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This chapter will explain the techniques (figure 3–1) used in a restoration project, providing enough technical background to get project planners pointed in the right direction. Some concepts underlying the techniques are explained as thoroughly as possible, while others are too technical to treat fully here. To address the most technical issues affecting your restoration project, recruit specialists with the needed expertise.

This chapter follows the sequence used when implementing a restoration project:
1. Select an appropriate plant community as a model for the restoration prescription.
2. Assess soil conditions and formulate treatments.
3. Select appropriate plant species and propagation methods (figure 3–2).
4. Identify methods for protecting the project from damaging environmental forces and human use.
5. Determine how the project will be documented and monitored.
6. Identify ongoing maintenance needs.

Figure 3–1—Many of the restoration techniques developed for use on arid lands also are beneficial on dry forested sites or alpine sites.

Figure 3–2—At Joshua Tree National Park, CA, tall pots are used to propagate deeply rooted plants native to the Mojave Desert.

3.1 Developing Site Prescriptions Based on a Reference Site

Much of the success of a restoration project involves treating the conditions that limit plant growth in the site’s degraded substrate. Some of the problems with a degraded site are obvious, such as erosion or compaction. Others are less obvious, such as the reduced availability of water late in the season or changes in microbial activity. This section
addresses three aspects of site evaluation:
1. Selection of a reference (example) site
2. Evaluation of the impacted site and the reference site
3. Analysis of soils and selection of treatments

3.1.1 Determining Reference Sites

One of the most difficult and important steps of the restoration planning process is determining what type of site treatment will be effective in achieving revegetation. Clues to potential treatments or target conditions are provided by selecting a suitable target plant community called the reference site, reference community, or even just reference (Clewell and others 2000). Selecting an appropriate reference site guides development of the site prescription, including the treatment of soils and vegetation.

Ideally, a representative disturbed-but-revegetated reference site that supports sustainable and appropriate vegetative cover would be selected. This reference site will illustrate the process of secondary succession—how natural systems reclaim a disturbed area. Perhaps your project is in an area that is in the latter stages of succession. In such a case, the reference site should be in an undisturbed area nearby that is representative of the plant community before disturbance.

Sections 3.1 to 3.1.1c discuss how to select a reference site. The more technical how-to information for evaluating soil condition and selecting appropriate plant species is covered in the sections on soils (3.1.2 to 3.1.6c) and plant selection (3.10 to 3.10.4).

True ecological restoration would restore the structure (species composition), process (the way ecosystem components interact), and function (overall energy flows) of the missing native plant community. Unless a restorationist has a very simple community to restore, ecological restoration may not be fully achievable, even after decades of recovery. Perhaps your goal stops short of restoration. You may be attempting to rehabilitate a site with native vegetation that can withstand ongoing use or to establish native plants on toxic mine tailings.

Fortunately, most wilderness restoration projects are small. Restoration usually addresses vegetative restoration or soil stabilization. The disturbances may not impair ecosystem processes and function. Our goal may not specifically include recovery of habitat for animal species. For a restoration site to fully recover its vegetative community, often soils and the associated animal species must recover as well.

To begin evaluating a site, become an observer of the landscape and ecosystem. Identify distinct plant communities within your ecosystem (figure 3–3). Notice how the vegeta-

Figure 3–3—Most landscapes are comprised of many different plant communities, each adapted to features such as slope, aspect, soil depth, and water availability. Understanding how your restoration site fits into landscape patterns is a critical part of planning.
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3.1.1 Choosing a Reference Site

Conceptually, the steps for selecting a reference site are simple. But understanding ecological processes and patterns is not. Your interdisciplinary team will help you bring the pieces of the ecological puzzle together. Together, the team will work to identify a reference site that reflects project goals and perhaps even sites with intermediate communities that represent steps during succession that lead toward the communities at the reference site. The Society for Ecological Restoration Science and Policy Working Group (2002) describes this approach as identifying an ecological trajectory to recover natural conditions on a site. If your short-term goals do not match your long-term goals, your prescriptions should attempt to meet your short-term goals while moving the site toward your long-term goals.

Choosing a reference site is easily confused with trying to freeze a moment in time. Don’t think of the reference site as a precise set of conditions. Rather, think of it as a range of natural conditions found on similar undisturbed or disturbed-but-revegetated sites. The restoration project will be designed to move the disturbed site toward this range of conditions. More than one reference site may be needed to express this range of conditions.

3.1.1b Identifying Undisturbed Reference Sites

It is virtually impossible to reconstruct the exact conditions of a site or to determine the exact vegetation that was on a site before it was disturbed. However, several sources of information can be the basis for ecological conjecture. The most important sources of information are nearby undisturbed areas that share slope, aspect, moisture regime, canopy cover, and similar features with the disturbed site.

To select reference sites, find areas that are well away from concentrated human use. Based on research conducted by the U.S. Department of the Interior National Park Service at Glacier National Park, a loss of species diversity was documented up to 6½ feet (about 2 meters) on either side of a trail (Hartley 2000). More than one similar area should be identified to form a composite picture of the missing vegetative community and its associated soil structure and other habitat components. In addition, the disturbed site should be examined for any surviving remnants of native vegetation.

The vegetation surrounding the disturbed site may or may not provide helpful information. If the features of the area surrounding the disturbed site are distinctly different from those of the disturbed site itself, the vegetation is likely to differ as well and the surrounding area may not be appropriate for a reference site.

For example, in the Cascades, Olympics, and Northern Rocky Mountains, typical subalpine parkland is comprised of a mosaic of vegetation types. The vegetation found in clumps of mature trees includes shrubs such as currant (Ribes) and rhododendron that don’t grow on open slopes in full sun. Ground cover within the tree clumps may include plants such as trailing bramble (Rubus), Sitka valerian (Valeriana sitchensis) or wood rush (Luzula). Partridgefoot (Leutkea pectinata) often dominates recent disturbances and seems to like areas of partial shade. Nearby sloping meadows may be an early successional community of forbs and grasses, a later successional community of heather and huckleberry, or a mix...
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of both. Flat areas at the bottom of slopes may be thick with the moisture-loving black sedge (*Carex nigricans*). But the plants that really like their feet in the water along boggy lakeshores or streambanks may be marsh marigold (*Caltha*) and different species of sedge.

The species of plants found growing on the tops of knolls and ridges will be those adapted to drier conditions, thinner soils, and more wind. Only a few plants, such as the early colonizing Parry’s rush (*Juncus parryi*) seem to grow in almost all of these settings. As an illustration of the complexity of vegetation types within an ecosystem, Roger del Moral (1978) identified 21 different recognized plant community types, including 11 forested community types and 10 alpine community types in his studies of a subalpine basin in the North Cascades (figure 3–4).

Sometimes it is necessary to view information in a broader historical context. For example, if an entire landscape has been changed because of a human-caused distur-

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Figure 3–4—Roger del Moral identified 21 different recognized plant community types in a subalpine basin in the North Cascades, WA, including 11 forested communities and 10 alpine communities (del Moral 1978).
bance, such as grazing or excessive trampling, historical records and range science may provide additional clues to the vegetative community before disturbance. Helpful sources of information might include historical photographs, vegetative surveys, field notes, or species lists.

On landscapes disturbed by grazing, different plants respond differently to grazing pressure. Although the most delectable ice cream plants may once have been common, they may be underrepresented or even missing after grazing. Species favored by disturbances, such as pussytoes (*Antennaria*), will be more abundant (figure 3–5). In such situations, it may be appropriate to select a disturbed-but-revegetated reference site rather than a pristine, undisturbed site.

### 3.1.1c Identifying Disturbed-But-Revegetated Reference Sites

Many project sites slated for restoration are so altered that plants from the historical plant community may not thrive there, even after being replanted. It is helpful to distinguish between a human disturbance that resembles a natural disturbance and a disturbance that results in an unnaturally stressful environment for reestablishing plants. If site conditions can be made more favorable, early- to mid-seral species that are adapted to disturbance are likely to succeed. If site conditions cannot be improved, it is important to select a reference site with a plant community adapted to these types of environmental stress. Few plants are adapted

Figure 3–5—In the subalpine landscapes of the Pacific Northwest, concentrations of pussytoes (*Antennaria*) indicate where large bands of sheep took their afternoon siestas. The invasion of pussytoes represents secondary succession, the succession that takes place after a vegetated landscape is disturbed.
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to withstand both high disturbance and high environmental stress (Chapin 1992). The factors likely to limit restoration success need to be identified (see appendix A, *Treatments To Manage Factors Limiting Restoration*). Reference sites should be selected that best portray the site characteristics and the factors that may limit success.

Examples of naturally disturbed areas to examine include slumps or slides, alluvial fans, avalanche paths, areas near retreating glaciers, recently flooded areas, and so forth. Trail or road cutbanks or the disturbed site itself also may be good indicators of potentially appropriate plant species for the restored site.

Damage to the soil structure and associated water relations often are the biggest challenge to reestablishing a desired plant community. Such challenges might include: loss of the organic soil layers (including micro-organisms), increased compaction, change in pH, increased toxicity, change in slope or drainage patterns, past or active erosion (figure 3–6), and changes in soil texture. Treatments, such as importing topsoil, soil amendments, or fertilizer, bear scrutiny. Consider the resource tradeoffs and remember to apply the minimum requirements principle. Additional environmental factors affecting plant establishment might include extremes of heat or cold, wind, grazing animals, and so forth.

Technological feasibility may limit some aspects of restoration, such as which tools might be used on remote sites. For example, if reestablishing the slope angle with heavy equipment is inappropriate or infeasible, the original plant community may be replaced with a different community. In wilderness, the option of using motorized or mechanized equipment would require an analysis to determine whether these methods are the minimum requirement for accomplishing project objectives. There are no easy cookbook answers to such ethical dilemmas. Each project must weigh such factors on a case-by-case basis.

Some dominant plant species are difficult to reestablish through restoration. For example, restoration of heather communities (figure 3–7) is problematic in the Pacific Northwest, as is the reestablishment of creosote bush in the deserts of the Southwest. Fortunately, reliable restoration protocols are being developed by the U.S. Department of the Interior National Park Service for these environments. See appendix C, *Detailed Propagation Methods for Beargrass, Heather, Huckleberry, and Partridgefoot*, for more information.

Figure 3–6—This sod continues to be eaten away by the wind and the burrowing of pocket gophers in the Alpine Lakes Wilderness, WA.

Figure 3–7—Matt Albright, greenhouse manager for Olympic National Park, WA, has successfully propagated a number of difficult species in the heath family. Several of his protocols are in appendix C.
Continued patterns of human use also may influence the selection of a reference site. If the project goals include allowing continued human use, the reclaimed site will require a resilient vegetative community. For these situations, find native plant communities nearby that mimic the conditions you must work within to reestablish vegetation. Plant communities on these reference sites might have revegetated themselves after a natural disturbance (such as fire), or they might be revegetating themselves naturally after a human-caused disturbance (such as an abandoned and now recovering campsite). These plant communities probably will represent an earlier seral community than that at the impacted site, but otherwise have similar site characteristics, such as topography, soil development, and shade.

For example, at Denali National Park in Alaska, road cutbanks slowly colonize with the same plant species that are found on naturally unstable slopes. The park decided to treat cutbanks using species that grew on naturally disturbed slopes (Densmore and others 1990).

In their work reclaiming toxic mining spoils on alpine sites in the Intermountain West, Brown and Johnston (1980) sought to reestablish a native stand of vegetation that “will resemble the posture of a native plant community when it becomes self-reproducing, stabilizes the soil on the site, and reaches a successional status involving native plant species of the area.” They acknowledged that recovery could take decades or even centuries, making it impossible to prescribe a mandatory timeframe.

The next step is to describe the assemblage of plant species, their relative abundance, and the soil structure at the reference site. If reference examples exist in the project area, note their location so they can be referred to for planning, project implementation, and monitoring.

If determining a reference site seems daunting, you can take some comfort from knowing that if you select the “wrong” plant species, they may eventually die out. Although it might be discouraging to lose some plants, letting nature shape the result is what restoration is all about.

### 3.1.2 Comparing the Reference Site and the Restoration Site

This section will help you identify conditions at the reference site that will serve as a realistic example of conditions at the impacted site after it has been restored.

#### Comparing Soils

For many wildland situations, the required or desired soil conditions for sustainable plant growth are not well known. Soil data and target nutritional or soil chemistry values from agricultural and horticultural systems may not be appropriate for revegetation projects in wildlands. Agricultural systems tend to have soils with nutrients in highly available forms. While wildland soils tend to have larger total nutrient contents, the nutrients are not as readily available as those in agricultural soils. The characteristics of wildland soils are best modeled by choosing a suitable reference site that represents the intended soil characteristics of the impacted site after treatment.

The following sections of this guide outline how to use topography, mineralogy or geology, general soil profile, and soil surface conditions to evaluate soil characteristics. More detailed lab analyses can provide technical nutrient data, but a good field evaluation can provide many important clues to site condition, soil condition, and the potential need for treatment. At many disturbed sites, field evaluations may be good enough for treatment. Plant community types or indicator species can be excellent indicators of long-term soil functions, because they indicate the integrated response of plants to site conditions over many seasons.

Evaluating soils on a field site requires a different investigative approach than the approach used for counting plants or species. The processes are often more important than a particular quantity. For instance, a wildland soil’s water-holding capacity is more important than its water content at any given time and the organic matter cycle is more important than the soil’s short-term nitrate content.

Even though we may measure some of the soil characteristics and contents in lab analyses, the processes that support
Selecting a Reference Site at Upper Florence Lake

Upper Florence Lake in the Alpine Lakes Wilderness sustained heavy sheep grazing for 70 years, resulting in substantial soil erosion and loss of vegetation (figure 3–8). The forces of wind and water erosion, as well as recreational use, continue to degrade this site. An adjacent meadow would indicate that the historical plant community was a well-developed heather and huckleberry meadow interspersed with sedges and herbaceous species. However, replacing the amount of topsoil needed to support a heath community would not be realistic. Several plant species have volunteered in the disturbed area, including black sedge (*Carex nigricans*, figures 3–9a and 9b), Parry’s rush (*Juncus parryi*, figures 3–10a and 10b), and partridgefoot (*Leutkea pectinata*, figures 3–11a and 11b). These species would suggest that a nearby sedge meadow or a south-facing slope with partridgefoot could serve as a reference site.
Figures 3–10a and 10b—Parry’s rush (*Juncus parryi*), drawings (top) and photo (bottom). Drawings courtesy of the University of Washington Press (Hitchcock and Cronquist 1976).

Figures 3–11a and 11b—Partridgefoot (*Luetkea pectinata*), drawing (top) and photo (bottom). Drawing courtesy of the University of Washington Press (Hitchcock and Cronquist 1976).
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Plant growth long after irrigation treatments or fertilizer amendments have ended are most important for long-term, sustainable soil regeneration. To determine whether the soil characteristics are appropriate for plant growth, conditions must be evaluated based on time scales that range from centuries (soil profile development), to decades (organic matter accumulation), months (water storage and microbial growth), days (nutrient cycles), or minutes (infiltration and surface erosion from the impact of raindrops).

While all soil characteristics interact, they can be assessed independently, allowing deficient conditions to be corrected without creating imbalances in related conditions. As each characteristic is considered below, look for ways that one characteristic influences another to provide an integrated network of plants, fauna, soils, and watersheds.

Landforms

Understanding how soils are influenced by landform position will help you find a suitable reference site for the impacted site.

The position of the selected site within the topographical landscape provides the first clues to the characteristics of the soils in an area. Soils that developed directly on the underlying rock (figure 3–12) are said to have been formed on residual parent materials (geological substrates) and can be expected to derive their chemical and textural characteristics from the underlying rocks.

Soils that form on transported substrates develop on parent materials that have been washed downstream, carried by glaciers (figure 3–13), or blown by the wind (aeolian deposits). The soils will acquire many of the characteristics of the transported source materials. Such soils often occur on low-lying areas. They may not resemble soils that developed on the local bedrock, even though the bedrock rises just a short distance away.

Figure 3–12—The green serpentine soils on these open slopes formed from the decomposition of parent material.

Figure 3–13—Glaciers transport glacial till.

How long a soil has been forming on a site influences how strongly the soil horizons will have developed. Some residual soils are very stable, remaining in place for hundreds of thousands of years. In these older soils, thick clay layers and well-developed soil horizons are generated as rocks weather and soil processes continue. Restoration of a disturbed site for revegetation of a plant community requiring these soil conditions requires careful replacement of various horizons of soil, paying attention to the thickness of each horizon.

Examples of sites requiring careful attention would include:

- Low-lying sites, such as vernal pools that require restricted drainage and standing water for certain periods in the spring.
- Level upland sites with high clay content that store moisture that is available for plants during periods of drought.
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A recently formed soil that has had little development of soil horizons can be regenerated after disturbance with relatively little treatment, because little soil development has occurred at the site. An example of such a soil would be the coarse soil with poorly developed horizons often found on glacial deposits or along riparian areas subject to frequent flooding.

Landform position also influences soil development. Soils on lower slopes are commonly deeper than soils on upper slopes, because gravity and water remove soil from the upper slope and deposit it lower on the slope. Soils in the bottom of old swales or draws can be especially deep compared to soils only a few feet (a meter) on either side of the drainage. Often, low-lying areas are more heavily impacted by human use than adjoining slopes because campsites and social trails tend to be more common on flatter terrain.

Unless rock is well fractured, soil drainage and plants' rooting depths often are limited by underlying layers of solid rock. Intensely fractured rock may not have much nutrient value, but it offers roots access to deeper water reserves during drought. Soils that form on transported substrates with fine-textured horizons (such as ash) overlying coarse-textured horizons (such as gravel) have a special limitation regarding moisture distribution. Water is retained in the smaller pores of the upper horizons and it may not flow downward into the coarse sandy or gravelly lower horizon. Roots often do not grow into the coarse lower horizon because it is comparatively dry. Such soils are found in the Enchantment Lakes Basin in the Alpine Lakes Wilderness of Washington, where a fine-textured soil from ash fall overlies coarse glacial deposits (Juelson 2001). This problem is discussed in more detail in section 3.1.4a, Soil Texture and Pore Size.

The aspect of a site can influence the depth of soil development. Soils on the north (shady) side of steep slopes tend to be cooler and moister. They have more plant growth and deeper soil development than slopes on other aspects. If the site is at high elevation, north-facing sites may be colder and hold snow longer, in which case soil development will not be as deep as on warmer, south-facing slopes.

Sometimes the fine and coarse sediments laid down by streamflow mimic soil horizons, giving the impression of soil development where there is none. The way to distinguish soil profile development from silt or clay-rich layers that were laid down by geological processes such as streamflow is to observe the pattern of layering over a broad, exposed slope—a slope about 15 to 30 feet (about 4.5 to 9 meters) wide or wider. Road cuts or exposed streambanks are the easiest way to see these formations. A shallow pit at the upper shoulder of the slope will show a profile that can be compared with a (usually) deeper soil profile lower on the slope.

In contrast, if the layers tend to follow the surface of the landform with its hills and swales, the layers would be attributed to soil-forming processes. If the layers are horizontal or follow the pattern of the local geological layers or fluvial (stream) deposits, they probably were laid down by geological processes. Another clue is that transported sediments often have patterns of alternating coarse and fine layers as a result of fluctuations in moisture (rainfall erosion versus dry ravel) or depositional energy (high or low streamflows).

Most prospective wilderness restoration sites, such as campsites, are likely to be stable, because they may be on relatively level ground. In other situations, slope failure could become an issue, such as in areas with excessive runoff, road cutbanks, mine tailings, or slopes undercut by old roads, trails, or streams. A soil scientist or geomorphologist on your team can evaluate the potential for slope failure in such areas. If slope instability is induced by human activities, slope stabilization may be addressed in the site prescription. Be careful to distinguish surface erosion issues from geotechnical issues that are larger in scale and that are not directly treatable by revegetation.

Mineralogy

You need to confirm that the mineralogy of the impacted site matches the reference site.

Observe the geology of the general area, or at least of the substrates on which the soils are forming. Soils derived from sandstones or granites tend to have coarse, sandy soil.
near their weathering sources (figure 3–14). If the area has had glacial activity, the fine materials may have washed into the site, making the soils finer, or the fine materials may have been washed away, making the soils coarser. Look at the sand grains with a magnifying lens. Have the grains been rounded by water? Or are the edges angular and cracked, as they would be after being frozen and ground down a slope by a glacier? Do the particles contain vesicular cavities (small gas bubbles) formed during rapid cooling of molten material after a volcanic eruption?

Soil Profile Development
You will need to evaluate the soil profile and soil formation at the impacted site, including the soil horizon development and the volume of soils in each horizon, comparing these soil characteristics to those of the reference site.

Compare soil profiles by digging at least two soil pits, one at the impacted site and one at the undisturbed reference site (figure 3–15). As described previously, the reference site may be a site that had previously been disturbed but is now revegetated. This type of comparison provides a general

Figure 3–14—The coarse, sandy soil of this high Sierra basin in the John Muir Wilderness, CA, is derived from granite. In restoration prescriptions, the parent material at the reference site should match the parent material at the restoration site.

Try to determine whether the region is derived from intrusive volcanics (granites or diorites with large crystals), or extrusive volcanics (fine-grained andesites or basalts). The intrusive (granite-like) materials have larger crystals and the rocks as a whole may physically weather and crumble more rapidly. The extrusive (ash-like) materials have smaller crystals so that rocks tend to chemically weather more quickly. Soils derived from extrusive materials will be deeper or have more clay. The parent material and mineralogy will be related to general trends in the water-holding capacity of soils and the abundance or scarcity of some soil nutrients, topics that will be covered later.

Figure 3–15—Soil pits should be excavated to the depth of root penetration.
estimate of how much the soil has degraded and how much treatment is needed to reestablish plant growth. Because organic matter and soil structure develop over many hundreds of years, an undisturbed native reference site may provide an unrealistic goal for soil regeneration spanning only a few years. For example, a dry, south-facing slope that develops a thinner soil may be a closer representative of the outcome at the project site than a deep, rich soil that has formed for many years on a valley floor.

Ideally, pits should be excavated to the depth of root penetration. Because many plants are deeply rooted, that’s not always practical. Usually most of the important aspects of the horizons can be observed in the top 3 feet (1 meter) of the pit or perhaps in the top 12, 20, or 28 inches (300, 500, or 700 millimeters) in shallower soils. For better lighting and photos, orient the pit so that the wall facing you will be in sunlight when you’re done digging. A pit about 20 inches (500 millimeters) across is usually wide enough to observe soil characteristics. Some soils have repeated patterns of mounds and swales, requiring careful placement of the pit.

**Estimating the Volume of Coarse Fragments**

Keep a pile of the coarse fragments that are excavated from the pit. Coarse fragments include:

- Gravels—Smaller than 3 inches (75 millimeters)
- Cobbles—3 to 10 inches (75 to 250 millimeters)
- Stones—Larger than 10 inches (250 millimeters).

Keep these separate from the finer soil excavated from the pit and estimate the volume of the coarse fragments as a percentage of the whole soil volume. For example, if the pile of rocks is half the volume of the pile with the rest of the soil, the soil would be 33-percent coarse fragments and 67-percent field fines. The coarse fragment (rock) content of a soil reduces the nutrient content, but can allow deeper rooting and can influence plant community patterns.

When samples are taken to the lab, the true fine soil—soil with particles smaller than the head of a pin, about 0.08 inch (2 millimeters)—is sieved out. The rocks and gravels are assumed to have little nutrient content and to dilute the fertility of the fine soil, but in some soils, even the coarse fragments (coarse woody debris and decomposed rock) have significant water-holding capacity or provide important nutrients. In such cases, they should be considered part of the plant community’s soil resource (Whitney and Zabowski 2004; Jones and Graham 1993).

**Soil Horizons**

If you look in a soil pit or on a roadside cut, you will see various layers in the soil. These layers are called soil horizons (see figure 1-14). The arrangement of these horizons is known as a soil profile.

**The O or Organic Horizon**

If the top horizon has more than 20-percent organic carbon, it is called the O horizon. This horizon includes dead material from plant leaves and roots, invertebrate animals, and micro-organisms. Undecomposed plant material on the soil surface is called litter, which decomposes into small pieces called duff. Beneath the layer of undecomposed plant material may be plant material that has broken down into small, unrecognizable pieces and organic residues. This material is called humus. It is usually a dark color and feels slippery or waxy.

While humus generally represents a very small portion of the soil profile (a few percent or less), it performs critical functions, such as holding water, maintaining a crumb structure, contributing nitrogen, and making nutrients more available to plants (Brady and Weil 2002). Humus also benefits other soil organisms, especially the Actinomycetes (a type of filamentous bacteria that creates the “earthy” smell of rich soil). Organic matter in the soil also reduces formation of physical soil crusts and reduces runoff.

Not all natural, undisturbed soils have organic matter horizons. Areas such as deserts or alpine fellfields (rock-strewn areas above timberline) may be so sparsely vegetated that there is very little leaf litter and no humus layer. Desert shrublands may have organic matter distributed in patches under shrubs, with none between the shrubs. Semiarid lands
have from just 0.5- to more than 8-percent organic matter in their soils. Tropical areas also may lack organic matter in the soil because organic matter breaks down so quickly in the warm, humid climate.

High-elevation forested areas with little soil development may accumulate organic materials in a thicker mat in the surface horizons, because materials decompose so slowly in these cold, dry areas. Disturbed areas in the Enchantment Lakes Basin of Washington had a 0.6-inch- (15-millimeter-) thick layer of duff, but foot traffic and lack of plant growth had eliminated this layer from areas that had been impacted by camping (Juelson 2001).

The organic horizons have technical names that are used in soil survey maps. These horizons are sometimes labeled from the top down as: Oi (fresh, undecomposed plant litter), Oe (distinct plant parts, but partially decomposed to fibers), and Oa (unrecognizable plant parts and humus).

The A or Topsoil Horizon

The A soil horizon is the top mineral soil horizon, meaning that it has less than 20-percent organic carbon. The A horizon is rich in organic matter that has leached from the O horizon, giving topsoil a dark brown or gray color. This horizon has the most biological activity, contains much of the soil’s fertility, and allows rainfall to infiltrate into the soil.

Infiltration of water from rainfall and snowmelt depends on a soil’s texture. Infiltration will be relatively rapid if soil texture is coarse or if individual soil particles have formed larger aggregates, separated by drainage pores. The size of these aggregates ranges from less than 0.04 inch to over 0.4 inch (1 to 10 millimeters) in diameter. The aggregates are shaped like small bread crumbs or popcorn.

If the A horizon is impacted or disturbed, some or all of the horizon may be lost. Foot traffic on the O or A horizons will grind these layers to dust that can blow or wash away rapidly. Finely powdered surface horizons indicate mechanical damage (traffic), even if they have not yet eroded away. When the aggregates are crushed, the soil pores are smaller, decreasing infiltration and increasing overland waterflow and surface erosion.

After excavating the soil pits, examine the exposed wall, looking carefully for small horizontal lines or fracture planes between packed or compacted soil (called platy structures). These horizontal structures form when soils are compressed while they are wet, as happens on a trail. The structures indicate loss of drainage and shallower root penetration. Scarification (surface tillage) can disrupt these platy structures, but unless organic matter is incorporated into the soil, the platy structures will quickly reform. If the soil has salt problems, white crusts will form on the surface of the A horizon or on organic matter in the O horizon.

You should observe the soil profile for signs of biological activity, paying special attention to the A horizon. Soil organisms are found primarily in humus, rotting wood, and the upper soil layers. Fungi have root-like structures underground (called hyphae) that form intricate webs (called mycelium). A fungal mycelium is readily observed as white or yellow web-like tissue in the soil or rotting wood. Mushrooms are the mycelium’s fruiting bodies. Mushrooms sprout when the soil reaches appropriate moisture and temperature levels. Insects, worms, or rodent activity are also signs of biological activity. Large pieces of rotting wood are critically important to the survival of fungi and arthropods (invertebrates such as insects and spiders). Rotting wood stores water long after the soil surface moisture has dried out.

In the Enchantment Lakes Basin of Washington, the A soil horizons at undisturbed areas had well-aggregated granular or crumb soil structure, while the impacted sites had platy soil structure, indicating compaction from foot traffic (Juelson 2001). Soil aggregates in the undisturbed soil provided more rapid infiltration of surface moisture and allowed roots to grow deeper on these droughty sites.

Perry and Amaranthus (1990) provide another dramatic example of soil degradation when fragile soils are disturbed. A highly productive forested site on decomposed granite soils in the Oregon Cascades was clearcut for timber. The site was treated with herbicide several times to reduce brush cover. Without plant cover and the organic matter plants provide, the aggregates degenerated and the coarse soil lost
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its structure. The soil’s ability to infiltrate water decreased and the nutrient-rich topsoil horizons washed away. The formerly productive forested site then only supported scattered annual grasses, ferns, and manzanita. Restoration efforts involved replanting the correct tree species and inoculating the soil with mycorrhizal fungi.

The E or Leached Horizon

The next soil horizon in coniferous forests is the E horizon, which is created by rapid loss of clay minerals, leaving a light-colored, sandy layer under the A horizon. These horizons are nutrient poor, and may contribute to unique communities of stunted or endemic plants. Many soils do not form an E horizon.

The B or Subsoil Horizon

As soils develop, clays, carbonates (lime), or salts gradually leach from the A horizon to the B horizon. In a soil pit, the crumb structure of the A horizon will be replaced by larger, blockier structures called blocks or prisms (up to 12 inches or several hundreds of millimeters in diameter). B horizons often are more intensely colored (brown, yellow, or reddish) than the A horizons.

Because the B horizon has higher clay content, it becomes the reservoir of moisture for plant growth during droughty seasons. If the A horizon has been lost because of erosion, the B horizon is exposed. This makes revegetation difficult, because the higher clay content of the B horizon can prevent infiltration. Unless the exposed horizon is modified to make it function more like an A horizon, plants may find it difficult to become established and grow adequate roots.

The C or Parent Material Horizon

The C horizon is little affected by soil-forming processes. If it is comprised of transported sediments, it will be loose, unconsolidated material. If the soil is forming on residual bedrock, the C horizon will be weathered enough to be dug with a shovel. On severely impacted sites with extensive erosion or landslides, the C horizon is the exposed soil that must be revegetated.

Observe how plants grow on nearby soils with simple A/C horizons (a thin A horizon over the C horizon) because this may be the only possible way to remediate remote or large and severely impacted sites. These simple A/C soil systems can be made to work over time, but plant communities growing on such simple soil systems will not develop in the

Did You Know?

About 25 percent of the total root biomass in a tall-grass prairie (figure 3–16) dies each year, contributing organic matter to the soil. The drier short-grass prairie contributes 50 percent of its root biomass to the soil’s organic matter each year, but the total root biomass in the short-grass prairie is less than in the tall-grass prairie.

Figure 3–16—Prairie junegrass (Koeleria macrantha). Photo by J. Lokemon, Northern Prairie Wildlife Research Center, U.S. Department of the Interior, U.S. Geological Survey.
same way as plant communities growing on complete soil systems.

If subsurface rocks are exposed at the site, look for ways to incorporate them into site design. They could be used to provide a hardened surface that can resist erosion and handle more foot traffic. The rocks can be used to help delineate sites or paths or to improve the microclimate for plants.

Sometimes layers of volcanic ash show up as reddish or gray bands (figure 3–17) separating the dark organic layers. Such soil profiles may mean that organic matter accumulated at an A horizon before an eruption buried that surface. Organics accumulated at the new surface, regenerating an overlying A horizon. These buried horizons could be used to cover exposed subsoil horizons. They may not be biologically active, but may contain residual organic carbon and may have a particle size distribution that is more suitable for plant growth than an exposed B horizon. You might consider using these buried horizons for restoration if you have opportunities to salvage soil.

When you examine an impacted site, determine which soil layers are missing relative to the reference site, and whether it is feasible to replace the missing layers. A change in soil depth (known as soil potential) probably will change the types of plants that can grow on a site. In some cases, as soil depth is lost, the same species may grow on the site but the plants may be smaller or may be spaced farther apart. In some cases, the impacted site (which could be an eroded trail) needs to be brought back up to grade. The project design should specify the type and amount of each soil layer needing replacement.

3.1.3 Evaluating the Surface Condition of Impacted Sites

The surface condition of the impacted site, including patterns of crust formation, compaction, erosion, and slope stability, should be compared to that at the reference site. Soils typically will be covered with a layer of plant litter and a fine, powdery layer of decomposed organic materials. If this layer is at the reference site, but is not at the impacted site, why is it missing? Does its absence indicate the zone of disturbance or a normal difference in soil formation?

Be cautious. Some natural areas, such as the rocky pavement of desert areas, do not have an organic layer. In such cases, the mineral surface of the ground may be exposed, but the upper sides of undisturbed stones and gravels probably have a dark patina. Because the patina takes a long time to form, it indicates a landscape that is relatively undisturbed.

Organic-rich layers may be present under plant canopies or in the lee area downwind of plant clumps, but not in the open areas between plants. Biological crusts (see section 3.1.3c, Evaluating Biological Soil Crusts) can help determine whether such areas have been disturbed. In alpine areas, lichens growing on rocks may indicate that the area has not been disturbed for many years (figure 3–18).
Another indicator of erosion is the presence of lag gravels. These lag behind when the fine soil surrounding them erodes away—the lag gravels often form a pebble pavement (figure 3–19). To confirm the presence of lag gravels, check the soil horizon to see whether more gravel is on the surface than in the next lower horizon.

The soil may have geological bands of gravel deposits. In such cases, there should be other examples of soil deposition elsewhere in the soil profile, such as fine and coarse bands from stream deposits. If the soil is made predominantly of fine particles, it could erode without lag gravels accumulating on the surface.

In any of the cases discussed above, if erosion is occurring, a depositional delta of fine particles should be visible somewhere nearby, either downstream or downwind. Deposits of fines may show up in small terraces—about 4 inches (100 millimeters) high—that accumulate behind plant litter or grass clumps, or as small deltas in low-lying areas where water slows. Depending on the slope and water velocity, these deltas may be several feet (a meter) to several yards (meters) away from the area that lost the fines.

When the surface litter is removed, fine particles in the soil are exposed to the impact of raindrops and to drying cycles between rains. Raindrop dispersion crusts will form within 0.04 to 0.08 inch (a millimeter or two) of the surface. These crusts may become weak to moderately strong. Sometimes this crust will have the horizontal platy structure that forms with compaction from foot traffic. If crusts form, the soil becomes less porous and less rain infiltrates. Precipitation and snowmelt increasingly flow overland, producing the surface waterflow that leads to particle transport and erosion.

3.1.3a Visual Clues for Evaluating Erosion

Erosion is caused by the impact of raindrops on bare soil, by the force of running water on the soil surface, by wind, and by rodent activity. Erosion is a natural process that leaves its signs across the landscape. Erosion from unnatural processes, however, often moves more soil more quickly than the erosion that occurs naturally. Erosion from unnatural processes produces significant impacts that require treatment. Both types of erosion are influenced by climate, soil type, slope, and vegetation type. Loam and silt loam soils are more erodible than clay or sandy soils. However, sandy granitic soils are highly erodible. Steep slopes are more erodible than...
gentle slopes. And well-vegetated slopes, especially those with a variety of root forms and aboveground biomass, are less erodible than areas with sparser vegetation.

Plant cover, surface debris, and biological crusts stabilize the soil. Bare soil between plants is the most susceptible to erosion. Soil compaction allows increased runoff. Trails that are poorly located or maintained funnel water into erosion channels (figure 3–20a). Sloped campsites lose soil in a downhill flow. Additional factors contributing to erosion include soil surface stability, soil aggregate stability, water infiltration, and organic matter content, all of which can be evaluated in comparison with suitable reference sites. Heavy grazing or weed establishment increases the risk of erosion.

than the upper horizons in the soil profile, the fine soil may have been eroded away, leaving the heavier rocks to “lag” behind (see figure 3–19). If the process is very slow, as it is in the desert, the rocks may have a dark, oxidized patina, indicating slow erosion rates. If the soil is actively moving away from the local area because of raindrop impacts, soil protected under bits of wood or rocks may form pedestals (small, uneroded columns of soil with a protective cap). This indicates a more rapid, possibly unnatural process.

• Exposed roots—If soil has moved since a tree or shrub grew roots into the soil, the exposed roots will show the old soil levels (figure 3–20b).

Figure 3–20a—Sheep driveways established in the 1880s became the Forest Service trail system in the high country of many wilderness areas. Because this former driveway was located on the fall line, running water continues to widen and erode this trail in the Alpine Lakes Wilderness, WA.

Clues for surface erosion and degraded soil condition at the impacted site relative to the reference sites include:

• Bare soil—Unless the soil has been recently disturbed (by a burrowing animal or fallen tree, for instance), the soil should have a protective biotic crust, a thin layer of organic duff, or an armoring layer of gravel or stones.

• Lag gravels or plants or rocks on “pedestals”—If the surface has many more gravels or stones

Figure 3–20b—Exposed roots show the old soil level.
• Terracettes—Level benches of soil deposited behind obstacles are an indication that erosion removed the surrounding soil (figure 3–21).

Figure 3–21—Vegetation growing on level benches of soil deposited behind rocks is evidence of past erosion.

• Waterflow patterns—An increase in the number, size, and connectivity of waterflow patterns (rills) between plants is an indication of erosion.

• Soil deposition at slope changes—Where a steep slope flattens into a shallow slope, the speed of waterflow decreases and sediments will deposit, forming a fan if soil is being eroded.

• Changes in thickness of topsoil—Thick topsoils in areas of deposition (swales or lower on slopes) mean soil has been lost higher up the slope (on the shoulder of the slope or midslope).

• Exposure of subsoil at the surface—Subsoils are marked by higher clay content, redder color, or larger blocky or massive soil structure. These subsoils may form small cliffs. The softer surface soils and deeper subsoils weather away, leaving the subsoil protruding prominently.

• Rills, headcutting (movement of a gully upslope by progressive erosion), and/or downcutting (deepening) in gullies—Rills (only about 0.1 inch or a few millimeters deep) are formed by moving water that has enough energy to carry sediment.

• Reduced plant vigor—As topsoil is removed, less moisture and nutrients are available for plant growth and plants are smaller.

• Long, unsheltered, smooth soil surfaces—Wide expanses of fines in playas or deltas, with silt accumulations behind rocks or shrubs in gullies are potential indicators of windblown sites.

• Exposed, erosive subsoil under a resistant cap—Look for evidence of rodents burrowing into terraces or pedestals, further eating away at the remaining soil. Pedestal faces relate to trails or old erosion patterns, not to natural landforms and stream hydrology (U.S. Department of Agriculture Natural Resources Conservation Service, Soil Quality Institute 2001c).

• Evidence of wind erosion—Wind-scoured areas between plants, a drifted or rippled soil surface, biological crusts buried by blown soil, loose sand on physical crusts, and soil or leaf litter accumulating on the leeward side of plants and obstacles are signs of wind erosion (U.S. Department of Agriculture Natural Resources Conservation Service, Soil Quality Institute 2001d).

Table 3–1 provides a summary of soil indicators you might consider during your soil assessment.
### Table 3–1 —Indicators of soil quality and their relationship to soil health. (Adapted from Guidelines for Soil Quality Assessment in Conservation Planning, U.S. Department of Agriculture Natural Resources Conservation Service, Soil Quality Institute 2001a)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Influence on soil function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil organic matter (SOM)</td>
<td>Improves fertility, soil structure, soil stability, nutrient retention, soil erosion, and available water capacity, but must be renewed by continued plant growth.</td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Soil structure</td>
<td>Good soil structure and aggregation increases water infiltration, retention of water and nutrients, and habitat for microbes, while decreasing erosion. Aggregates are destroyed by traffic and plant removal.</td>
</tr>
<tr>
<td>Depth of soil and rooting</td>
<td>Deeper soil increases site potential (annual weeds vs. forbs vs. shrubs vs. trees). Soil compaction, plow pan, and impermeable rock layers reduce growth.</td>
</tr>
<tr>
<td>Infiltration and bulk density</td>
<td>Soil structure increases and bulk density decreases water movement, soil porosity, and soil workability (soil tilth).</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>Soil reaction (pH) has wide ranging influences on biological and nutrient availability, and on plant species that are appropriate for restoration.</td>
</tr>
<tr>
<td>Electrical conductivity (EC)</td>
<td>EC is a measure of salinity, which influences plant growth, microbial activity, and the formation of salt crusts.</td>
</tr>
<tr>
<td>Cation exchange capacity (CEC)</td>
<td>The capacity of soil to hold nutrients for plant use. Specifically, CEC is the amount of negative charges on clay and humus that are available to hold positively charged ions.</td>
</tr>
<tr>
<td>Extractable nitrogen (N), phosphorus (P), and potassium (K)</td>
<td>These plant nutrients are essential for growth. Excess nutrients may degrade local watersheds.</td>
</tr>
<tr>
<td><strong>Biological</strong></td>
<td></td>
</tr>
<tr>
<td>Microbial biomass carbon (C) and nitrogen (N)</td>
<td>Microbes catalyze the decomposition of organic matter to release nutrients for continued plant growth. The microbial biomass provides a repository for carbon and nitrogen, creating a long-term nitrogen supply.</td>
</tr>
<tr>
<td>Potentially mineralizable nitrogen (PMN)</td>
<td>An operational pool made up of microbial plant litter and animal scat that provides a medium-term nitrogen supply. Soils with low PMN have short-term and often insufficient supplies of nitrogen.</td>
</tr>
<tr>
<td>Soil respiration</td>
<td>Respiration indicates microbial activity, which relates to nutrient cycling, organic residue formation, soil aggregation, root health, and symbiotic associations.</td>
</tr>
</tbody>
</table>
On the undisturbed site, you can expect to see several types of evidence of soil stability if erosion processes are minimal (except in areas such as naturally occurring badlands or sites at high elevation). Evidences of stability include an accumulated layer of plant litter and powdery organics in the O horizon, formation of weathering patinas or dark stains on surface rocks, aggregated soils, and a lack of surface erosion patterns, including pedestals or deltas formed by transported particles. Biological crusts formed by bacteria, fungi, lichens, algae and mosses that tolerate drying are another desirable feature of stable soil. Crusts create a natural protective layer at the ground surface that resists erosion.

3.1.3b Evaluating Physical Soil Crusts

Soil surfaces often develop a structured surface layer called a soil crust. A physical crust is a thin, compressed layer of soil minerals that indicates a loss of soil aggregate structure, decreased water infiltration, and increased runoff. Physical crusts are commonly formed by raindrop splash, erosion, and intense fire. Physical soil crusts support very little biological activity.

A physical crust is likely to be found on a site that has very little organic material where the soil aggregates are disintegrating into single-grain particles. A physical crust may form after a restoration treatment once the soil has been decompacted. The combination of a smooth surface and the lack of organic matter provide conditions for the formation of physical crusts. Physical crusts reform quickly after disturbance as raindrops disperse the fines and settle them into a thin, dense layer. Drying allows the crust to harden. Many wilderness campsites or social trails are firmly compacted, but they would not be said to have a crust because the surface is not denser or more structured than the underlying soil profile.

Excess salt in the soil can promote a chemically induced physical crust. Salt crusts appear as white areas that coat the existing soil surface. Some physical crusts formed by the evaporation of small pools of water are harmless. These have been observed in granitic areas where a pool of rain has evaporated and left a frost-like ring of salt crystals on pine needles on the forest floor. Lowland areas and arid environments can generate more serious salt accumulations, which are visible as some pattern of light-colored evaporates (salt crystals) from groundwater or rainwater. The salt may be left in lines that form on the sides of ponded areas, at the top of mounds of soil, or as rings around seeps. The measurement of salinity will be covered in section 3.2.2, *Soil Nutrients, pH, and Salts*.

To evaluate a site for physical crusts, lift the soil surface with the tip of a knife and look for cohesive layers parallel to the soil surface. Physical crusts (figure 3–22) will have no evidence of organisms, such as dangling plant roots or cyanobacteria holding the layers together. Fragments of a physical crust will fall apart (slake) when they are placed in water. This test is used to distinguish them from cemented layers that would occur in drier environments. Platy structures parallel to the soil surface that disintegrate in water are the clues to identifying physical crusts. Well-aggregated soils break into round crumb structures rather than platy structures.

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The formation of a physical crust will deter a site’s recovery. First, crusts indicate a soil low in organic matter. Raindrops disperse the soil into particles that clog pores in the soil, impeding plant growth. Second, the crust’s low infiltration rate means rainwater and snowmelt will not seep down into a soil, but will run off the surface as sheet flow. Third, crusts suggest that salts or too many fine particles may cause drainage or nutrient problems. Tillage can disrupt crust, but organic material must be amended into the soil to keep the crust from reforming during the next rain. Foot traffic can disrupt a surface crust, causing it to disappear, but it will reform readily.

3.1.3c Evaluating Biological Soil Crusts

Some crusts are beneficial. A biological or microbiotic soil crust is comprised of bacteria, fungi, algae, lichen, mosses, or liverworts that form at the soil surface, stabilizing the soil, improving water infiltration, and increasing the flow of water and nutrients to plants. Biological crusts have an uneven surface and pore spaces that increase infiltration, reducing runoff. Although biological crusts can enhance seed germination, depending on the type of crust and plant species involved, in very hot deserts biological crusts may inhibit germination. Unlike physical crusts, biological crusts have high levels of organic matter, typically are the colors of the organisms that form them, and are not prone to slaking in water.

Although biological crusts do not form in all soil types and vegetative communities, the presence or absence of a biological crust is critically important in some environments. Biological soil crusts are common in arid and semiarid regions and in alpine areas with little litter accumulation. Crusts also have been studied in native prairies, in the sandy soils of Glacier Bay, AK, and even in the Antarctic.

Biological or microbiotic crusts also are referred to as cryptogamic, cryptobiotic, and microphytic crusts, depending on the type of organisms present. Biological crusts form when living organisms or their byproducts create a surface crust of soil particles bound by organic materials (figure 3–23). In disturbed sites, look for biological soil crusts in fenced areas, lightly used areas under shrubs, or between closely spaced rocks.

Figure 3–23—This electron micrograph shows soil particles bound by the sheaths of micro-organisms found in biological crusts. Photo courtesy of the U.S. Department of Agriculture Natural Resources Conservation Service.

Biological crusts vary tremendously in thickness, texture, color, and in the species that form them. For example, the cyanobacteria that are dominant in arid soils form pinnacles up to 6 inches (150 millimeters) high (figures 3–24a and 24b). Other soils may have moss or lichen growing on the surface (U.S. Department of Agriculture Natural Resources Conservation Service, Soil Quality Institute 1997 and 2001b). A common pattern is for a moss or lichen crust to form terracettes, benches 2 to 4 inches (50 to 100 millimeters) wide that are flatter than the slope angle. Because the terracettes are stable when wet, they trap sediment and persist during rains.
Figures 3–24a and 24b—Intact biological soil crusts (top) provide many ecological benefits. They stabilize the soil, increase nutrient flow to plants, and provide safe sites for seeds to germinate (bottom).

Rocks or large plants often serve as microhabitats, creating safe sites for biological crusts and other plants to grow around or under. In evaluating the reference site, note such features and include them in the restoration prescription, if feasible. The rocks provide shelter, additional moisture from runoff, shade, heat, and protection from trampling.

3.1.4 Soil-Water Relations

A soil’s ability to provide water for plant growth is influenced by three factors:

- Infiltration of moisture
- Water-holding capacity
- Overall size of the rooting volume

3.1.4a Soil Texture and Pore Size

Infiltration is governed by the size of pores in the soil. Healthy soils are about 50-percent open pore space. That space is divided into many individual pores of various sizes. The distribution of large and small pores determines how well the soil soaks up moisture and holds it for plant growth. Large, continuous pores allow rainwater or snowmelt to infiltrate into the soil. These pores are created by burrowing insects and worms, old root channels, and spaces between large soil aggregates. Small pores, on the other hand, retain

If a biological soil crust has been broken, compressed, or removed because of grazing pressure or compaction (figure 3–25), the soil is susceptible to wind and water erosion, as well as the formation of a physical crust. In addition, the biological crust loses some of its ability to fix nitrogen. If biological crusts are buried by blowing sand, they will die. Fire also can kill organisms that form biological crusts. For more information on biological soil crusts, visit the U.S. Geological Survey Canyonlands Research Station’s Web site at http://www.soilcrust.org.

Figure 3–25—Biological soil crusts are easily damaged.
water that plants can use later. The small pores are mainly spaces between clay and silt particles.

Infiltration can be improved by the formation of soil aggregates, which create voids between adjacent clusters of soil particles. Macroaggregates are 0.01- to 0.4-inch (0.25- to 10-millimeter) groups of soil particles glued together by soil organic materials and fungal hyphae. Spaces between aggregate clusters are large enough for water to flow through. Gravity can pull water through pores that are as large as about 0.1 inch (several millimeters) or as small as about 0.0003 inch (7 micrometers)—10 times thinner than a human hair. When water falls on degraded sites, it often does not infiltrate. Instead, the water begins to flow overland, generating erosion and transporting sediment.

3.1.4b Available Water-Holding Capacity

After water has infiltrated, the soil’s ability to hold water until plants use it is called the available water-holding capacity (AWC). This value is estimated from the maximum soil water capacity after a rain minus the residual water plants cannot withdraw from the soil. The maximum soil water capacity is called the field capacity, defined as the water content after the soil is drained by gravity after a rain. This amount is estimated by applying suction with a pressure of about –0.0142 British thermal units per pound (–33 joules per kilogram) of soil. This negative pressure used to be described as “–1/3 bar” (1 bar is normal atmospheric pressure). Residual water left when crop plants can no longer remove moisture (wilting point) is set at –0.6449 British thermal units per pound (–1,500 joules per kilogram, formerly –15 bar”). Some wildland plants can withdraw water to pressures of –2.1496 British thermal units per pound (–5,000 joules per kilogram, formerly –50 bar).

While compost, soil aggregates, root channels, and animal burrows help increase infiltration of moisture into the soil, they have less effect on the water retained during droughty periods. Clay content is the primary soil characteristic that influences the amount of water retained in the soil during drier conditions. In such conditions, water is estimated to be held in pores 0.00001 inch (0.16 micrometer) or smaller (based on a hypothetical circular pore). Clay particles are 0.0001 inch (2 micrometers) or smaller. The spaces between these particles create pores of the appropriate size to store water that can be withdrawn by a plant during dry conditions. Often, wildland plants can withdraw water held in pores smaller than 0.000002 inch (0.05 micrometer). Because only clay-sized particles provide such small pores, little else in the soil can provide this kind of long-term moisture retention.

Generally, if soil AWC was less than 10 percent, moisture retention was increased with organic amendment using yard waste components (Curtis and Claassen 2005). If the soil’s AWC was greater than 10 percent, net water availability remained about the same after amendment, although infiltration increased. If organic amendments are near the surface, however, they may dry out by evaporation before plants can access their stored water later in the year. Moisture deep in the profile is more likely to be available to plants during dry times. Another way to increase moisture availability is to increase rooting volume by decompacting the soil.

The distribution of pore sizes controls water relations in soils. The pore structure tends to be more open in the upper horizons compared to the lower horizons. This distribution occurs because organic materials that accumulate in the A horizon increase particle aggregation. The smaller pores in the clay-rich B horizon pull harder on the soil moisture, drawing it deep into the soil profile. When fine-textured substrates are on top of coarse-textured substrates (small pores over large pores), soil water may not percolate deeply into the soil. It may remain near the surface where it can evaporate or run off.

An example of this situation occurs in the Enchantment Lakes Basin of the Alpine Lakes Wilderness in Washington where fine-textured ash soils overlie coarser mixtures of ash and glacial gravels (Juelson 2001). Water is retained in the upper horizons, especially when the impacts of foot traffic cause soils to lose their structure. A potential treatment