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Soil Disturbance Rehabilitation: A Desk Guide to Techniques and Monitoring

Cover photo—Soil displacement on an undisturbed, single-equipment pass trail and a multiple-equipment pass trail.

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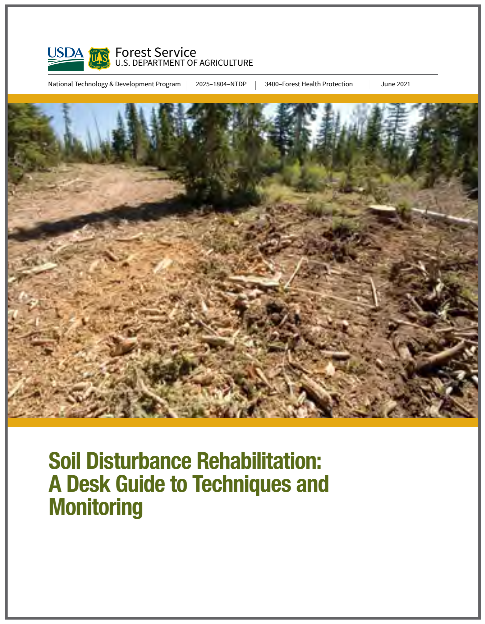

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Executive Summary

Soil rehabilitation is reestablishing disturbed soil back to healthy conditions to raise site productivity as quickly as possible. Soil rehabilitation is a field of interest for the U.S. Department of Agriculture, Forest Service and an important resource management strategy that promotes and enhances ecosystem restoration. Site productivity directly relates to soil physical, chemical, and biome health; vegetation growth rates; and the biodiversity within plant and animal community assemblages. The National Forest Management Act regulates actions that substantially or permanently impair site productivity. It directs the Forest Service to protect, improve, and maintain renewable resources of denuded or deforested lands (USDA 1976)—the focus of this guide. Principles of soil rehabilitation are complex, and solutions are not simple, but resource managers can dramatically improve soil quality by developing site-specific, cost-effective rehabilitation plans. Each site approach should specify the required equipment and operating conditions to move forward successfully. The planning approach, appropriate methodology, equipment selection, and use of trained operators are crucial. Variability within results among sites should be expected, based on the individual site conditions (soil textures, organic matter, rock fragment size, landscape, and hydrology). More information is needed on the beneficial effects of the current methods when determining future forest productivity and timber operations—specifically on the productivity gains resulting from topsoil retention, decompaction, scarification, tillage, subsoiling, soil amending, revegetation, and reforestation. This guide provides descriptions of these techniques and the essential information gaps affecting their use.

Chapter 1—Introduction

Healthy soil is essential to the success of site restoration and rehabilitation efforts that lead to successful regeneration. The resource manager understands how soil physical, chemical, and biological properties interact. Soil ecological knowledge (SEK)—knowledge of the soil properties belowground to aboveground—is critical to success in implementing soil rehabilitation. Soil rehabilitation requires an integrated process, rather than a piecemeal approach (Heneghan et al. 2008)—with the SEK of a resource manager who understands the soil and vegetation that may influence aboveground and/or belowground attributes. Reaching rehabilitation goals depends on knowledge of the site's specific characteristics, its historical condition, how degraded the soil is, and the processes that produced the soil disturbance.

The resource manager works on Federal, State, industrial, or private lands to reduce soil disturbance during timber harvesting operations. These operations can cause significant soil compaction, displacement, rutting, and erosion. These direct impacts can vary within sites based on harvesting methods, the types of machinery used, the extent of machine impacts, and individual site conditions. For example, skidding operations tend to displace the top organic layer of soil, exposing the mineral soil below. Temporary road construction required for crews and equipment to access harvesting units removes topsoil and surface vegetation, causes soil compaction, interrupts natural hydrology, and leads to soil erosion. Additionally, conducting timber harvesting operations when conditions are suboptimal (e.g., when the ground is saturated) causes deep ruts and further increases the likelihood of soil damage. The U.S. Department of Agriculture, Forest Service has developed soil disturbance indicators and soil quality guidelines to evaluate how specific management practices affect soil properties. Forest Service resource managers can assess soil disturbance indicators qualitatively through visual observations or quantitatively by collecting soil samples for subsequent analyses. The Forest Service uses a qualitative visual approach and classifies the extent, degree, and duration of soil disturbances into the following categories (Page-Dumroese et al. 2009):

- Loss of forest floor (figures 1-1 and 1-2)
- Increased compaction (figure 1-3) or platy structure (figure 1-4)
- Topsoil displacement (figure 1-5)
- Development of deep ruts (figure 1-6)
- Severe burning (figure 1-7)

Figure 1-1—Loss of forest floor in a western spruce-fir forest.

Figure 1-2—Loss of forest floor in a longleaf pine and slash pine forest.

Figure 1-3—Compacted soil from the main skid trail indicating that the skid trail may have been used during suboptimal moisture conditions.

Figure 1-4—Platy soil structure from the main skid trail.

Figure 1-5—Topsoil displacement in a lodgepole pine forest. The soils here are shallow to moderately deep and are at high risk of erosion with removal of ground cover.

Figure 1-6—Deep ruts created with a single equipment pass with subsequent puddling.

Figure 1-7—Soil damage from severe burning.

Soil quality guidelines help resource managers determine the extent of soil disturbance and the impacts on soil productivity and hydrologic functions. Schoenholtz et al. (2000) determined that chemical and physical soil properties—such as bulk density, infiltration rates, soil chemistry, respiration rates, and changes in microbial and vegetation communities—are important indicators of soil quality to evaluate ecosystem functioning. Soil quality guidelines provide a reference areal extent limit. Harvest crews should strive to keep the amount of disturbance below this limit, and resource managers usually take actions to remediate the site if conditions exceed the limit. The areal extent concept is similar to a "threshold of irreversibility" (Laycock 1991). The threshold is often not easy to detect or quantify, but once an ecosystem reaches that threshold, returning it to proper functioning may be difficult.

For example, in the Forest Service Manual (FSM), the limit for detrimental soil disturbances is no more than 15 percent of an activity area (U.S. Department of Agricuture, Forest Service 2011). This limit ensures that the site or soil may recover from damage within a reasonable period (figures 1-8 and 1-9).

Figure 1-8—A site recovering from soil disturbance two years after harvesting.

Figure 1-9—Fine roots found throughout a soil sample indicate root biomass and soil recovery at the site in figure 1-8.

Not all disturbances are detrimental, and resource managers should assess conditions on a site-specific basis. According to the Council on Environmental Quality, which oversees the National Environmental Policy Act, actions for mitigating soil disruption include:

- Avoiding impacts
- Minimizing impacts
- Rectifying impacts by repair or rehabilitation
- Reducing or eliminating impacts over time
- Compensating for impacts

Soil rehabilitation treatments focus on remedying compaction, amending soil, and reestablishing vegetative cover (figures 1-10 and 1-11). Figures 1-12 and 1-13 show understory vegetation growth from a rehabilitated site leading to an acceptable surface soil texture. Decompaction methods (described in the Mechanical Treatments section) remedy compaction by breaking up high soil bulk density areas. Organic matter supplementation (described in the Soil Amendment Treatments section) helps increase plant rooting depth and microorganisms, provides increased pathways for water infiltration, and improves nutrient cycling and carbon storage processes (figure 1-14). Figure 1-15 illustrates rehabilitated soil conditions that resulted from a supplemental organic matter treatment.

Figure 1-10—Signs of increased compaction in the main skid trail over the single-pass trail.

Figure 1-11—Increased resistance is apparent along with visual indicators of compaction deeper into the profile.

Figure 1-12—Understory vegetation rehabilitation with improved soil health.

Figure 1-13—A closeup of the acceptable surface soil texture from soils at the rehabilitated site in figure 1-12.

Figure 1-14—Mulch provides cover and reduces erosion.

Figure 1-15—A closeup of soil conditions within the skid trail covered in mulch.

An essential step for resource managers to determine the effectiveness of rehabilitation methods is to define clear, inherent, results-oriented goals that achieve proper soil or ecosystem functionality or site productivity. These goals involve factors, such as the assemblage of plant and animal communities, nutrient cycling and hydrologic functions, and the production of roots and shoots within a designated period (Allen 1992). Soils develop and evolve over decades (even centuries), and actions a resource manager takes to restore or rehabilitate soil functions will not provide immediate results. However, proper rehabilitation measures can produce suitable conditions for minerals, microbes, organic matter, nutrient cycling, and water infiltration to develop over time. Powers and Avers (1995) found that short-term sampling provides reference data and indicates initial conditions. Long-term data is still essential for evaluating treatment effectiveness and indicates soil and forest floor recovery (figures 1-16 and 1-17).

Figure 1-16—A sampling quadrat used to evaluate forest floor recovery.

Figure 1-17—A closeup of the soil structure from the site in figure 1-16.

The authors compiled this *Soil Disturbance Rehabilitation Desk Guide* using outcomes and examples from various national forests throughout North America, coupled with extensive literature reviews. The guide covers rehabilitation methods and their applicability, ease of implementation, challenges, relative effectiveness, and accompanying results.

Chapter 2—Soil Rehabilitation Methods

Resource managers often prefer to avoid or minimize impacts to the soil to maintain forest health. Avoiding detrimental disturbance is also much less expensive than rehabilitating and repairing soil damage. National forest management practices (harvest or fire activities) significantly alter stand vegetation dynamics and complex soil functions. These activities modify the physical, chemical, and biological factors that affect healthy ecosystem functions. Skidding operations can cause deep ruts, remove organic matter, and expose mineral soil. The type and quantity of heavy equipment and the number of passes affect the degree of soil compaction. Heavy machinery, such as bulldozers, used to access the harvested areas can remove topsoil and vegetation, interrupting hillslope hydrology and causing soil erosion. Restoration crews may use heavy equipment in preparing sites following harvest operations to remove undesired and competing vegetation, create planting spaces, or prepare the soil for natural regeneration. This process itself may lead to further soil impacts.

Additionally, equipment turning on steep slopes can expose lower-productivity subsoils through displacement (figures 2-1 and 2-2). Burning slash and reducing residue can kill soil organisms, volatilize nutrients, and alter organic matter. Removing the overstory plants changes soil temperature and moisture regimes, thereby altering microbial community structure and function. Responsible forest management practices include remedying the effects of these types of ecological damage. Methods for soil rehabilitation include:

- Mechanical treatments
- Soil amendment treatments
- Revegetation treatments
- Soil hydrology treatments for riparian areas
- Natural ecological succession over time

Figure 2-1—Deep ruts and surface soil displacement from turning equipment.

Figure 2-2—Soil displacement on an undisturbed, single-equipment pass trail (left side of photo) and a multiple-equipment pass trail (right side of photo).

Mechanical Treatments

Most measurable impacts from harvest operations are specific to the local climatic regime, landform, slope aspect, and topography (Heninger et al. 2002). Considering each site unique and treating each site separately may produce the best results. Certain restoration activities adapted to local climates and specific soil textures may work better than others. Comparing soil quality at the disturbed site to an adjacent or nearby reference site that remains undisturbed can provide a benchmark for restoration (figures 2-3 and 2-4). Soils composed of sand, silt, and clay make up three broad soil texture groups—fine, medium, and coarse. Fine-textured soils include clay loam or clay, medium-textured soils include silt loam or loam, and coarse-textured soils include sandy loam or sand.

Figure 2-3—A sampling quadrat at an undisturbed, reference site.

Figure 2-4—A closeup of the soil structure from the undisturbed, reference site in figure 2-3. Notice the abundance of roots throughout the sample.

The British Columbia (B.C.) Ministry of Forests *Soil Rehabilitation Guidebook* used a method that dictates soil rehabilitation best management practices based on soil texture. Soil texture influences the impacts of soil compaction. In coarse, sandy soils with abundant large pores, some conversion to smaller, more compacted pores can benefit plant growth. Smaller pores delay water passage through the soil and increase the amount of water available for plant uptake (Hillel 1971). However, in finer-textured soils, the effect of compaction on plant roots and growth is usually negative, especially in clay, where most large pores are between soil aggregates. Compaction smashes these aggregates into a visually apparent platy structure that lacks large pores. Compacted clayey soils can become waterlogged, leading to oxygen deficiencies that cause plant roots to die (Hillel 1971). Clayey soils are typically firmer than other soils when dry. They are still highly susceptible to compaction, rutting, and puddling when wet or moist, consequently posing problems in forest road design. Therefore, understanding soil texture is essential during both forest management planning and subsequent rehabilitation efforts.

Forest Floor

The forest floor contains many organic materials (specifically in the topsoil layer) that are important to a forest ecosystem. Maintaining organic materials during harvesting activities is critical. These materials protect the mineral soil from erosion or compaction, act as a mulch to limit evaporation from the soil, and provide a home for microbes that perform the essential functions of nutrient cycling and carbon sequestration, enabling successful revegetation. Protecting organic matter during harvesting is critical because it often takes decades for this layer to recover.

Topsoil Retention

Topsoil is the fertile, upper layer of mineral soil with a higher organic matter content. It often has many macropores that are necessary for water infiltration, nutrient movement, and soil aeration. Organic matter, plant roots, fungal hyphae, clay binding, aluminum, and iron hydroxides stabilize mineral soil aggregates and macropores. Root expansion, soil fauna, and freeze-thaw and wet-dry cycles are crucial for creating and stabilizing soil aggregates. Organic matter content influences aggregate stability in surface soils and can prevent mineral soils from severe compaction damage. Plotnikoff and Bulmer (1999) report that organic soils (e.g., peat) are especially susceptible to displacement, rutting, and puddling because these soils have low load-bearing strength (figure 2-5). Subsoils typically have a denser parent material, such as clay or compacted till, a high sand content with low water-holding or nutrient-storing capacities, larger amounts of coarse fragments (equal to or more than 35 percent—"skeletal with lots of coarse fragments"), or high amounts of calcium carbonate. Bulmer (1998) noted that subsoils have a firmer, more stable structure due to clay-rich subsoils with low organic matter content.

Land management activities (road construction, skid trails, and landings) often remove or degrade the mineral topsoil (Steinfeld et al. 2007a, 2007b). However, retaining and protecting the forest floor benefits forest productivity by supporting the structure and aeration in clayey soils and the water-holding capacity of sandy soils. Sand naturally has a higher infiltration rate than clay, so the available water-holding capacity in sandy soils may be limited (Hillel 1971). One method to improve this is to add organic matter, which helps both clayey and sandy soils retain water, while also supplying nutrients.

Retaining and stockpiling topsoil (mineral soil and organic matter) at a site involves stripping, possibly transporting, storing, and then returning the soil to the site. Separating the forest floor from the mineral soil and then adding it to the mineral soil surface when returning to the site has beneficial effects. Sanborn et al. (1999a) found total carbon, nitrogen, and sulfur concentrations increased by adding topsoil to a degraded site and concluded that this treatment helped restore fertility in fine-textured soil. Abdul-Kareem and McRae (1984), Miller (1984), and Ross et al. (1992) also found that the stockpiling process had varying effects on the chemical and biological properties of the reserved soil (stripped, stored, and added back). For example, Visser et al. (1984), observed an immediate loss of organic carbon and reduced microbial biomass in the reserved soil. They added glucose to stockpiles

Figure 2-5—A puddled soil condition shows the effect of both a structureless condition and an impaired hydrologic function.

and found that the soil responded more slowly to the addition of glucose than soil from undisturbed and cultivated treaments, due to gradual decomposition of organic materials. However, they did not find any unfavorable adverse effects on decomposition rates or primary productivity. According to Hogan and Drake (2009), resource managers planning to reuse mineral topsoil must consider:

- A short storage time of 3 months or less
- Covering the stockpile to retain moisture
- A method for preventing compaction
- A method for preventing subsoil mixing

While stockpiling may be tedious and time consuming, it is more effective than importing mineral topsoil or the forest floor. However, resource managers could potentially use topsoil salvaged from other projects to supplement the material onsite (B.C. Ministry of Forests 1997).

Scarification

Scarification is "scratching" or breaking up and loosening the soil to a shallow depth using hand tools or machines. Scarification distributes the forest floor by rearranging the plants' litter and mixing it with or exposing some of the mineral topsoils below. Scarification may also include removing competing vegetation and surface organic matter. Removing competing vegetation allows seedlings to reach a free-to-grow state faster and expand their root systems to capture water resources. However, depleting surface organic matter alters nutrient cycles and soil water-holding capacity and, if the scarified areas are large, may result in erosion (Greacen and Sands 1980).

One way to evaluate the effectiveness of scarification is to monitor the recovery of vegetation. Cole and Spildie (2007a, 2007b) evaluated various restoration treatments and examined shallow, sandy, and acidic soils derived from granitic substrates. After 10 years, the nonscarified treatment plots had an average plant cover of less than 1 percent. The scarified treatment plots had an average plant cover of 3 percent. This difference, though small, indicates the potential benefits of scarification. Aoyama et al. (2009) used a scarification treatment in northern Japan to examine natural regeneration. The scarification treatment was highly successful, resulting in a 150-fold increase in growth compared to the nonscarified treatment site. The improvement to soil density and availability and distribution of nutrients enhanced the growth rate. In the central Rocky Mountains, Esquilín et al. (2008) studied soil scarification and subsequent wildfire impact on microbial community structure in ponderosa pine (*Pinus ponderosa*) forest floor. They concluded that soil scarification aided seedling establishment, long-term soil carbon reserves, and microbial communities. Johansson et al. (2013) experimented with various scarification techniques. They found that the techniques yielded varying seedling tree growth rates during the establishment phase. Still, all scarified plots had more than twice as many naturally regenerated trees as nonscarified plots for the same period during the establishment phase. Cole and Spildie (2007b) also found evidence that scarification can complement other restoration techniques.

Decompaction

Forestry equipment can cause soil compaction and soil displacement (figures 2-6 and 2-7), leading to an altered soil ratio of micropores to macropores (Page-Dumroese et al. 2006, Visser et al. 1984). The loss of macropore space changes water infiltration rates, alters soil microbes, and ultimately changes the soil chemistry. Compaction reduces the space in soils available for holding water, resulting in water accumulation (puddling) at the soil surface (refer to figures 1-6 and 2-5). Areas where heavy equipment use is most intense—such as roads, trails, and log landings—are the most susceptible to soil compaction (Case and Donnelly 1979, Kochenderfer 1977). Compaction also exposes mineral soil, displaces topsoil and the forest floor, and removes

Figure 2-6—Compaction and soil displacement caused by heavy equipment.

Figure 2-8—A soil clod created from the heavy equipment at the site in figure 2-7.

Figure 2-7—A sampling quadrat at a site with heavy equipment wheel tracks created from operating in suboptimal moisture conditions.

nutrients in the forest floor (surface horizons). Heavy equipment used during timber harvesting can pack soil particles closer together (figure 2-8), increasing soil bulk density (Stuart and Edwards 2006). Changes in bulk density affect root penetration and development, water-infiltration and -holding capacity, oxygen exchange, microbial activity, and nutrient cycling (Hogan and Drake 2009). Reduced water infiltration rates and water-holding capacity exacerbate the potential for erosion.

Decompaction involves breaking up high bulk density areas by physically shattering the massive (consolidated soil) or platy (thin "plates") soil structure. This process creates macropore spaces and networks for increased movement of air, water, and organisms. Resource managers may use various terms, like soil tilling, ripping, disking, subsoiling, decompaction, to describe the treatment. However, the same terms may not refer to the same techniques in different geographic areas. Decompaction can be accomplished with a variety of equipment pulling multifunctional subsoiling implements with teeth of various shapes (Archuleta and Baxter 2008; Kees 2008). Just as soil texture can affect compaction, it can also influence decompaction efforts. It is easier to remedy coarse, lighter-textured sandy soils than fine, heavier-textured silty and clayey soils (Page-Dumroese et al. 2006). Decompacting fine-textured soils must achieve friable (easily crumbled) characteristics to improve soil properties and plant regeneration success (Archuleta and Baxter 2008).

Banning et al. (2011) compared skid roads to undisturbed areas and found that soil rehabilitation efforts using decompaction techniques on the roads may restore soil functions and bulk density. Smeltzer et al. (1986) found that a loamy, sandy soil site in a northern hardwood forest in Vermont exhibited reduced fungal and bacterial populations on compacted plots but recovered to natural levels after 4 years.

Tilling

Tilling—using hand tools or machines to physically break up shallow, compacted soils—is a decompaction technique that can decrease bulk density and improve water infiltration (Curtis and Claassen 2009). Studies by Heninger et al. (2002) indicate that tilling increases site productivity when crews use it to incorporate soil amendments into topsoil.

Similar to other rehabilitation techniques, tilling requires resource managers to consider site conditions. The soil at a site must be healthy enough to transfer the tilling equipment's energy through a substantial portion of the soil profile. The relationship between soil texture and moisture content determines soil strength at any given time (Bulmer 1998). In coarse, sandy soils, moisture has less influence than in finer, clayey soils, where moisture content can substantially reduce soil strength (Bulmer 1998; Hillel 2004). Tilling to restore fine-textured soils is a major advance in soil restoration, but resource managers must time treatments to coincide with optimal soil moisture conditions (Sanborn et al. 1999a and 1999b). In contrast, Luckow and Guldin (2007) found that soil moisture did not alter decompaction effectiveness in rocky soils. Simple tilling treatments are most effective for returning coarse- and medium-textured soils to full productivity but are inherently more difficult with fine-textured soils (da Silva et al. 1994; Sanborn et al. 1999a, 1999b).

Curtis and Claassen (2009) showed tilling alone decreased bulk density in all soil textures examined. Tilling increased saturated hydraulic conductivity in soils that did not contain large amounts of coarse fragments. It also decreased the sediment yield in three out of four soil parent materials (igneous, metamorphic, and sedimentary), but not in decomposed granite soils. In soils with few coarse fragments, tilling and incorporating compost into the soil further increased saturated hydraulic conductivity and reduced erosion.

Air tilling is a technique in which crews blow compacted soil away from a tree root zone and reapply it to the larger area, thereby decompacting and invigorating soil and root systems (McIntyre 2011). McIntyre found that air tilling alone was not as successful as combining the method with fertilizer and mulch, which reduced soil strength by 75 percent. Fite et al. (2011) found that, when increasing organic matter was the primary management goal, mulching appeared to be just as effective as the more time-consuming and expensive tilling-fertilizing-mulching process.

Rock Rippers

Rock rippers are tooth-like attachments mounted on the back of a tractor (Bulmer 1998). Ripping is a decompacting technique that uses a shank (and possibly a subsoiling tooth) to disrupt compaction. Rock rippers can till the soil without inverting it; the rippers move the soil ahead, to the side, and up (Andrus and Froehlich 1983). Bulmer (1998) found that rock rippers are considerably less effective at loosening compacted soils during a single pass (45 percent) when compared with winged subsoilers (70 to 90 percent). Therefore, rock rippers usually require multiple passes to ensure the teeth areas are tilled (Andrus and Froehlich 1983, Bulmer 1998).

Soil properties also influence a resource manager's decision to employ this technique. Bulmer (1998) proposes using rock rippers for shallow tilling (e.g., on course-textured soils with moderate gravel content). Archuleta and Baxter (2008) also reported that pulling a rock ripper with a bulldozer has major limitations and they do not recommend it.

Winged Subsoilers

A winged subsoiler lifts soil slightly without smearing or compacting the soil below its wings (B.C. Ministry of Forests 1997).

Winged subsoilers have a wing attached to the tines' side that allows the subsoilers to lift soil and fall back without much mixing. According to Bulmer (1998), they can maintain a constant depth, regardless of irregularities in the soil surface (e.g., mounds and logs). The constant force applied by winged subsoilers results in consistent fracture patterns and clod size. When properly operated, the winged subsoiler creates narrow trenches around the shanks. It is a practical method for decompacting large areas with relatively uniform conditions. However, the winged subsoiler is not useful on sites with many large rocks or buried logs (B.C. Ministry of Forests 1997). Newer, more advanced winged subsoilers include a tripping mechanism that allows individual shanks to travel over buried wood or rock and then return to a tilling position (Bulmer 1998).

The B.C. Ministry of Forests (1997) claims that a winged subsoiler can break up the soil without burying the forest floor or topsoil and can even leave vegetation intact when operated correctly. Another advantage of winged subsoilers is their ability to work at a greater depth than nonwinged implements and maintain the depth with greater consistency than other rippers (B.C. Ministry of Forests 1997, Bulmer 1998). Winged subsoilers more efficiently decompact larger areas in a single pass than nonwinged rippers and tillers; they are the most effective implement for decompacting large areas with uniform conditions (B.C. Ministry of Forests 1997).

Bulmer (1998) and Plotnikof and Bulmer (1999) showed the rehabilitative effectiveness of winged subsoilers on coarser soils. However, success varies on finer-textured soils (McNabb et al. 1993). Further limitations of winged subsoilers include limited improvements in surface bulk density (Kolka and Smidt 2004).

Kees (2008) evaluated mechanical specifications of various subsoiling shanks and tips and their relative effectiveness. He concluded that subsoilers required more than one pass to break up compacted soil effectively. Archuleta and Baxter (2008) describe three types of subsoiling attachments that perform functions in addition to subsoiling:

- A subsoiling grapple rake with two curved shanks that rip 20 to 30 inches deep and a colter blade on the front that cuts woody debris into smaller pieces
- A subsoiling excavator bucket with curved shanks and an optional colter blade that decompacts before recontouring
- A subsoiling brush cutter hitch with a masticating head for chipping woody vegetation

Andrus and Froehlich (1983) and Bulmer (1998) reported that winged subsoilers loosened 80 to 90 percent of compacted soil in a single-pass operation. Rock rippers and brush blades loosened less than 45 percent of compacted soil, and a disk harrow loosened only 20 percent of compacted soil.

Kolka and Smidt (2004) evaluated subsoiling, recontouring, and conventional road closure (control sites) on soil bulk density, surface runoff, sediment production, soil moisture content, and seedling growth on forest roads in Kentucky. The forest roads are composed of gravelly to very gravelly silt-loam soils. They found that subsoiling produced more sediment than recontouring, but both treatments resulted in similar surface soil bulk density. They also found that eastern white pine (*Pinus monticola*) trees grew taller and achieved larger diameters on recontoured and subsoil sites when compared with control sites.

Excavators

Excavators are often used for remediation work because of their versatility. They have several attachments that crews can use to meet different soil rehabilitation objectives (B.C. Ministry of Forests 1999), including:

- Manipulating slash
- Mixing
- Mounding
- Spreading mulch
- Tilling

Resource managers can also use excavators for:

- Areas with limited access
- Areas with steep slopes
- Continuous topsoil replacement
- Loosening and filling in ruts
- Mixing forest floor and organic amendments with surface mineral soils

One benefit of using an excavator for tilling is that the equipment operator can work from one central position while covering a wide arc (Archuleta and Baxter 2008). Because the operator can work while gradually moving the machine backward, the excavator removes any compaction it causes, and the subsoiling effect becomes more uniform over the treated area. The excavator operator can also spread logging slash, chips, or sawdust over the surface after subsoiling to prevent the formation of surface crusts and encourage water infiltration (Hillel 1971).

Soil Amendment Treatments

Figure 2-9—A closeup of soil structure below the mulch layer.

Soil amendments include living or once-living materials (such as compost, biosolids, biochar, or mulches) that aid in soil recovery (figure 2-9). In areas with no forest floor (e.g., roads, skid trails, log landings), the resource manager can incorporate these materials into the topsoil to reduce soil compaction, and increase soil water retention, add nutrients, and promote biological activity (Sanborn et al. 1999a, 1999b). In areas where the forest floor is intact, crews can apply organic amendments (e.g., biochar) to the surface. The amendments will gradually decompose and provide health benefits to the mineral soil. Archuleta and Baxter (2008) showed that soil amendments of 25 percent organic matter to 75 percent soil (by volume) produce positive effects on soil and vegetation. Using local soil amendments is more economical because they are usually bulky, and their weight increases transportation costs. Resource managers can evaluate the effectiveness of soil amendments using vegetative cover or growth, and sometimes the nutrient content of mixed layers as metrics. In some locations, adding carbon-rich organic amendments (e.g., woody residues, coarse wood, and biochar) may have negative consequences for revegetation efforts if soil nitrogen concentrations are low. Resource managers who use high-carbon soil amendments should consult with a soil scientist to understand soil nutrient concentrations to ensure that decomposition and other soil functions proceed uninhibited.

Logging Slash

Logging slash, the most readily available amendment material, may be practical where topsoil retention is not an option and subsoils are cold, dense, and deficient in organic matter (B.C. Ministry of Forests

1997). Slash consists mostly of large, woody material with a high carbon-to-nitrogen ratio and may require fertilizer to prevent nutrient deficiencies (B.C. Ministry of Forests 1997). Debris consisting of needles, fine branches, and foliage can enhance soil nutrients and increase soil organic matter content (figure 2-10), but the nutrients may leach from these materials after one winter (B.C. Ministry of Forests 1997, Borders et al. 2006).

Shuman and Sedbrook (1984) examined the use of sawmill residues to reclaim mine spoils and found that a 7.5-centimeter layer of wood waste on the surface of clayey soils improved productivity. Further, within 3 years of incorporating woodchips (140 megagrams per hectare), both Miles and Brown (2011) and Bulmer et al. (2007) observed a growth response for white spruce (*Picea glauca* [Moench] Voss). However, despite initial growth advantages to seedlings, Bulmer et al. (2007) found after 8 years that soil amendments, including wood waste, did not significantly affect the height of lodgepole pine (*Pinus contorta*).

Bulmer and Krzic (2003) indicated that soil temperature might increase when crews add organic amendments to log landings, improving tree growth. They also found that surface mineral soils 0 to 7 centimeters deep on landings rehabilitated with wood waste showed no differences in total carbon, nitrogen, or cation exchange capacity compared with a control plot. However, at 10 to 17 centimeters deep, the mineral soils had higher total carbon and nitrogen, higher cation exchange capacity, and exchangeable calcium, magnesium, and potassium levels, suggesting that constructing the landings caused minor losses of organic matter and nutrients. Alternatively, these conditions may have resulted from residual nutrients accumulating from upper horizons in the soil. The data indicating the residual nutrients accumulating from upper horizons in the soil coincided with higher clay content in landing subsoils (Bulmer and Krzic 2003). Wood waste applied at a medium rate of 112 tons per hectare (a layer 7.5 centimeters deep) improved productivity in clayey soils (Bulmer 1998, Shuman and Sedbrook 1984).

Figure 2-10—A closeup of soil cover with debris of needles, foliage, branches, and woody litter mulch used for topsoil retention and soil moisture retention.

In the Lake Tahoe area, Grismer (2007) studied soils decompacted to a depth of at least 0.3 meters and rehabilitated with coarse organic material (woodchips, tub grindings, composted woodchips, or coarse overs) incorporated into the soil at a rate of 4,000 kilograms per hectare. Over time, these treatments resulted in significantly more onsite infiltration and a reduction in sediment yield.

Sawdust

Bulmer et al. (2007) found that carbon concentration in sawdust declines significantly after 3 years, and nitrogen concentration increases, leading to a much lower carbon-to-nitrogen ratio than other woody materials with higher nitrogen concentrations that have decomposed for several years. They also found that using aged sawdust helps prevent the adverse effects of reduced nitrogen availability. However, unless the site has a chipping mill or sawmill nearby, there are usually few local sources for sawdust. Bulmer et al. (2007) reported a rehabilitated log landing study in Canada that found that seedlings on plots with tilling alone produced the most volume over 3 years. Trees growing in plots amended with sawdust tended to have more volume after 3 years than trees growing in plots amended with woodchips. Plots with heavy woodchips left as a surface mulch produced the lowest tree growth volume after 3 years. The differences may have resulted from changes in nutrient availability or colder soils (Bulmer et al. 2007).

Manure, Hay, Agricultural Straw, and Wood Strands

Manure provides good organic material that contains nitrogen, phosphorus, and potassium. Hay from local meadows is unlikely to introduce invasive or nonnative plants. However, the B.C. Ministry of Forests (1997) found that straw or hay blown onto a site during windstorms can introduce invasive grasses. Resource managers have used straw or hay for postwildfire rehabilitation on sites prone to erosion and on decommissioned roads to improve water infiltration. Wood strands manufactured from small-diameter timber or low-value veneer provide an alternative to agricultural straw. Foltz and Dooley (2003) found that wood strands can effectively reduce up to 98 percent of erosion at a site. Wood strands produced onsite also do not introduce nonnative species to the site.

Pulpmill Sludge

Pulpmill sludge has a high carbon-to-nitrogen ratio and small particle size. It decomposes more rapidly than woody residues but will likely require fertilization to prevent nutrient deficiencies (B.C. Ministry of Forests 1999). Similar to agricultural straw, pulpmill sludge decomposes rapidly and may not promote lasting changes to soil properties, especially in coarse-textured soils (Sanborn et al. 1999a, 1999b).

Sewage Sludge

While sewage sludge has a high nutrient content, its high water content increases transportation costs. Additionally, crews require specialized pumping and spraying equipment to apply the slurry far from a road. Harrison et al. (1994) found that using sludge on forest sites may induce secondary nutrient deficiencies in trees because the sludge has high nitrogen levels. The B.C. Ministry of Forests (1999) recommends caution when using sewage sludge because its nutrient levels vary and it contains trace metals. U.S. regulations also restrict sewage sludge application within 50 feet of a stream or watercourse.

Biosolids

Biosolids, including municipal composts, may be available near populated areas. Nutrient concentrations in biosolids are typically lower than in sewage sludge but higher than in logging residues. Biosolids are a source of organic matter (B.C. Ministry of Forests 1999) and can be a source of nutrients, depending on the type of biosolid (Page-Dumroese et al. 2018).

In California, Curtis and Claassen (2009) found that municipal compost incorporated into four different soil parent materials increased soil carbon content by 2.0 percent and soil nitrogen content by 0.2 percent. Biosolids helped to increase plant-available water in soils where the water content was below 10 percent. Aboveground biomass increased whether crews tilled it into the soil or not. Incorporating biosolids helped belowground biomass. Tilling and incorporating compost into lahar and serpentine soils significantly increased surface-saturated hydraulic conductivity in the soils, compared with nontilled and noncomposted soils. Curtis and Claassen (2009) found no difference in saturated hydraulic conductivity between treatments in decomposed granite and sandstone soils. They showed a 20-percent change in plant-available water content by incorporating compost to the lahar and serpentine soils compared to nontilled plots. Both lahar and sandstone soils have sandy-loam textures, but Curtis and Claassen (2009) found that differences in parent materials resulted in very different water-holding properties. They also found that soil particles in lahar soil are porous, producing high plant-available water content (24.4 percent). In contrast, sandstone soil has a more typical plant-available water content at 9.6 percent.

Cole and Spildie (2007a, 2007b) found that compost used for rehabilitation at high-elevation campsites showed increased vegetative effects over time, being least pronounced in the first years after application. After 10 years, campsite plots that received organic materials and compost amendments had considerably more plant cover than plots that received no amendments, but the differences were not statistically significant. Graminoids and forbs generally responded positively to soil amendments, but tree seedlings did not. Amending campsite soil with both organic materials and compost almost completely restored soil characteristics.

Biochar

Biochar is a carbon-rich product obtained by burning biomass in a controlled, closed container with limited air. Resource managers can improve soil water-holding capacity and carbon storage or remediate contaminated mine sites using biochar (Levine 2010, McElligott et al. 2011). Many forest stands are overstocked because of past wildfire suppression efforts, creating conditions that could lead to future increased wildfire activity, insect infestation, or disease. Wildfire suppression and the reduced use of broadcast burning have also reduced natural charcoal (black carbon) in many forest soils. Under normal conditions, soil acquires charcoal naturally when sites burn. Biochar may help restore forest soil charcoal levels to normal; help rehabilitate soil nutrient retention, water-holding capacity, and carbon sequestration; and mitigate greenhouse gas emissions (Page-Dumroese et al. 2017).

Fertilizers

Fertilizers are chemical or organic preparations crews apply to the soil surface or mix into the topsoil to add nutrients, such as nitrogen, phosphorus, and potassium. Many tree nutrition cooperatives around the country provide expert advice on the types of fertilizers available, the appropriate amounts to use for each forest species, and the best times to fertilize for the most effective results. Among the universities with tree nutrition cooperatives are University of Washington (west coast species), University of Idaho (inland northwest species), and North Carolina State University (east coast species).

According to the B.C. Ministry of Forests (1999), a single, broad chemical fertilizer application is usually not enough to restore the nutrient capital of degraded soil. Applying a large dose when seedlings are small has also been shown to be ineffective. Young plants cannot use applied nutrients all at once, and the soil loses nutrients through leaching or volatilization over time. Overfertilizing young seedlings may also cause problems. The B.C. Ministry of Forests (1999) reported damage to young seedlings at an application rate of 100 kilograms of nitrogen per hectare, while older trees usually tolerate this fertilization level. The risk of fertilizer damage increases when moisture decreases and temperatures increase. If the forest floor is displaced, most of the broad-application nutrients will leach or erode from the site. Therefore, matching fertilizer application rates with site conditions and growth phases is critical (Page-Dumroese et al. 2018).

Fertilizer can enhance the early establishment and growth of targeted species, building soil structure, and organic matter content (nontargeted species will also grow faster). A resource manager cannot consider a site adequately rehabilitated if the survival and growth of vegetative cover require continued fertilization. Local soil-testing laboratories can provide information on soil nutrient levels and determine what nutrients to add through fertilization (Van den Driesche 1974).

Petersen et al. (2004) studied roadside revegetation in Bryce Canyon National Park in Utah. They found that fertilization helped soil-stabilizing vegetation develop rapidly but was unnecessary for the long-term development of revegetated plant communities. They also found that the effects of fertilization declined over time and were minimal after 4 years, and that local seed outperformed commercial, nonlocal seed. Using appropriate soil microsites (e.g., shaded, intact forest floor) helped seedlings emerge and survive. Once vegetation was established, fertilization was not needed.

Organic fertilizers available today have slow-release, low nitrogen-phosphorus-potassium ratios and include ectomycorrhizal fungi. These fungi form a symbiotic relationship with the roots of various plant species and have been shown to improve water and nutrient uptake (B.C. Ministry of Forests 1999). Application rates for organic fertilizers are higher than those for conventional fertilizers, but the slow release of nutrients makes a second application unnecessary. Page-Dumroese et al. (2018) found that slow-release fertilizers applied on sandy loam soils in western Montana did not produce the flush of noxious weeds that typically accompany the application of chemical fertilizers with high nitrogen content.

Mulches

Mulches are nonliving materials spread on top of the soil to reduce erosion. They also conserve moisture and moderate soil temperatures to help establish vegetation (B.C. Ministry of Forests 1997, 1999). Graves et al. (1980) studied mulch applied at 1.0-, 2.5-, 5.0-, and 10.0-centimeter increments and found that moisture content changed significantly between the applications. Soil temperatures did not change significantly with mulches more than 2.5-centimeters thick. Bulmer (1998) found a 2.5-centimeter layer of bark mulch improved stocking levels for three deciduous tree species established from seed, compared with control treatments with no bark mulch. Daytime soil temperatures tend to be lower for mulch treatments than soils with no added treatments (Bulmer et al. 2007), so crews must be careful to limit the depth of the mulch to prevent soils from staying frozen too long into the growing season.

Resource managers often use mulch to control postfire erosion on denuded slopes. MacDonald and Robichaud (2007) compared the effectiveness of mulching, hydromulching, scarification, and seeding of postfire erosion treatments with polyacrylamide on burned slopes in Colorado. They found that straw mulch and hydromulch applied aerially reduced sediment production by more than 90 percent during the first year. The mulch deteriorated and no longer reduced sediment after 3 years, but natural revegetation processes had taken over by that time. Straw was the most cost-effective mulching method. Groen and Woods (2008) focused on aerial seeding and straw mulch on postfire erosion in northwestern Montana. The first year after a fire in areas prone to erosion, straw mulch (100 percent cover at 2.24 megagrams per hectare) helped reduce sediment production rates by 87 percent compared with untreated control areas. Aerial seeding had little effect.

Napper et al. (2006) discussed various treatments and their effectiveness in stabilizing burned areas and preventing or reducing wildfire effects by reducing erosion and establishing vegetative cover. FireScience.gov <https://www.firescience.gov/> provides continuous updates on projects and published research related to fire, including fuel treatments and their effects. Though these studies focus on vegetation treatments, some relate to nutrients or organic matter in the soil. For example, Archuleta and Baxter (2008) found that subsoiling helped native species growth and increased soil nutrients.

After a Colorado fire in 2000, crews treated the severely burned soils with seed and mulch. Wagenbrenner et al. (2006) studied the site for 3 years. They found that applying mulch at 2.2 megagrams per hectare provided more ground cover and lower sediment yields than control areas.

Thick Mulches

The B.C. Ministry of Forests (1997, 1999, 2002) research found that a thick application (5 to 10 centimeters) of straw, hay, logging residues, or transplanted forest floor material improved the survival of trees at drought-prone sites because these materials decomposed slowly, keeping fine-textured soils moist and preventing the growth of grasses.

For three consecutive growing seasons, Miller and Seastedt (2009) applied 7.5 centimeters of woodchips created from the slash of a fuel-reduction project near Boulder, CO. They also applied sugar fertilizer (ammonium nitrate) to some experimental plots to alter the plant-available nitrogen levels. Plots with woodchips produced half of the understory species compared with plots without woodchips, but the nitrogen manipulation did not affect species richness in either plot. Plant cover increased in all plots over time, though many of the plants were not native to the area and were most likely introduced during the fuel-reduction project. Overall, woodchips inhibited ground cover, including the richness of native species. Only some of the potential ground cover species benefited from the increased moisture provided by the woodchips. During the first 2 years after thinning, applying woodchips did not reduce plant-available soil nitrogen at ambient fertility levels. Still, it did present a physical barrier that influenced ground cover establishment patterns. In contrast, where Miller and Seastedt (2009) applied woodchips, native shrubs attained more relative cover.

Thin Mulches

The B.C. Ministry of Forests (1997, 1999, 2002) found that thinner mulches (1 to 5 centimeters) helped with the germination and establishment of grasses and legumes (in contrast to tree species) on drought-prone sites, highly erodible soils, sandy surface soils, and slopes with southerly or westerly exposures. The mulches provided protection when crews applied them over seeds.

Manufactured Mulch Mats and Blankets

Mulch mats can be plastic or fiber. They must have close contact with the soil surface to be effective, limiting their suitability at various sites. Also, because of their cost, crews generally use them in limited situations where erosion control is critical (e.g., lining a ditch and at bridge crossings) (B.C. Forestry 1997, 1999, 2002). Cole and Spildie (2007a, 2007b) used mulch blankets as one method for helping to rehabilitate campsites at high elevations but found the blankets had no appreciable effect. Despite this finding, crews frequently use mulch blankets for high-elevation restoration projects with positive results.

Revegetation Treatments

After harvesting operations disturb a site, one measure of site productivity is the recovery of vegetation. The vegetation that returns to a site should be composed primarily of native species found at the site before the disturbance and should include keystone species critical for the ecosystem's proper structure and function (Aronson et al. 1993). Resource managers designing rehabilitation projects should clearly understand site-specific native plants and their role in local soil health. Understanding the preexisting vegetation communities enables an efficient transition during replanting. A quick return of native vegetation reduces the chance that nonnative, invasive species will occupy the disturbed space.

Resource managers revegetate a disturbed site by replanting the landscape and rebuilding the soil with the overall objectives of retaining soil moisture, stabilizing topsoil, reducing erosion, and ensuring plant diversity. The Forest Service and U.S. Department of the Interior, Bureau of Land Management, have approved several commercial products to establish native plant species. Combinations of tilling, adding soil amendments, controlling moisture, using different seed mixes, and transplanting species provide different results, depending on the location (from flat bottomlands to high alpine sites). Some plants can accumulate toxic materials, serving as filters and buffers when used at abandoned mine sites. Monitoring is an essential part of the rehabilitation process. Resource managers must monitor treated sites over multiple years to quantify the effectiveness of the treatments; observe plant diversity, growth, and development; and determine the overall success of the rehabilitation efforts. Monitoring can also help determine when an ecosystem is not functioning as anticipated, enabling managers to try alternate rehabilitation methods as necessary.

The B.C. Ministry of Forests (1997, 1999, 2002) recommends using native grass and legume seed mixes first to control erosion, then choosing vegetation with ecological characteristics compatible with the long-term site objectives. Native grasses and legumes can restore and maintain soil structure and prevent surface erosion in the short term, especially in medium- and fine-textured soils. Crews can then plant native shrubs and hardwoods to help build the forest floor and enhance biodiversity and mineral soil development.

Grismer (2007) and Grismer et al. (2009) showed through rehabilitation work in the Lake Tahoe Basin that seeded perennial grasses were established successfully and provided the highest and most consistent cover when combined with woodchip amendments. These plots had the highest infiltration rates and no runoff or erosion. Seeded plots amended with compost and biosolids, providing 2,000 kilograms of nitrogen per hectare, developed the second-best type of cover. After 3 years, the compost plots had more plant cover. Grismer et al. (2009) concluded that the soil's parent material was also affected. With all factors being equal, volcanic soils supported more plant growth (as measured by foliar cover and biomass) than granitic soils. The highest foliar cover Grismer et al. (2009) measured at the sites with volcanic soils was 95 percent. In comparison, the highest foliar cover at the sites with granitic soils was only 50 percent, perhaps reflecting the very low nutrient levels of granitic soils.

Symbiotic, nitrogen-fixing plants can help with rehabilitation efforts by restoring soil processes. Nitrogen-fixing plants fix dinitrogen (N_2) through microbial symbiosis and can increase carbon and nitrogen levels in soils. Scientists consider these plants as pioneer species because of their presence on degraded soils. They are best for increasing productivity in nitrogen-deficient soils and help increase available potassium. However, when uncontrolled, nitrogen-fixing plants such as Scotch broom (also a persistent noxious weed), red alder, and ceanothus can suppress regenerating seedlings (Grismer et al. 2009; B.C. Ministry of Forests 1997, 1999, 2002).

Bulmer (1998) showed on restored oil and gas well sites in Alberta, that mesic (containing moderate moisture) and subxeric (containing little moisture) sites provided the best conditions for successfully growing lodgepole pine. Trees planted on landings grew more poorly than trees planted on adjacent portions of cutover harvest units, regardless of the planting method. Bulmer et al. (2007) found that planting only lodgepole pine at a high stocking density on coarse-textured landings could be a more cost-effective reforestation option than using wood waste as a soil amendment. However, without amending the soil, restoring ecosystem functions may take longer.

Cole and Spildie (2007a, 2007b) studied high-elevation (upland) campsites, and found that over 10 years soil cover doubled. However, this increase was still low because vegetation cover at the campsites was far from the 50-percent cover typical of undisturbed sites. Seedling cover did increase almost threefold in the first 4 years after the campsites' closure, then declined substantially for the next 3 years, and increased slightly by the 10-year mark. The 12-percent mean vegetation cover on campsites 10 years after closure represented substantial vegetation recovery progress compared with the 0 percent mean vegetation cover typical of these campsites before closure. Most treatments were not beneficial for restoring native species composition. Transplanting proved the only effective way of establishing native shrubs on the campsites. Transplanting species on plots amended with organics and compost produced significantly better results than transplanting on plots that were only scarified. Manual planting is the best way to ensure proper species, function, and growth (Barton et al. 2008).

Manual planting is often the best way to revegetate rehabilitated ecosystems. In Canada, McConkey et al. (2012) showed that planting native or appropriate species by hand ensures that:

- Trees or other vegetation get a jump on competing vegetation.
- The appropriate species grow on the site.
- Trees or vegetation cover the soil more rapidly.

Additionally, planting native trees and other native plants expedites healthy ecological functioning at the site.

Soil Hydrology Treatments for Riparian Areas

Controlling water is one rehabilitation treatment that affects many aspects of soil function. Retaining enough moisture in the soil at upland sites for plants and organisms to grow is one end of the soil moisture spectrum. Restoring riparian forests is the other end of the spectrum.

Restoring riparian forests often requires regulating when and how long soils remain saturated, either through natural processes or by using headgates (gates that control water flow). Moisture regimes in riparian areas range from seasonal saturation to semi- or permanent inundation (Barton et al. 2008). Given this range of moisture conditions, it is not surprising that various species of plants survive various levels of saturation and oxygen. Nutrient cycling also varies with saturation conditions, and plant-available water levels change with soil texture. In many riparian areas, crews accomplish revegetation through planting, often planting willow sticks. As with upland sites, these areas were manually planted to ensure proper species, function, and growth (Barton et al. 2008).

Compared with upland forests, the soil characteristics in riparian areas are less likely to show wide fluctuations in surface hydrology caused by periodic wet and dry periods. As Barton et al. (2008) demonstrated in a study of Carolina bays, integrating soil parameters into models used to evaluate isolated hydroperiods in depression wetlands may better reflect long-term saturation conditions. Exchangeable acidity, total nitrogen content, and total carbon content are indicators of soil reduction/oxidation; Barton et al. (2008) found all of these conditions to be good indicators of hydroperiods at a Savannah River site in South Carolina.

Natural Ecological Succession Over Time

Another method of treating soil degradation is letting time pass, allowing local climatic conditions to reestablish disturbed areas to naturally regain healthy soil conditions and forest ecosystems. Not intervening has no costs but may not provide the desired results (e.g., nonnative plant species may invade or soil hydrologic function may worsen). Natural freeze-thaw and shrink-swell processes associated with seasonal changes may reduce soil compaction. Several studies conclude that vegetation may respond quickly (Druckenbrod and Dale 2012, Hope 2006), but bulk densities may take decades to improve (Luckow and Guldin 2007). Surface soil compaction may decrease after several years, but deep soil compaction is slower to recover (Page-Dumroese et al. 2006). Flinn and Marks (2007), Gass and Binkley (2011), Lloyd et al. (2012), and Maloney et al. (2008) all investigated soil functions, such as nutrient dynamics and microbial activity. They found that ecosystem processes recovered more quickly after active rehabilitation efforts. The type of disturbance also affects recovery times (Bataineh et al. 2006, Rawiniski and Page-Dumroese 2008).

Allowing soils to recover without rehabilitation is a slow process that may not produce the desired results. The following sections provide examples of passive treatments used to address soil damage from various sources.

Cut-to-Length Logging

Labelle and Jaeger (2011) examined the impact of cut-to-length logging on soil bulk density (compaction) in New Brunswick. They assessed bulk density to compare prelogging and postlogging conditions at two different timber harvest areas over 5 years. Using a nuclear moisture and density gauge (figure 2-11), they assessed bulk density at points inside the machine track and outside the track. One site had sandy silt soil with 21 percent clay, the second site had silty sand with 7 percent clay and 15 percent gravel. Labelle and Jaeger (2011) postulated that, over time, natural processes, such as frost heave during the winter and biological activity outside of the frost period, would loosen the compacted soil. After 5 years, they found no change from the immediate postlogging soil bulk density measures (i.e., no natural recovery). They also explored the effects of machine weight, the number of machine passes, the soil water content, and organic matter on soil bulk density.

Figure 2-11—A geophysical (neutron) soil moisture and density gauge.

Skid Trails

Froehlich et al. (1985) studied skid trails of varying ages in central Idaho. They found that the surface layer took 20 years to recover on loamy sand granitic soils and more than 25 years on fine-loamy volcanic soils. They also found that deeper soils required even longer recovery times. They concluded that high initial increases in bulk density coupled with slow recovery rates might affect long-term tree growth and likely alter site hydrology because water cannot infiltrate as deeply into the soil. Repeatedly entering partially cut stands, if crews cannot reuse existing skid trails, can compact and adversely affect large areas.

Tracked Vehicles

Druckenbrod and Dale (2012) studied understory plants in an oak-pine forest in the military training area at Fort Benning, GA, to determine how the plants responded to disturbances from tracked vehicles. After two growing seasons, the metrics they examined—including total understory cover, bare ground cover, species richness, and family richness—did not indicate much difference between treatment plots and control plots. Druckenbrod and Dale (2012) used the Raunkiaer (1934) life form methodology and found that some species had not recovered after 2 years.

Timber Harvesting

Rawiniski and Page-Dumroese (2008) found no recovery in bulk density 16 years after timber harvesting at a southwest Colorado site. The persistent compaction levels at the site hindered the growth of vegetation. They conducted this study in the cryic (cold) zone, where reversing the compaction effects may not be possible.

Gas and Oil Wells

Vitt et al. (2011) studied plant recovery on two reclaimed gas/oil production well sites in the peatland complex of Alberta. The well sites contained mineral fill. They found that native sedges and willows grew well in the reclaimed areas and that weedy species varied, depending on treatments and water levels. They concluded that early wetland plant communities can establish abandoned well sites containing rewetted mineral soils, but they could not determine if the reestablished plants would ever resemble the site's predisturbance plant community.

Wildfire

Bataineh et al. (2006) studied the effects of wildfire on the production and composition of understory plants 30 years after a burn. They found that the reestablished vegetation in the burned areas differed from vegetation in the unburned or prescribed-burn areas. Understory plant production in the burned areas was higher than the unburned areas. They also found that the overstory structure differed between areas that experienced high- and low-intensity fires, unburned sites, and prescribed-burn sites.

Grazing

Gass and Binkley (2011) examined the impacts of deer and elk grazing on soil processes in Rocky Mountain National Park, CO. Surface soil textures at the study site ranged from sandy loam to mucky peat over clay loam. They found that soils in grazed plots had higher bulk densities, lower moisture, and lower carbon and nitrogen concentrations than ungrazed (enclosed) paired plots. They resampled the soils in the ungrazed plots 12 years after the initial sampling and found these plots had lower bulk densities and higher carbon and nitrogen concentrations than the grazed paired plots.

North American Long-Term Soil Productivity

The B.C. Ministry of Forests (1997, 1999, 2002) established sites in the interior areas of British Columbia to examine soil sensitivity and resilience to disturbance as part of the North American Long-Term Soil Productivity Project. Hope (2006) summarized results from study plots of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) sites, where he applied organic matter and compaction treatments and then planted Douglas fir and lodgepole pine seedlings. He found that bulk densities on the study plots were higher after compaction and were highest on compacted, scalped (forest floor removed) plots. Compaction decreased porosity and scalping reduced the growth of pinegrass. A high percentage of seedlings survived after the treatments. Scalping increased soil temperature and decreased soil moisture, which may have contributed to the growth of taller Douglas fir seedlings on these plots compared to other plots at the sites. However, the combination of scalping and compaction decreased the height and diameter of Douglas fir seedlings on the study plots compared to other plots.

Soil Compaction

Luckow and Guldin (2007) compiled 20 years of compaction data from the southeastern States. They found that rocky soils (15 to 35 percent gravel) were less susceptible to soil compaction than nonrocky soils (less than 15 percent gravel). The bulk density of rocky soils was 20 percent lower than nonrocky soils after 15 to 20 years. Luckow and Guldin (2007) also revealed that a slight increase in bulk density resulted in a substantial decrease in water infiltration rate. They estimated it would take 50 to 80 years for the density levels of skid trail soils to recover to near-natural density levels. They also noted that using logging equipment on nonrocky soils during wet conditions worsened soil compaction and consequently, reduced surface water infiltration. They concluded that resource managers can minimize soil compaction by logging during dry seasons.

Forest Roads

Lloyd et al. (2013) examined restoration methods for abandoned and recontoured forest roads 30 years after restoration. They found similarities in aboveground recovery, but differences in belowground properties between the two types of roads. Shrubs and trees on abandoned roads had a slower rate of succession than on recontoured roads. Abandoned roads also had lower saturated conductivity, lower soil organic matter content, lower total carbon, and lower total nitrogen than recontoured roads. These results suggest that recontouring roads accelerates (by hundreds of years) the recovery of soil organic matter, total carbon and nitrogen pools, and associated soil process rates. Belowground properties and processes on abandoned roads remained degraded 30 years after closure and revegetation.

Legacy Land Use

Maloney et al. (2008) examined legacy land-use effects on soil properties at Fort Benning, GA. They estimated that bulk density recovery to a reference condition might take 83 years at shallow depths and up to 165 years at 30 to 40 centimeters. After 55 years, disturbed sites had lower soil carbon and nitrogen stocks than reference forest stands, but reforested stands had similar carbon and nitrogen stocks to reference forest stands.

Coal Mines

Shrestha and Lal (2008) evaluated the effects of postrestoration land uses (forest, hay, and pasture) on soil properties at a reclaimed coal mine area. After 28 years, they found that the surface soil after each land use had similar bulk density to undisturbed forest soils but lower bulk density than agricultural soils. Increased biological activity, increased soil organic carbon, and increased root growth may have contributed to lower bulk densities after hay and forest uses. Forest and hay use also enhanced water infiltration and created more stable soil aggregates than pasture use.

Abandoned Agricultural Fields

Flinn and Marks (2007) examined the legacy of agricultural activity in central New York. They compared environmental conditions of secondary forests (established 85 to 100 years earlier on previously plowed fields) and primary forests (never harvested). Secondary forests and primary forests had similar tree densities, tree sizes, soil pH, understory light, and earthworm activity. However, soils in secondary forests had less organic matter, less total carbon, and less extractable phosphorus in the top 10 centimeters and altered vegetation composition.

Mahaney (2010) examined the decomposition dynamics of two old-field grasses compared with native prairie grass in Michigan. Within 2 years, Mahaney (2010) found that native grasses had higher decomposition, as measured with the litterbag method, and higher carbon-to-nitrogen ratios, reflecting different litter decomposition rates and shifting bacterial communities. Often, studies only evaluate vegetation growth or bulk density recovery after a site treatment. This study demonstrates the importance of understanding ecosystem processes such as decomposition rates.

Chapter 3—Methods and Tools for Measuring the Effectiveness of Rehabilitation

To determine the effectiveness of soil rehabilitation treatments, resource managers and soil scientists can measure soil properties and compare them to a reference condition area—an undisturbed or minimally disturbed area used as a natural representation or benchmark. Using the same methods consistently over time enables an accurate evaluation of rehabilitation treatments. Soil development takes decades (or longer), so resource managers monitoring rehabilitation efforts must consider restoration time and select from a range of options for parameters to measure and measurement methods to use. The following sections summarize and provide source references for various methods of measuring rehabilitation efforts.

Bulk Density

Bulk density is one of the most common measures of soil compaction. Core sampling is a rapid method for collecting bulk density samples, but excavation methods are more suitable for rocky soils. A core sample is extracted by pushing a steel coring device into the soil. The excavation method involves digging out the soil to measured depths. Nuclear methods (Page-Dumroese et al. 2006) can quickly provide a lot of data, but rocks limit the data's reliability, and licensing for nuclear methods is costly. Collecting bulk density samples also enables researchers to analyze the samples for the physical, chemical, or biological properties of the soil, such as organic matter content and available water (Bulmer 1998).

Determining a critical value for bulk density is not straightforward. Bulk densities depend on:

- Soil characteristics, such as texture and organic matter content
- Site conditions, such as climate and soil moisture regime characteristics
- Criteria for evaluating when vegetative growth is affected

Jones (1983) defined the critical value as the point at which bulk density reduced root growth to 20 percent of optimum. Daddow and Warrington (1983) summarized several studies. They concluded that growth-limiting bulk densities for sandy loams and loamy sand soils were about 1,750 kilograms per cubic meter. In contrast, growth-limiting bulk densities for clay, silty clay loam, silty clay, and silt soils were about 1,400 kilograms per cubic meter. However, Daddow and Warrington (1983) concluded that their data were limited to soils with less than 3 percent organic matter, 10 percent rock-fragment content, and particle densities of 2.65 megagrams per cubic meter. Additionally, though they provided recommendations for forest soils, Daddow and Warrington (1983) used soils from agricultural lands for their study. Bulmer (1998) considered bulk densities of 1.2 to 1.4 megagrams per cubic meter to be growth-limiting for most ecosystems.

Collecting bulk density soil cores in rocky forest soils can be difficult. Using a core sampler of the appropriate size is critical. When rocks are larger than the soil core sampler, resource managers can overestimate the mineral soil's bulk density and underestimate rock fragment content. Several methods for determining soil bulk density do not use a core sampler but provide a consistent and accurate bulk density (Page-Dumroese et al. 2006). Resource managers can correct bulk density values for gravel content by measuring the rock mass and volume of material larger than 2.0 millimeters. Grossman and Reinsch (2002) measured rock volume using the water displacement method. Page Dumroese et al. (2006) and Flinn and Marks (2007) found that the water displacement method works best for rocky forest soils (figures 3-1 and 3-2). Loosened, mulched, and amended soils tend to compress during coring, resulting in overestimated bulk densities. Other methods for determining soil bulk density in these soil types (such as clod density or the soil's resistance to penetration) may be more appropriate.

Figure 3-1—Preparing a site to determine soil bulk density using the water displacement method.

Figure 3-2—Measuring soil bulk density using the water displacement method.

Penetrometers

Penetrometers measure soil strength. Some penetrometers mount on trucks and work to great depths. Simple, one-person penetrometers are also available (figure 3-3). The National Technology and Development Program (NTDP) evaluated three models of handheld penetrometers and described the results (Kees 2005). Penetrometers provide information about soil strength, but moisture,

Figure 3-3—Using a one-person soil penetrometer to determine soil strength.

porosity, and rock or root content affect the collected data. Resource managers must carefully observe the soil moisture content when collecting data and to ensure accuracy of long-term monitoring, they must collect future data under similar moisture content conditions.

Bulmer et al. (2007) studied Canadian forest landings using a small cone penetrometer shaft and tip (308 cone angle, 4-millimeter-diameter base, 40 millimeters long) attached to a handheld force gauge (Transducer Techniques Ltd., Temecula, CA) to determine the mechanical resistance of the soil. Bulmer et al. (2003) also studied a Canadian oil and gas rehabilitation project using a mini penetrometer to determine its average mechanical resistance values. The mechanical resistance of soil depends upon soil water content and bulk density. They found that, during June, when soils were wet, bulk density had a greater influence on soil's mechanical resistance than in July, when water content changed. The mini penetrometer worked well but had a shallow sampling depth. Soil moisture content affected the readings of both the mini penetrometer and the larger version.

Resource managers can also use impact hammers to estimate soil strength. The Clegg impact hammer with a 2.5-kilogram weight (Lafayette Instruments

Company, Lafayette, IN) drops a weighted accelerometer from a standard height. It measures its deceleration on impact with the soil surface, reporting a Clegg Impact Value (CIV). Soils with high CIVs have more unconfined compressive strength and impede root growth more than soils with low CIVs (Fite et al. 2011).

Vegetation

Roadside Revegetation: An Integrated Approach to Establishing Native Plants (Steinfeld et al. 2007b) discusses developing a continuum of reference sites that have varying lengths of time since their disturbance. The handbook also discusses integrating the revegetation plan into the overall project implementation, monitoring the site, maintaining records of work done on the ground, and maintaining plantings. It explains various soil cover protocols, species cover, species presence, plant density, and plant attributes (height and diameter).

Two ways to estimate foliar cover are the plant cover-point method and ocular estimates, which may vary between observers. However, as Grismer (2007) noted, using the same observer each time to estimate foliar cover on the same site reduces the error in ocular estimation. Because having the same person monitor a site year after year is not always feasible, the Cover Management Assistant program (Steinfeld et al. 2011) provides an easy method for standardizing estimates of vegetation and other soil covers. Another method is to estimate the area of canopy cover using a 1-meter-square quadrat with a 5- by 5-centimeter grid (Cole and Spildie 2007a, 2007b). Miller and Seastedt (2009) used point-intercept quadrat sampling to study species composition and the percentage covered by each species. The Forest Soil Disturbance Monitoring Protocol sampling method (Page-Dumroese et al. 2009) is also appropriate for assessing the degree, extent, distribution, and duration of soil disturbances and the percentage of cover, particularly on larger rehabilitation projects. Using a laser-point frame to measure ground cover by species (Van Amburg 2003) is another viable alternative for assessing the type and quantity of forest cover. In studies at Fort Benning, GA, Clarke (1986) and Dale et al. (2008a, 2008b) examined the effect of military training activities on understory vegetation, soil quality, species composition, and succession by surveying all vegetation less than 1-meter high within each plot using a modified form of the cover system. Druckenbrod and Dale (2012) assigned cover classes to each species present: total understory, bare ground, and leaf litter.

Booth et al. (2006) found that digital images offer three main advantages over field assessments:

- They provide a permanent record that researchers can reanalyze.
- Researchers collect numerous digital images from a site, increasing the sample number and improving the accuracy of the measurement at each point.
- They are relatively inexpensive to collect.

Researchers usually decide on the best sampling methods based on the type of data they need, the amount of time they have to collect the data, and the level of precision they require (figure 3-4). Resource managers may do the same but are often constrained by both the time and money required to conduct monitoring efforts.

Root Biomass

Researchers rehabilitating forest soils have a strong interest in the relationship between climate, tree growth, and carbon sequestration as evidenced in root biomass, which can be determined through a variety of methods. Sequential root coring has long been a favorite method of researchers. In this method, roots within the soil core are dried and weighed to get a rough approximation of total root biomass (figure 3-5). Vogt et al.(1998) found that

Figure 3-4—A field crew using various sampling methods.

Figure 3-5—A root biomass assessment.

sequential root coring results varied because of how trees allocate photosynthates (a sugar or other substance produced by photosynthesis) to fine roots.

Similarly, Curtis and Claassen (2009) measured root biomass by augering into test plots and taking soil samples at 0 to 10, 20 to 30, and 40 to 50 centimeters. They dried the samples (105 °C for 48 hours), sieved them to 2 millimeters, then removed the roots by hand and weighed them. They found they could measure belowground biomass by determining the ratio of root biomass within a soil sample to its total mass.

Soil Moisture

Traditionally, researchers determined soil moisture content by weighing, drying, and then reweighing a sample in a laboratory (referred to as "destructive sampling" because the researchers had to remove soil from the study sites). However, this may not be the best method for collecting real-time measurements. Poff (2002) used a handheld time domain reflectometer to measure volumetric soil moisture content (adjacent to the penetrometer) in rainfall simulation plots (before rainfall) at a depth of 120 millimeters. Recent technology advances in soil moisture and temperature sensors make monitoring soil moisture content in real-time easy and inexpensive. Researchers can link this data to local, regional, and national weather stations and use them in climate models.

Soil Microbes

Researchers can analyze soil organism content using physical or chemical extraction. Boerner et al. (2008) described several chemical extraction methodologies. Extracting methylated, ester-linked, fatty acids from fresh soil samples is one method of analyzing microbial community composition (Gass and Binkley 2011). Because of the close association between soil decomposition and nutrient cycles, O'Neill et al. (2010) suggested using an indicator species analysis to estimate microfaunal organisms that researchers can correlate to soil health practices. Ascher et al. (2009) found that newer techniques, such as sequential extraction and genetic fingerprinting of soil metagenomes, have become prevalent. These DNA techniques are useful for determining how soil biota is recolonizing disturbed soil compared to the reference site (Ascher et al. 2009).

Nutrients

Researchers can use soil combustion to determine mineral soil nutrient content for elements associated primarily with organic matter (such as carbon, nitrogen, and sulfur). For metals, such as calcium, magnesium, potassium, and iron, all-purpose extractants are suitable (Page 1982). Many soil conservation districts, university laboratories, or private laboratories can perform these analyses. Researchers can also purchase rapid-test kits to determine pH, active carbon, and other soil chemical properties.

For studies, researchers use many different lab techniques and specific tests to define the data they need. For example, Foster et al. (1988) and Foster and Wright (1990) used the percolation method for phosphorous sorption capacity proposed by Richardson (1985) to analyze field-moist, sieved soil. Allen (1995), Brookes et al. (1985a, 1985b), and Bruland and Richardson (2004a, 2004b) used the chloroform fumigation extraction method to analyze microbial biomass carbon. Driessen et al. (2011) found that the cumulative carbon released over the soils' 14-day incubation period produced mineralizable carbon content from the chloroform fumigation extraction.

Dodla et al. (2008) used solid-state, 13-carbon nuclear magnetic resonance to determine the molecular carbon composition of wetland soil organic matter. Kalra and Maynard (1991) used the Bray P1 method to determine available phosphorus. Hendershot and Duquette (1986) used barium chloride to displace exchangeable cations (exchangeable potassium, calcium, and magnesium) and determine cation exchange capacity. Bulmer et al. (2007) and Kalra and Maynard (1991) used a 1:2 soil-to-water extract to determine electrical conductivity and pH levels.

Researchers can measure organic matter content by loss on ignition at 5,008 °C for 2 hours. Nelson and Sommers (1996) found that ignition loss may overestimate organic matter content due to losses of carbonates and structural water from clay minerals. Still, carbonates do not decompose below 7,508 °C. Flinn and Marks (2007) found their method yielded accurate estimates of organic matter content for soils.

Gass and Binkley (2011) determined the potentially mineralizable nitrogen (the quantity of nitrogen that could be available under ideal conditions) using ammonium-N in a KCl extract of soil following a 1- or 2-week anaerobic incubation at 308 °C. Nitrogen availability can also be determined by ion-exchange resin bags (Binkley and Matson 1983) to indicate ammonium-N and nitrate-N's relative availability.

These tests are all necessary for maintaining healthy soil, but they may not be possible from a practical standpoint of soil restoration. The presence of earthworms (Geissen et al. 2008) or fine root production may be useful surrogates for determining soil chemical properties.

Organic Matter

Soil fertility is linked to the content of soil organic matter. The amount of organic matter present in the soil directly relates to the kinds and amounts of amendments used, vegetation production, decomposition, mineralization, erosion, and leaching. Soil organic matter also increases the stability of soil aggregates. The aggregate stability test is a consistent method that researchers can repeatedly use over time.

Bruland and Richardson (2004a, 2004b) found that soil organic matter has a significant positive correlation with moisture, clay, silt content, and water-holding capacity; the phosphorus absorption index; and microbial biomass carbon. It has a significant negative correlation with bulk density and the percentage of sand, indicating that soil organic matter is an essential indicator of soil quality. They also found that soil organic matter may be the best single variable to measure when assessing wetland sites under budget and time constraints. It provides information on other soil properties and processes. This is also true of upland soil types.

Chapter 4—Conclusions

The objective of soil rehabilitation is to return the soil properties of the entire site to pre-disturbance site conditions. Site rehabilitation is a complex process that reestablishes both plant and soil assemblages, with efforts to reproduce the ecological community that existed before the disturbance (Aronson et al. 1993, Simberloff 1990). Resource managers can more easily achieve site rehabilitation using rehabilitation methods that increase future productive capacity and the forest ecosystem (Angima and Terry 2011).

This desk reference provides information about soil rehabilitation methods, site-specific revegetation techniques, and the use of various organic amendments to promote native plant growth and healthy soil biomes. To have a successful restoration result, resource managers must use native plants. Simply allowing soils to recover without planned rehabilitative intervention is a slow process and is unlikely to produce the desired outcomes.

Resource managers can maintain soil and ecosystem functions by restricting the areal extent of soil compaction, promptly replanting disturbed areas, and leaving cull logs and patches of the undisturbed forest floor. Peterson et al. (2014) found that preserving organic matter at a site maintains nutrient cycling. The vital attributes of water storage and water availability are critical to the success of any forest maintenance and rehabilitation efforts.

Resource managers can measure soil quality indicators (physical, chemical, and biological properties) to evaluate soil function. Using the appropriate measurements with the appropriate rehabilitation method will help improve ecosystem rehabilitation. As the nutrient cycle's efficiency recovers and inputs of organic matter increase, mycorrhizal fungi, soil microbes, terrestrial macroinvertebrates, and native vegetation begin to recover. Resource managers should consider methods for measuring soil rehabilitation and multiyear monitoring approaches to quantify treatment effectiveness and the rehabilitation's overall success.

Restoration or rehabilitation science is a relatively young discipline. However, incorporating biology, soil ecology, and engineering into restoration efforts is critical. Resource managers should use soil-centric information to describe both prerestoration conditions and to define the restoration treatments required. Resource managers can also use soil data to help decide the best responses for aiding the recovery and restoration efforts. Callaham et al. (2008) determined four things about rehabilitation efforts:

- Soils are alive! Researchers should view soil micro- and macro-fauna as both indicators and agents of soil recovery.
- Soils have history. Considering the development of soil attributes over centuries is key to understanding soil and vegetation responses.
- Soils are extraordinarily variable. Taking into account the spatial and temporal variability of rehabilitated soils will help guide monitoring and recovery expectations.
- Soil functions in a functioning ecosystem integrate physical, chemical, and biological components, and resource managers need to consider these components when devising restoration treatments.

Glossary

Clay—Very fine-grained soil with particles less than or equal to 0.002 millimeter (U.S. Department of Agriculture soil texture classification) or with particles that exhibit clay-like characteristics (Unified Soil Classification System).

Effectiveness—The degree to which objectives are achieved, and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs.

Erosion—Processes of soil- and rock-particle detachment and transport over an area by wind, water, gravity, ice, and chemical action.

Fertilizer—Any substance applied to soil to increase the soil's nutritional content for establishing vegetation.

Gravel—Coarse-grained soil with particles less than 75 millimeters but greater than or equal to 2 millimeters (U.S. Department of Agriculture soil texture classification), or with particles less than 75 millimeters but greater than or equal to 4.75 millimeters (Unified Soil Classification System).

Infiltration—The passage of water from the surface to the ground, where it is stored or travels for a relatively long period.

Loamy soils—Soils classified as sandy loam, fine sandy loam, very fine sandy loam, loam, silt loam, silt, clay loam, sandy clay loam, and silty clay loam (U.S. Department of Agriculture soil texture classification).

Mulch—Organic or inorganic materials placed on or near the surface of the ground to assist with germination, establishing vegetation, and reducing erosion and sediment yield. Mulches that contain fiber can be classified as long-fibered or short-fibered. In general, straw, hay, and shredded hardwood bark are long-fibered mulches, and hydromulch, wood fibers, cellulose, and paper are short-fibered mulches.

Reference condition—A set of conditions that represent the potential for natural conditions (may be a minimally impaired site with the least anthropogenic influences). The reference condition represents the best range of conditions that can be achieved.

Rehabilitation—The process of returning a site to good condition, perhaps with a different structure and function than the predisturbance condition.

Restoration—The process of returning a site to a former or unimpaired condition.

Revegetation—A general term for reestablishing vegetation on a disturbed site.

Ripping—Using mechanical equipment to shatter compacted soil. Used interchangeably with subsoiling.

Sand—Medium-grained soil with particle sizes less than 2 millimeters but greater than or equal to 0.05 millimeters (U.S. Department of Agriculture soil texture classification), or with particles less than 4.75 millimeters but greater than or equal to 0.075 millimeters (Unified Soil Classification System).

Sediment—Individual rock or soil particles that result from erosion.

Sediment yield—The amount of sediment that reaches a particular point of interest.

Seepage—Infiltration or percolation of water through rock or soil to or from the surface.

Silt—Fine-grained soil with particles less than 0.05 millimeter but greater than 0.002 millimeter (U.S. Department of Agriculture soil texture classification), or with particles less than 0.075 millimeter that exhibit characteristics of silt (Unified Soil Classification System).

Soil amendment—Any substance applied to a soil (often in a liquid form) to alter soil properties, such as permeability, erodibility, chemical composition, or nutrients.

Soil quality—The capacity of a soil to function within ecosystem boundaries and sustain biological productivity, maintain environmental quality, and promote plant and animal health.

Subsoil (noun)—A deeper layer of soil that frequently has a different soil texture than the topsoil and includes different levels of organic matter, roots, microbes, porosity, and water-holding capacity.

Subsoil (verb)—A mechanical process of disrupting compacted layers of soil to improve infiltration (used interchangeably with ripping).

Tilling—A mechanical process for controlling soil erosion long-term and for reestablishing a plant community. It may involve shattering compacted soils, incorporating soil amendments, and roughening soil surfaces to prepare seedbeds.

Topsoil—The horizon directly below the litter layer. Topsoil characteristics include high organic matter, abundant roots, healthy microbial activity, good infiltration rates, high porosity, high nutrient content, and high water-holding capacity.

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Soil rehabilitation is reestablishing disturbed soil back to healthy conditions to raise site productivity as quickly as possible. Soil rehabilitation is an important resource management strategy that promotes and enhances ecosystem restoration. Principles of soil rehabilitation are complex, and solutions are not simple. However, resource managers can dramatically improve soil quality by developing site-specific cost-effective rehabilitation plans, using appropriate methodology, selecting proper equipment, and using trained operators. This desk guide reviews the literature and describes various soil rehabilitation methods.

Keywords: fertilizer, hydrology, manure, mulch, penetrometers, ripping, soil amendments, soil bulk density, soil compaction, soil disturbance, soil microbes, soil moisture, soil organic matter, soil porosity, subsoiling, tilling, topsoil

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