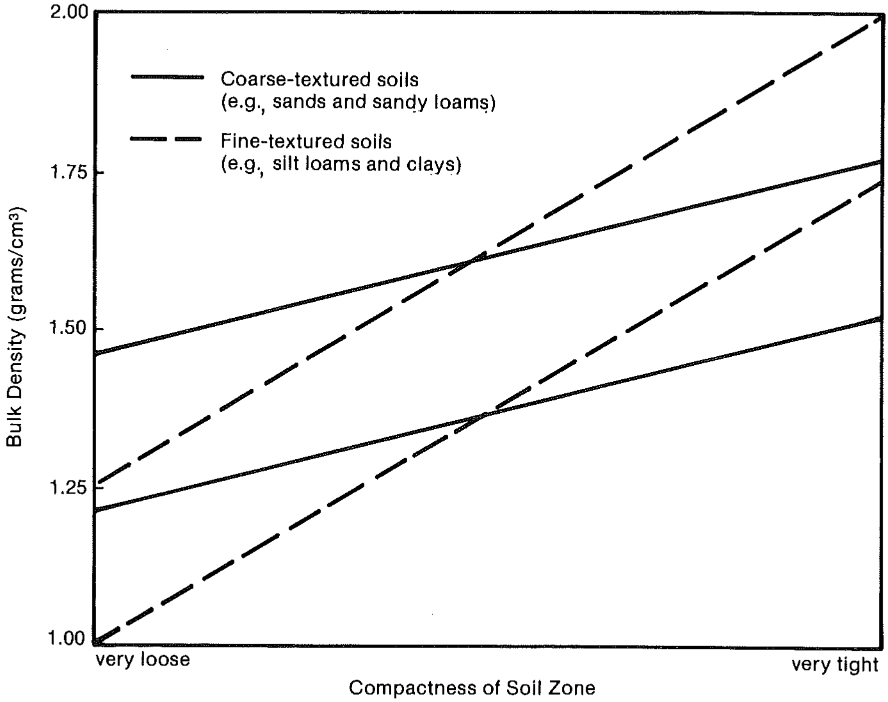

FIGURE 2. Generalized relationship between compactness and the range of bulk densities common in sandy soils and in those of finer texture. (*Source*: Brady 1990.)

The Soil Profile

Soils are not uniform in texture and structure for a given depth. Examination of a vertical section of soil shows the presence of more or less distinct horizontal layers, differing in color, composition, and other properties. Such a section is called a *soil profile*. A typical soil profile will consist of four primary horizontal layers or *horizons* (Fig. 3). These primary horizons, the O, A, B, and C horizons, are subdivided further and may or may not be present in any given soil.

The O, or organic horizon is formed above the mineral soil and often consists of both an O^1 and an O^2 horizon. The O^1 horizon consists of litter—recognizable leaves, twigs, fruits, and dead plants and animals. When this litter decomposes to an unrecognizable state, it is called humus, the primary component of the O^2 horizon. Surface organic horizons are extremely important to healthy soils. They cushion the impact of rainfall and other erosional agents, including recreational use, on

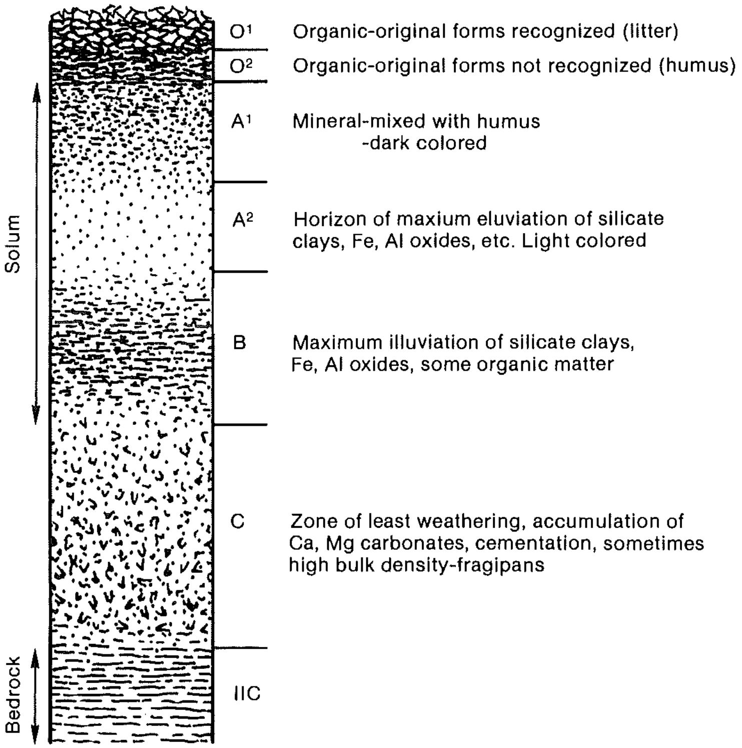

FIGURE 3. A conceptual mineral soil profile showing the four major horizons that may be present. (*Source*: Adapted from Buckman and Brady, 1969. Reprinted with permission of Macmillan Publishing Co., Inc. From *The Nature and Properties of Soils*, 7th Edition, by H. O. Buckman and N. C. Brady. Copyright© 1960, 1969 by Macmillan Publishing Co., Inc.)

underlying mineral horizons. They are important zones of biotic activity and help in the absorption of water. As a source of humus that can move downward into the soil, the organic horizons contribute to the maintenance of healthy soil structure, water relations, and aeration. They are also an important source of nutrients, critical to the maintenance of soil fertility. Unfortunately, the O horizon is often pulverized and removed by recreational utilization of sites receiving concentrated use.

The A horizon is the uppermost layer of mineral soil. It is characterized in moist climates by the leaching of nutrients by downward-moving water and acid solutions. It is subdivided into an upper A^1 horizon, in which organic matter is constantly being added to mineral soil through litter decomposition and mixing by soil organisms, and a lower A^2 horizon, a zone of leaching. Biotic activity is most concentrated in the A^1 horizon.

Below the A is the B horizon, characterized in moist temperature climates by the accumulation of iron and aluminum oxides and minute clay and organic particles, all derived from leaching of the A horizon above. In more arid regions, it is characterized by accumulation of soluble salts such as calcium carbonate. As a result, the B horizon is usually finer-textured and darker-colored than either the A horizon or the original parent material, except in arid regions where accumulated salts are light-colored.

The C horizon is below the zone of accumulation. It has been little affected by biotic activity and consists primarily of disintegrated parent material, similar to that from which the A and B horizons were derived.

IMPACTS ON SOILS

The major impact to soils in wildland recreation areas results from trampling. Trampling and vehicle use cause soil compaction, increased soil density and penetration resistance, changes in soil structure and stability, losses in litter and humus layers, reduced infiltration rates, greater runoff, and increased erosion (Cole and Schreiner 1981; Marion and Cole 1996). In addition to changes in the physical properties of soils, trampling may lead to changes in soil biology and chemistry. Altered macro- and microhabitats in soil and litter result in major changes in the species composition of soil microflora and fauna (Duffey 1975).

The direct weight loads to the ground surface imposed by hikers, backpackers, packstock, and off-road vehicles impose stresses of considerable magnitude on the ground flora and soils of recreational areas (Kuss, Graefe, and Vaske 1990). Data indicate that an adult hiker population made up of an equal number of men and women averaging 150 lb (67.5 kg) in weight with boots and clothing (9.9 lb, 4.5 kg) would exert a ground pressure of 11.7 lb/in.^{2} (0.82 kg/cm^2) of bearing surface when standing at full weight on one foot, as occurs during each step taken (Holmes and Dobson 1976). This translates to roughly 132–180 tons per hiker mile, depending on the stride of the individual. By comparison, Lull (1959) reported that horses may exert pressures as high as 40 lb/in.^{2} (2.77 kg/cm^2).

Manning (1979) provides a useful conceptualization of recreational trampling impact on soils as a seven-step cycle (Fig. 4). Where present, the first step in the cycle is a reduction or removal of the leaf litter and humus layers—the O horizon. Trampling, surface runoff, and, in some places, raking of the site for aesthetic or fire safety reasons contribute to loss of this litter cover. The second step, a reduction in organic matter incorporated into the mineral soil, occurs in some places but not in others. Removal of surface litter cuts off much of the source of organic matter so that in time, as existing soil organic matter decomposes, soil organic matter should decline. Indeed, this does occur in some places. In others, however, some of the pulverized surface organic matter is transported down into the soil by percolating waters, where it accumulates in dark bands (Monti and Mackintosh 1979). In these cases soil organic matter actually increases in response to recreational use.

Regardless of what happens in the first two steps, the third step—compaction—always occurs. Susceptibility to compaction of soil by the pressures of trampling or vehicular travel is increased by loss of organic matter, both at the surface and in the soil, but it will occur in any case. Through compaction, soil particles are forced to pack together more tightly, eliminating much of the interstitial pore space. Soil struc-

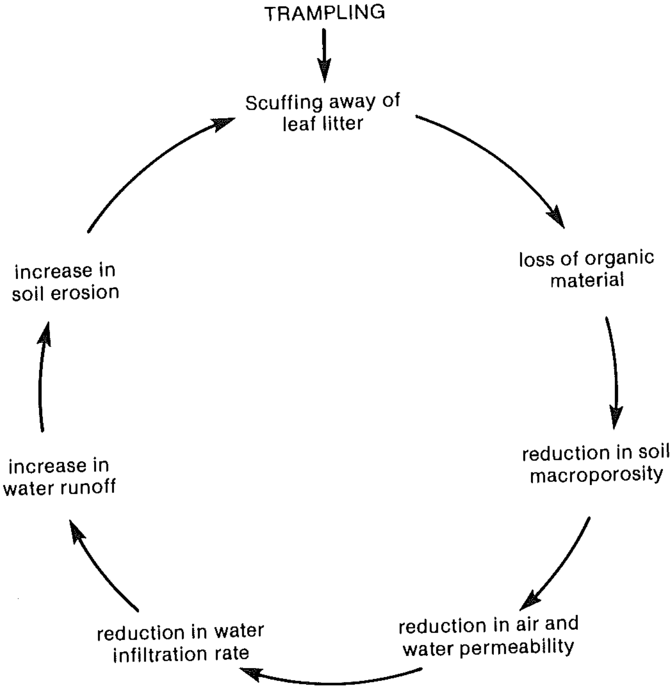

FIGURE 4. Soil impact cycle resulting from human trampling. (*Source*: "Impacts of Recreation on Riparian Soils and Vegetation," by R. E. Manning (1979) in *Water Resources Bulletin* 15(1):30–43. Reprinted with permission of the American Water Resources Association.)

ture is also disrupted as aggregates are broken up and forced together. The result is a reduction in total porosity and macroporosity; the volume of micropores is not greatly affected.

This reduction in macroporosity initiates a chain of events that carries through the sixth step of the cycle, with profound implications for "health" of soils. Because macropores are the primary conduits for the free movement of air and water, their reduction seriously impedes soil aeration and the percolation of water into the soil. Because less water can move through the soil, less can enter the soil, and water infiltration rates are reduced. This can lead to reductions in soil moisture and resulting water stress on plants, although this impact is pronounced only in certain places at certain times. A more universal impact is increased surface runoff, the inevitable result of rainfall on soils with low infiltration rates. This greatly increases the potential for erosion, step seven, particularly if slopes are steep and soils are erosive. Severe erosion truncates soil profiles, and it exacerbates soil impacts by washing away even more surface organic matter, hence the view of the impact process as a never-ending cycle. Let's now take a look at how serious these impacts are in various recreational situations.

Organic Matter

The magnitude of organic matter loss varies with amount of use, the recreational activity involved, and environmental conditions. In desert areas, for example, where organic horizons are very thin and patchy, if present at all, any use of any kind rapidly eliminates organic matter. As the organic matter is so sparse to start with, such losses represent a severe impact. In forested environments, effects vary between deciduous and evergreen forests. Deciduous forests accumulate much more leafy litter in the fall after the main use season. This can promote more rapid overwinter recovery. Litter loss is particularly pronounced and rapid on paths and trails. Trampling is highly concentrated, and the frequency of steep slopes and water channelization contribute to surface erosion of litter from much of the trail surface. On a newly opened nature trail in England, the passage of 8000 people reduced the volume of forest leaf litter by 50 percent in just one week (Burden and Randerson 1972).

Legg and Schneider (1977) found that after two seasons of camping, litter on forested campsites in Michigan was limited to one year's leaf fall, and the humic layer (the O^2 horizon) had been eliminated. The annual leaf fall is rapidly removed within several months after the beginning of each camping season even on light-use sites (Fig. 5). In most cases hardwood litter is more rapidly eliminated during the main use season, but it recovers more rapidly over the winter. Differences in litter cover, between light- and heavy-use sites, were much less pronounced after the fourth year of use (1972) than after the third. In a park in northwest Ontario, Monti and Mackintosh (1979) also reported that most organic litter is lost even with light use.

Loss of litter is less pronounced on campsites in wilderness areas where use is not so great. In the Boundary Waters Canoe Area, Minnesota, litter and humus layers on

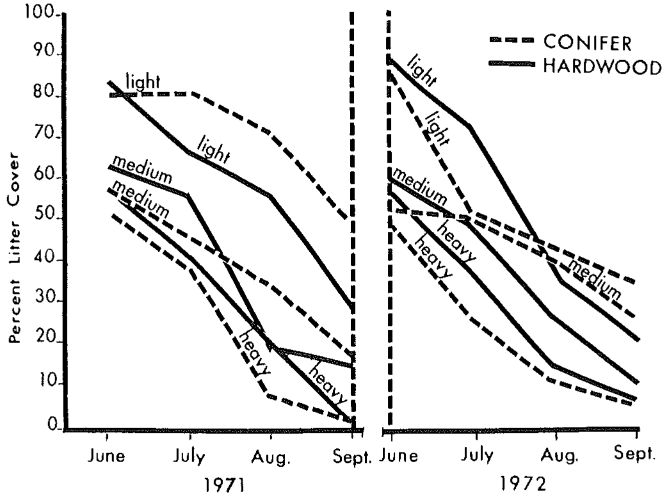

FIGURE 5. Average percent litter cover on established camping units over two visitor use seasons. Note the percent recovery during the off-season, Sept. 1971 to June 1972. (*Source*: Legg and Schneider 1977. Reproduced from *Soil Science Society of American Journal*, Volume 41, pp. 437–441, 1977 by permission of the publisher.)

campsites were reduced in thickness an average of 65 percent below undisturbed control areas (Frissell and Duncan 1965). In the Eagle Cap Wilderness, Oregon, about one-half of the organic horizon has been removed on campsites (Cole and Fichtler 1983). In some places, however, all organic matter has been removed. The mineral soil (A horizon) beneath was exposed over about 30 percent of the Eagle Cap campsites. On the most infrequently used sites little litter was lost. The thickness of organic horizons was reduced only 3 percent on soils used no more than a few times per year. This compares with reductions of 21 percent and 68 percent on sites used about 10 to 20 nights per year and more than 25 nights per year, respectively. Results from 10 years later showed differences between low-use and high-use sites to be even greater (Cole and Hall 1992).

Little litter is likely to remain on trails or campsites that are frequently used, particularly those with roaded access, after they have been used for several years. On lightly used campsites in more remote areas, however, little litter loss may occur if organic horizons are thick. This is very different from the situation in regard to soil compaction where substantial compaction occurs even on very lightly used sites. In places where litter cover is sparse, such as desert areas, even light recreational use can eliminate all litter.

There is some debate about what happens to surface organic matter once it is pulverized. Certainly, most of it is eroded away. However, several researchers report that some of the pulverized organic matter accumulates in the uppermost zone of the A horizon. On Eagle Cap campsites, for example, the organic matter content of the upper 5 cm of mineral soil was 20 percent higher on campsites than on controls. Other researchers report the opposite. Settergren and Cole (1970) found organic matter to be mixed through the surface layers of control sites but absent in campsite soils.

Loss of soil organic matter is serious because it makes the soil more prone to many soil impacts that follow (Marion and Merriam 1985). Susceptibility to reduced rainwater infiltration and nutrient cycling, as well as increased surface erosion, profile truncation, and soil compaction, are all increased when organic matter is removed. Elimination of the surface litter and humus layers greatly reduces the soil's ability to capture rainwater, accumulate and replenish soil organisms and nutrients, and cushion the mineral soil against the impact forces that cause compaction.

Profile Truncation

Destruction of the protective organic horizon leads to an accelerated rate of wind and water erosion, which removes a large proportion of the fine-sized particles on the exposed soil surface. In addition, unprotected mineral soil is readily compacted by human trampling. As a result of the combination of organic matter destruction, wind and sheet erosion, and compaction, the soil profile is reduced in depth, or truncated. Tree roots are commonly exposed and suffer mechanical damage as a result of soil profile truncation (Fig. 6).

FIGURE 6. Tree roots exposed by soil erosion and compaction. (*Photo*: D. N. Cole.)

The profiles of heavily used campsites average 3 in. shallower than those of nearby control sites in the Missouri Ozarks (Settergren and Cole 1970). The profile of one badly abused campsite indicated that as much as 9 in. of surface soil had disappeared following extensive recreational use. In a study of Michigan backcountry campsites, the A^1 horizon was completely eroded from moderately and heavily used sites by the end of four seasons of use. In contrast, the A^1 horizons on control sites were more than 5 cm deep, on average (Legg and Schneider 1977). Therefore, 5 cm had been lost in just four years.

Soil Compaction

Compaction, whether by trampling, vehicular use, or some other source of pressure, is a commonly documented effect of recreational use. The major techniques used to document soil compaction are (Speight 1973):

Penetrometry. Records the force necessary to drive a rod a known length into the ground

Bulk Density. A direct measure of soil density (weight to volume ratio)

Permeability. A measure of how rapidly water permeates the soil

Conductivity. A measure of soil density based on conductivity to electricity or gamma rays

Although these methods measure different characteristics, they all document increased compaction, the forcing of individual soil particles into closer proximity, thereby reducing the area occupied by interstices (Manning 1979). Compaction of soils by recreational use is reflected in increased values for bulk density, penetration resistance, conductivity, and decreased permeability values.

Comparing the degree of compaction found in different areas is difficult because of differences in site conditions and measurement techniques. Bulk density values vary greatly between soil types; certain inherently dense, uncompacted soils (e.g., sands) have even higher bulk densities than soils on highly compacted recreation sites. Examples of reported increases (over control sites) include 0.1 g/cm^3 on Eagle Cap Wilderness campsites (Cole and Fichtler 1983), 0.2 g/cm^3 on campsites in the Delaware Water Gap National Recreation Area (Marion and Cole 1996), 0.4 g/cm^3 on developed camp and picnic sites in Rhode Island (Brown, Kalisz, and Wright 1977), and 0.2 to 0.4 g/cm^3 on paths and trails (Liddle 1975). Dotzenko, Papamichos, and Romine (1967) recorded a bulk density of 1.60 g/cm^3 in a heavily used campground in Rocky Mountain National Park. In off-road vehicle areas, surface bulk densities over 2.00 g/cm^3 have been reported (Wilshire, Nakata, Shipley, and Prestegaard 1978). Weaver and Dale (1978) measured bulk density after experimentally trampling a grassland 1000 times by a hiker, a horse, and a motorcycle. Bulk density increased 0.2 g/cm^3 with hiker use and 0.3 g/cm^3 with horse and motorcycle use.

Soil penetrometer readings also show wide variation in amount of increase. Penetration resistance typically increased 71 percent on campsites in the Bob

Marshall Wilderness, 89 percent in the Rattlesnake, 139 percent in the Mission Mountains, and 220 percent in the Boundary Waters Canoe Area (Cole 1983). In the Bob Marshall the median penetration resistance on sites used by parties with horses was 4.0 kg/cm^2 compared with only 2.6 kg/cm^2 on backpacker-only sites. Higher values and greater increases indicate increasing force needed to penetrate the soil, a reflection of increased compaction. Although soil penetrometer readings are much easier to record than bulk density and more replicate readings can be taken, they vary with differences in water content and other soil characteristics. Consequently, comparison between sites and even over time on the same site should be treated with caution.

In all soils the top layers of the mineral soil are the most compacted; organic horizons are not very susceptible to compaction. Except in areas used by off-road vehicles, compaction on recreation sites is seldom evident more than 5 to 6 in. below the surface (LaPage 1967). Compaction of ORV areas is evident at depths exceeding 3 ft (Wilshire, Nakata, Shipley, and Prestegaard 1978). Unfortunately, it is compaction of the surface soils that is more critical to the alteration of water and air movement, vegetation rooting zones, and the habitat of soil organisms.

The degree of soil compaction is influenced by many soil factors, including organic matter, soil moisture, and soil texture and structure. In general, the soils most prone to compaction are those with a wide range of particle sizes (e.g., loams), those with a low organic content, and those that are frequently wet when trampled. On dry, extremely sandy soils, compaction can even be beneficial. Total porosity remains high because the sand particles simply cannot be pushed together closely; however, some of the macropores are reduced to micropore size, allowing the soil to retain more water, thereby benefiting plant growth.

Degree of compaction varies seasonally. Recovery occurs over the winter season in temperate zones as compaction is lessened by frost action, lack of use, and possibly wind rocking of trees. If all use is curtailed, compaction of recreation sites can be expected to return to normal within about a decade. With continued use any overwinter recovery is short-lived. With the beginning of the next use season, recovery stops and renewed compaction eliminates any overwinter loosening by early summer (Legg and Schneider 1977). Figure 7 illustrates this well.

Evaluation of the significance of compaction per se is difficult. Certainly, the effect of compaction on water and air movement can create serious problems. As the example of the dry, sandy soil illustrates, however, there are cases in which a more dense soil can actually be beneficial. Two direct, plant-related, negative consequences of compaction are the hindrance of plant root elongation and the lack of suitable regeneration sites on compacted soils. Figure 8 illustrates the effects of compaction on the ability of seeding roots to penetrate soil. Serious root impedance occurs at much lower densities on the more fine-textured silt loam soil. On coarser soils, it is difficult to compact soils to a level where pores are too small to penetrate. A poorly developed root system decreases establishment of plants and, for established plants, reduces vigor and growth. Compaction reduces germination through its effect on the smoothness of germination sites. Seeds of different species require a diversity of microhabitats in which to germinate. Germination is usually greater on

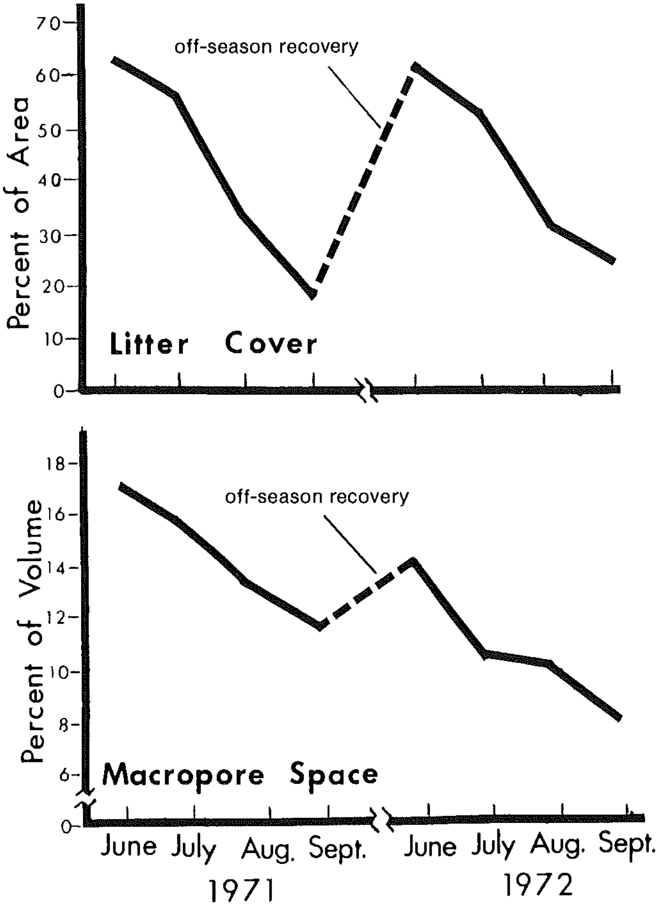

FIGURE 7. Impact recovery during the off-season is short-lived, as impacts resume at the beginning of the new camping season. (*Source*: Legg and Schneider 1977. Reproduced from *Soil Science Society of American Journal*, Volume 41, pp. 437–441, 1977 by permission of the publisher.)

rough surfaces that offer heterogeneous habitats. Compaction typically creates a homogeneous, smooth surface on which germination is inhibited.

Macroporosity and Infiltration Rate

On the central core of developed campsites, Monti and Mackintosh (1979) found that the area of macropore space declined from about 25 percent of soil volume to 2 or 3 percent. Stohlgren and Parsons (1986) found soil compaction and related pore space to increase 2 to 3 times between the periphery and core zones of campsites. These changes are particularly pronounced on fine-textured soils where macropore space is low initially, and susceptibility to compaction is high on account of the smaller soil

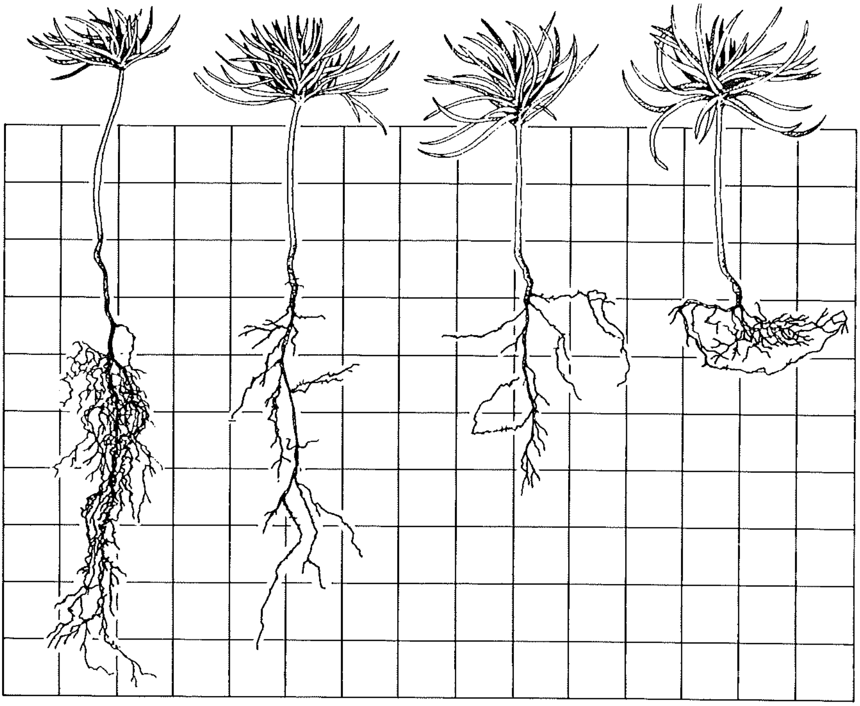

FIGURE 8. Effect of soil bulk density at 1.2, 1.4, 1.6, and 1.8 g/cm^3 on Austrian pine seedling growth on sandy loam soil (2 cm grid). (*Source*: Zisa, Halverson, and Stout 1980.)

particles. However, even in sand dune soils, loss of macroporosity can be severe enough to cause anaerobic (low oxygen) conditions (Liddle and Greig-Smith 1975). Smaller soil pore size reduces the mass flow and diffusion of air within the soil and curtails movement of nutrients (Liddle 1975). The movement of O_2 and CO_2 is retarded in the soil, which can lead to respiration and growth problems for vegetation (Legg and Schneider 1977). Root activity decreases as does the ability to absorb water and nutrients. The soil microbiota is adversely affected, and the decomposition of organic matter is slowed.

Legg and Schneider (1977) observed decreases in macropore space on newly opened campsites over a four-year period. In conifer stands macropore space declined from 31.6 percent (control measures) to 17.1 percent after two years to 8.6 percent after four years. The rate at which macroporosity is reduced diminishes with time; macroporosity probably stabilizes at some low level after about five years. Loss of macropores, after both two and four years of use, was greater on heavy-use sites than on moderate- or light-use sites. Even on light use sites, however, four years of use eliminated two-thirds of the macropores.

Reductions in water infiltration rates are probably the most important environmental consequence of compaction. On picnic areas in Connecticut, Lutz (1945) found reductions of 80 percent in sand soils and 95 percent in sandy loam soils. On the sandy loam sites the average length of time for the infiltration of one liter of water was 86 minutes in the picnic area and 4 minutes in the undisturbed area—a twentyfold difference. On the coarser textured sandy soil, loss of macropores was less severe, and infiltration on the picnic site was four times as fast as on the sandy loam picnic site; one liter infiltrated in 20 minutes.

James, Smith, Mackintosh, Hoffman, and Monti (1979) report a similar twentyfold reduction in infiltration on developed campsites in Ontario. Less severe reductions are characteristic of the less heavily used campsites in wilderness areas. In the Bob Marshall Wilderness, for example, Cole (1983) measured both instantaneous infiltration rates (the time it takes for the first centimeter of water to enter the soil) and saturated rates (the time for the first 5 cm of water). Instantaneous rates for campsites were less than one-third of controls, and saturated rates were one-sixth of controls.

More severe reductions in infiltration have been found in off-road vehicle areas. In one California area, infiltration rates were almost 40 times slower on motorcycle tracks than in adjacent undisturbed areas (Wilshire, Nakata, Shipley, and Prestegaard 1978). Organic matter content and soil texture and structure greatly influence both infiltration rates and the severity of reductions in infiltration rates.

Compaction appears to occur rapidly with light use. Even in wilderness areas low use sites are usually nearly as compacted as high use sites. In the Boundary Waters Canoe Area, increases in bulk density were two-thirds as high on sites used fewer than 12 nights per year as on sites used more than 60 nights per year (Marion and Merriam 1985). In the Eagle Cap, Missions Mountains, and Rattlesnake Wildernesses increases in penetration resistance and infiltration rates were significantly greater on sites used fewer than five nights per year than on sites used many times more (Cole and Fichtler 1983). Macroporosity is also greatly reduced even at low use levels. The relation between compaction-related impacts and amount of use is highly curvilinear—a little use causes most of the impact (Marion and Cole 1996). This is different from the case of litter loss, in which it often takes at least a moderate amount of use before a substantial amount of litter is lost (Cole and Hall 1992).

Soil Moisture

Soil moisture usually decreases as compaction increases, because compaction reduces infiltration and the amount of water available to the soil. However, compaction can also increase the amount of capillary pore space and, consequently, the moisture-holding capacity of soils. This situation is explained by the fact that when the soil is compacted, noncapillary pores too large to hold water against the force of gravity may be reduced to capillary sizes at which they can hold water. Lutz (1945) found the field capacity of trampled sites on sandy loam soils to be 8.9 percent higher than on control sites. Field capacity is the amount of water held in the soil after any water added to the soil has had a chance to drain downward. This increase in field capacity comes at the expense of reduced air capacity and, ironically, a reduced rate of water infiltration.

Settergren and Cole (1970) conducted one of the more detailed studies of soil moisture on a campground in the Missouri Ozarks. Both the field capacity and the permanent wilting point—the moisture left after plants have removed all the water they can—were reduced on campsites. The most significant measure of moisture—that available to plants—was about the same on campsites and controls. At no time was moisture at the 12-in. depth unavailable to plants, although recharge after precipitation and the rate of moisture depletion were both much slower on campsites (Fig. 9). Note the more rapid loss of moisture in dry June and the more rapid increase after late August rains on controls. Although adequate moisture was available at the 12-in. depth, available moisture dropped to zero at the surface in late August. This must be fairly common, given the severe wilting and stag-heading of tree crowns. These seasonal moisture limitations in surface soils are responsible, along with compaction, for creating a poor rooting environment for trees near the surface. A scarcity of shallow roots limits the ability of trees to utilize any surface moisture recharge that occurs in late summer.

The inability of the compacted soil surface to take up water restricts soil moisture recharge, which is particularly important to the survival of herbaceous vegetation during dry months. Many of the annual grasses, sedges, and herbs forming the recreation area ground cover vegetation during the early part of the summer succumb later to severe surface moisture limitations.

The effects of recreational use on soil moisture are complex and variable, being related to factors such as soil compaction, texture, organic content, density of forest cover, and exposure to sun and wind. Soil moisture can also influence rates of compaction and related impacts. Compaction-density penetration resistance relationships

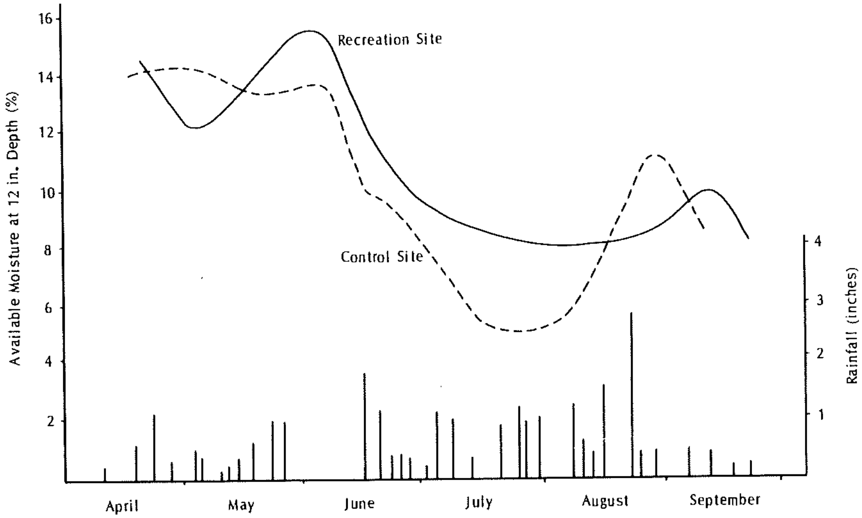

FIGURE 9. Rainfall and moisture availability, Missouri Ozarks, 1973. (*Source*: Settergren and Cole 1970.)

may be reversed when soils contain high moisture levels (Quinn, Morgan, and Smith 1980). Laboratory experiments revealed that soil penetration resistance decreased with increased trampling levels when imposed on a sandy loam at moisture contents near field capacity (45 percent). These findings were confirmed by Whittaker (1978) and Kuss and Jenkins (1985) who reported that under field conditions in Great Smoky Mountains National Park and the White Mountains National Forest (where high soil moisture was combined with fine-textured soils), penetration readings of surface soils declined under hiking pressures of light to moderate intensities. Generally, effects on soil moisture content are probably of less importance than many of the other impacts that have been discussed. They are probably most significant where available moisture declines in soils that were inherently droughty under undisturbed conditions.

Soil Erosion

Erosion is the most permanent, and therefore most serious, of soil impacts. Whereas soil compaction, loss of organic matter, and some other impacts will recover to some degree during periods of nonuse, erosion usually continues, once initiated, whether use continues or not. Gully erosion of trails, in particular, is likely to continue even without use. Most erosion is not caused by trampling or camping. Soil is eroded mostly by wind and water; recreational activities provide the circumstances for erosion and increase its rate of occurrence but are seldom the actual agents of erosion.

Although the most important agent of soil erosion is water, wind is an important erosional force in peat or sandy soils. Wind erosion of sand dunes is the best example of large-scale erosion triggered by recreational activity (Speight 1973). Where recreation destroys the vegetation that stabilizes dunes, the sand is freely moved by wind. Tens of hectares may be eroded at a single site, causing dune erosion to be the most obvious and often quoted impact of recreation in Great Britain. In the United States, wind erosion of dune ecosystems is primarily a problem in the national seashores of the Park Service, lakeshore parks on the Great Lakes, and desert dune areas used by off-road vehicles. Boardwalks to channel visitor use and prohibitions on camping and vehicular traffic are common means of limiting vegetation disturbance and resulting wind erosion.

Water erosion in recreation areas occurs primarily in two forms: sheet and gully. Sheet erosion of campsites, picnic areas, and other fairly level recreation sites occurs when water flows in a sheet across broad expanses of ground, picking up material as it moves. This impact was discussed earlier in this chapter under the heading of "Profile Truncation." Gully erosion, an even more serious problem to recreation management, occurs where water is concentrated in channels. This increases its erosive power. Gully erosion is a common problem on roads, trails, and sometimes on stream banks. Ketchledge and Leonard (1970) have measured trail erosion in the Adirondack Mountains that amounts to an increase in both trail width and depth of 1 in. per year. Surface erosion of up to 2 ft was reported on footpaths near campsites along the Colorado River in Grand Canyon; 1-ft reductions were common (Dolan, Howard, and Gallenson 1974). On a lineal distance basis, trail soil erosion exceeding

1 ft in depth averaged 239 ft per mile, with a cumulative total of 14.6 miles (4.5%) of sampled trails in the Great Smoky Mountains National Park (Marion 1994).

Paths made by horses and trail bikes create conditions that invite accelerated gully erosion. Horse traffic causes significant compaction to the underlying soil layers, thus reducing water infiltration and increasing surface runoff. In addition, the action of a horse hoof tends to dig up and puncture the soil surface. Loose, unconsolidated soil is more prone to erosion than compacted soil and, as a result, the potential for erosion increases on horse trails as compared with hiker trails. A comparison of the erosional impacts of hikers, horses, off-road bicycles and motorcycles showed that the sediment yields from horse trails were greater than those from any other type of use (Seney and Wilson 1991). Four-wheel drive vehicles and trail bikes in the steep and moist southern Appalachian Mountains make trails that erode in places to depths of 6 to 8 ft (Fig. 10). In an off-road vehicle area in California, the annual erosion rate was estimated to be 11,500 tons per km^2. This is 30 times higher than the rate at which the U.S. Bureau of Reclamation considers erosion to be a serious problem (Wilshire, Nakata, Shipley, and Prestegaard 1978). In a study of riverways, Hansen (1975) could not attribute much of the streambank erosion that was occurring to canoe use. Much was natural; some was linked to vehicular access by people fishing, picnicking, or simply watching the floaters.

The extent of erosion on a recreation site is determined by many factors. Slope, drainage, and climate are important (Jubenville and O'Sullivan 1987; Marion 1994).

FIGURE 10. Off-road vehicles have caused excessive erosion on this trail in the Cherokee National Forest, Tennessee. (*Photo*: W. E. Hammitt.)

Erosion is likely to be more serious on steep slopes where water tends to be channelized and in climates with infrequent but intense rainfall. A sparse ground-cover vegetation and lack of an organic horizon also make a site prone to erosion. The most erosive soils are homogeneous-textured soils, particularly those high in silt or fine sands and low in organic matter. Shallow soils may quickly erode down to bedrock.

Other Soil Impacts

Additional impacts, which have been investigated in less detail, include effects on temperature, organisms, and chemistry. Loss of vegetation and surface organic horizons removes an insulating layer, which leads to a greater range of soil temperatures. Temperatures are higher in summer and during the day; they are lower during winter and at night. During winter, soil in trampled areas was observed to be frozen to a depth of 3 to 4 cm whereas under taller vegetation in minimally used areas, the soil temperature remained above freezing (Chappell, Ainsworth, Cameron, and Redfern 1971).

The effect of snowmobiles on soil temperature regimes can be particularly pronounced. Compaction of snow reduces its insulating ability. Wanek (1971) found the duff layer (O horizon) under snowmobile trails to be 11°C cooler than under the undisturbed snow. The A^1 soil horizon under the compacted snow froze approximately one month earlier and thawed an average of 2 to 3 weeks later in the spring. This shortened growing season can be detrimental to the life cycle of flowering plants, particularly those in alpine ecosystems. As Wanek (1974) states:

> The colder temperatures retard the growth and flowering of early spring flowers and reduce their seed productivity and viability. In addition, perennial herbs having large underground storage organs often perish due to intracellular ice crystals producing cytolysis, dehydration, or extracellular ice masses which disrupt tissues. (p. 50)

Changes in soil temperature regimes and decreases in organic matter and air pore space also affect soil organisms. Colder temperatures under snowmobile trails were the presumed cause of a hundredfold reduction in soil bacteria and a two- to tenfold reduction in soil fungi (Wanek 1971). Speight (1973) summarized the influence of trampling on bacteria in woodland soils, whereby bacteria decreased by about one-half. Other studies have shown similar effects on soil fauna and microflora. Ground vegetation communities, before trampling, contain a complex assemblage of animals that feed on dead plants or on fungi, algae, and bryophytes, which grow on decaying material. For example, when areas of a chalk grassland ecosystem were trampled, a serious reduction in arthropods, earthworms, mollusks, and snails occurred (Chappell, Ainsworth, Cameron, and Redfern 1971). Less understood but of particular concern are adverse effects on mycorrhizal fungi (Cole 1990). Mycorrhizal fungi improve nutrient uptake and water absorption in plants and thus often are a limiting factor in revegetating disturbed areas (Reeves, Wagner, Moorman, and Kiel 1979). Reeves reported that 99 percent of the plant cover in undisturbed sites in Colorado sagebrush country contained mycorrhizal fungi, whereas less than 1 percent were found to contain the fungi in severely disturbed areas.

The compaction of soils and loss of pore space can also lead to soils being poorly oxygenated, creating more potential for anaerobic microenvironments and forms of bacteria. Speight (1973) found that nitrifying bacteria, which need an abundance of oxygen, were unable to survive in trampled soils and that anaerobic bacteria were twice as abundant as other forms. Because soil bacteria involved in nitrification (conversion of NH_4 to NO_3) are obligate aerobes, changes in soil structure and aeration, such as occur under heavy soil compaction, adversely affect the availability of nitrate to plants. Between the two processes of denitrification and nitrification, it is possible that nitrogen shortages will occur in soil-impacted environments, such as in campsites and picnic areas. Kuss, Graefe, and Vaske (1990, p. 17) state that "the general conclusion can be drawn that changes in microhabitat caused by a decline in litter and air spaces in the soil are more important than actual physical destruction of individual organisms."

Several changes in soil chemistry have also been recorded on recreation sites. A number of studies have found increases in soil pH on campsites; recreation use somewhat reduces acidity. Results of changes in the concentration of various nutrients have been notably inconsistent. Table 1 shows the relationship between concentrations of nitrogen, phosphorus, and other elements to bulk density, soil moisture, and organic matter in sandy loam soils. Heavily compacted core areas within campsites were compared with intermediate zones and the little disturbed periphery of these areas. Total nitrogen declined by 62 percent from the periphery areas to the heavily impacted zones. Phosphorus showed only a 15 percent decline, whereas K, Mg, and

TABLE 1. Variations in Vegetation Cover and Selected Soil Characteristics as Influenced by Use Levels

Item	Core	Intermediate	Periphery	Percent Change Periphery to Core
Vegetation cover (%)	1.1	15.3	24.8	–96
Soil bulk density (grams/cc)	1.3	0.7	0.5	+171
Macronutrients (ppm)				
N (Total)	28.6	40.4	74.8	–62
NH_4	24.8	36.5	70.6	–10
NO_3	3.8	3.9	4.2	–10
P	47.9	28.1	56.4	–15
K	50.3	65.2	107.2	–53
Mg	7.2	11.4	37.6	–81
Ca	108.8	181.0	967.3	–89
pH	3.7	3.6	3.5	+5
Soil moisture (%)	17.0	39.8	51.6	–67

Source: Stohlgren and Parsons 1986.

Ca declined significantly from periphery to core of the campsites; NO_3 nitrogen was essentially unchanged, suggesting that mineralization of ammonia was inhibited throughout the area by low pH and other unknown factors (Stohlgren and Parsons 1986). All the change were accompanied by a 171 percent increase in bulk density. Cole and Fichtler (1983) found that Mg and Ca concentrations doubled and that Na increased significantly on campsites in the Eagle Cap Wilderness. The authors suggest that the pH and nutrient increases "probably resulted from the scattering of materials, such as campfire ashes, excess food, and soap, as well as from reduced leaching as a result of slower infiltration rates." Chappell, Ainsworth, Cameron, and Redfern (1971) found decreases in nitrate and phosphate, compounds that were unaffected by use in the Eagle Cap. Probably a number of soil impacts, particularly reductions in organic matter, reduced aeration, and impoverishment of soil organism populations act to reduce concentrations of certain soil nutrients; however, this tendency can be compensated for by pollution of the site and reduced leaching. Most of these changes are small, and their significance is not well understood.

Impacts Associated with Campfires

Soil impacts resulting from collecting and burning wood in campfires are quite different from those associated with other activities on campsites and trails. Therefore, they will be discussed separately here. The removal of firewood need not cause the serious problems suggested by some proponents of banning campfires. Nutrient supplies should not be severely depleted in areas where wood is gathered. The majority of soil nutrients supplied by trees are contained in the leaves, needles, and small trees, not the larger branches and small boles of trees that are usually used for firewood (Weetman and Webber 1972). Neither will soil organic matter by substantially reduced. Again, the majority of organic matter added to the system comes from leaves and twigs, tree components seldom collected for firewood. The trampling of leaf and small twig litter is likely to have more of an effect on carbon cycling than the gathering of firewood (Bratton, Strombert, and Harmon 1982).

The most serious effects of firewood gathering result from the collection of large pieces of downed wood, those larger than 3 in. in diameter (Cole and Dalle-Molle 1982). Decaying wood of this size plays an important role in the environment that has only recently been appreciated. Moreover, its role cannot be replaced by any other component of the ecosystem. Decaying wood has an unusually high water-holding capacity, making it important to the water relations of droughty sites in particular. It also accumulates nitrogen, phosphorus, and sometimes calcium and magnesium. Therefore, use of this wood could result in nutrient impoverishment. Decaying wood is the preferred germination site for certain plant species and is a preferred growing medium for microorganisms. Ectomycorrhizal fungi, which develop a symbiotic association with the roots of many plants, improving their ability to extract water and nutrients from infertile soils, are frequently concentrated in decaying wood. Thus, removal of large pieces of wood can be detrimental to soil productivity.

Generally, the area affected by firewood removal is small and locally concentrated. However, this activity can greatly increase the area of disturbance around campsites. In Great Smoky Mountains National Park the area disturbed by firewood gathering was more than nine times the size of the devegetated zone around campsites (Bratton, Hickler, and Graves 1978).

The area disturbed by burning of firewood in campfires is even smaller; however, the effects are considerably more serious. Fenn, Gogue, and Burge (1976) examined the effects on soil of burning 140 lbs of wood, a much larger amount than would be burned at one time in most campfires. Their fires altered organic matter to a depth of 4 in. and destroyed 90 percent of the organic matter in the surface inch of soil. Fires also cause pronounced changes in soil chemistry. Reported fire effects included the loss of nitrogen, sulfur, and phosphorus, increases in pH and many cations, and reductions in the moisture-holding capacity, filtration rates, and mycorrhizal fungi populations of soil. Overall, these changes constitute a sterilization of the soil, likely to render the site less hospitable for the growth of vegetation and likely to require 10 to 15 years to recover, particularly if the site has been used for some time (Cole and Dalle-Molle 1982). Unfortunately, the only other information on campfire effects must be extrapolated from studies of forest and slash fires. In such fires it is common to lose most organic matter, nitrogen, sulfur, and phosphorus and to reduce the soil's moisture-holding capacity and infiltration rate (Tarrant 1956). Because the effects of campfires are so dramatic, many managers try to concentrate them in one place to avoid excessive damage.

SUMMARY

1. Recreational use causes reductions in surface organic horizons and compaction of mineral soil. Compaction leads to loss of macroporosity and reductions in water infiltration rates. This reduces aeration and water movement in the soil, altering the character of soil organism populations and adversely affecting plant vigor and growth. Increased surface runoff often results in accelerated erosion, causing both profile truncation and gully erosion.

2. Where it occurs, erosion is the most serious of these impacts because it is essentially irreversible. Recovery rates vary greatly, particularly with factors like amount of biotic activity, length of the growing season, and the nature of temperatures and moisture fluctuations. Erosional losses are likely to require centuries to recover. Most other impacts should usually recover in a decade and many can be speeded up through human intervention.

3. Compaction-related impacts, particularly reduction in macroporosity and infiltration, occur rapidly with low use. Initial low use causes most of the change, with further use causing less and less additional impact. If surface horizons are thick, loss of litter is less rapid and is pronounced only when use levels are moderate to high. Amount of erosion is related more to site factors than amount of use because the main agents of erosion are water and wind, not trampling.

4. Activities engaged in and type of use affect what impacts occur as well as their severity. Camping and picnicking cause most of these impacts to be severe because use is highly concentrated; however, erosion is less pronounced because use areas are generally flat. On trails, erosion is the most serious problem because of steep slopes and channelization of water. Erosion problems are aggravated when use is by horses or motorized vehicles, because they often loosen the soil rather than compact it. This makes it more easily moved by water, the main agent of erosion.

5. Susceptibility to impact varies between soils and with site factors. Compaction is most pronounced on fine-textured soils, soils with a wide variety of particle sizes, and soils low in organic matter. Erosion is most pronounced in soils with homogenous textures, particularly those high in silt and fine sand and low in organic matter. Erosion is more likely on steep slopes, shallow soils, places with sparse vegetation cover, and places where runoff is concentrated.

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