Soil compaction is one of the most serious site limitations to establishing native plants on disturbed lands such as closed roads. Subsoiling or ripping is the recommended treatment for compacted soils, and this article describes the development and utilization of 3 new, multifunctional subsoiling implements for use with an excavator. The subsoiling grapple rake was designed specifically for resolving the severe soil compaction that develops with the repeated heavy equipment use on timber sales. The subsoiling excavator bucket has been used for road decommissioning and watershed restoration projects. The subsoiling brush cutter has proven useful in a variety of projects including pre-commercial thinning, forest health, fuel reduction, forage enhancement, and brush removal. Nitrogen-fixing shrubs and small trees are ideal for road decommissioning projects because they are aggressive pioneer plants that also improve site fertility.


KEY WORDS
soil, compaction, restoration, revegetation, site preparation, road decommissioning

NOMENCLATURE
USDA NRCS (2008)

A n exciting new policy requires the use of native plant materials in revegetation, restoration, and rehabilitation on all National Forest lands (USDA Forest Service 2008). On many restoration sites, soil compaction is a major impediment to native plant establishment. Decades of timber harvest and recreational vehicle traffic have created acres of severely compacted soils in need of restoration. Most older timber sale units were logged with bulldozers that hauled logs to landings on a series of spur roads, which created a vast road network (Figure 1A). The original management objective was for these road systems to be used again for other silvicultural entries and forest recreational activities. In recent years, however, the role of timber harvest has been greatly reduced on Forest Service lands and so these old logging roads are being closed or "decommissioned." It
has been estimated that, on a national basis, the Forest Service is decommissioning around 3280 km (2038 miles) of road per year for a variety of reasons (Schaffer 2003), such as:

- to prevent environmental degradation,
- to reduce impacts associated with motorized recreational uses,
- to meet specific management requirements defined in national forest plans or court orders, and
- to avoid long-term road maintenance costs.

DELETERIOUS EFFECTS OF SOIL COMPACTION

Most people think of soil as a solid entity, but healthy, productive forest soil is a mixture of mineral and organic particles, a network of pores that contain either air or water. The weight and vibration of heavy vehicles crush soil particles together and reduce porosity—this is particularly damaging when soils are wet (Adams 1998). Compaction has manifold effects on the physical and biological properties of a soil, including limiting water movement and soil aeration, restricting root growth and elongation, and disrupting nutrient dynamics. In severely compacted soils, water infiltration is essentially nonexistent (Switalski and others 2004).

One of the most damaging effects of compaction is the destruction of large soil pores called macropores (Figure 1B). Besides being essential for water infiltration and drainage, macropores are where new roots are able to grow. These large pores also allow air exchange that is necessary for root respiration and the health of beneficial soil microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria. Soil microorganisms are critical to the creation and maintenance of soil porosity. When actinomycetes and bacteria decompose soil organic matter, they leave polysaccharide gums on the surrounding sand, silt, and clay particles.

Figure 1. The extensive network of roads constructed during timber harvest (A) results in severely compacted soils (B) that are challenging to revegetate with native plants (C). As a direct result of soil compaction, all the tree seedlings shown in photo C did not survive the first summer. Graphic A by Jim Marin, Photo B by Thomas D. Landis, Photo C by David Steinfeld.
which glues the particles together. Soil fungi are also involved in organic matter decomposition, especially woody residues like sawdust. The mycelial strands of these fungi grow between soil particles and bind them together into flexible “crumbs” that resist compaction (Davey 1984).

To document the amount and degree of soil compaction and to monitor how much natural recovery occurred over time, a comprehensive study of forest sites across North America was established. When plots were established, soil compaction could be measured to a depth of 30 cm (12 in). When the same sites were monitored again after 5 y, however, compaction had decreased in the surface layers but did not change significantly in lower soil horizons. In particular, fine-textured soils showed little recovery (Page-Dumroese and others 2006).

Compacted soils are challenging for both seeding and planting of native plants. Germinating native plant seeds have a difficult time penetrating compacted soils, whereas seeds of many exotic weeds thrive under these conditions. Not only is it physically difficult to create planting holes in compacted soils but even if they are planted, native nursery stock or wildlings fail to thrive largely because of soil compaction (Steinfeld and others 2008). During wet weather, compacted soils become waterlogged, which further reduces the health of outplanted stock (Figure 1C). Stunting and chlorosis are common because the young plants have not been able to form the mycorrhizal or rhizobial associations that are essential for long-term health and vigor.

THE NEED FOR SUBSOILING

When constructing and maintaining forest roads, compaction is an engineering objective to encourage rapid water runoff. When these roads are closed or decommissioned, however, the objective changes by 180 degrees—now the goals are to reduce compaction and encourage the water infiltration that will stop runoff and soil erosion (Luce 1997).

Subsoiling, also known as ripping, is the physical shattering of soils with heavy equipment and is the preferred treatment for severely compacted soils. The difficulty of reducing soil compaction with subsoiling varies with soil texture, being easier with lighter-textured sands and more difficult with heavier-textured silts and clays (Page-Dumroese and others 2006). When employed in a variety of ecotypes across North America, subsoiling was found to reduce erosion, improve infiltration, enhance revegetation, and discourage weed establishment. Subsoiling decommissioned forest roads and promptly revegetating them reduces the risk of weed invasions, and road closure eliminates vehicle access, which is the primary vector for introducing weed seeds (Switalski and others 2004).

Subsoiling is commonly accomplished with either a bulldozer or an excavator. Using a bulldozer that pulls ripper shanks through the soil is the traditional method (Figure 2). Although it is the easiest and least expensive, bulldozer subsoiling has several limitations. The tracks of the bulldozer create their own soil compaction if traveling over subsoiled areas; and the fixed ripping teeth produce uneven coverage when the bulldozer changes direction or maneuvers around obstacles. From our perspective, however, the most serious limitation is that bulldozers cannot perform other soil treatments, such as spreading organic matter over the soil surface.

Excavator subsoiling is a much newer option and can effectively subsoil by pulling the tines of a specially modified grapple rake or bucket through compacted soil. One benefit of excavator subsoiling is that the equipment can work from one central position while...
covering a wide arc (Figure 2). Because the operator gradually works backward, any compaction caused by the excavator itself is removed, so the subsoiling effect is more uniform over the treated area.

In addition, the excavator can spread woody material, chips, or sawdust over the surface after subsoiling to prevent formation of surface crusts and to encourage water infiltration (Luce 1997). Bradley (1997) found that mulch prepared from forest slash prevented soil surface sealing and increased water infiltration. Longer shreds of organic matter are preferred over smaller particles because longer strands create interconnecting pathways for water, air, and roots. Any amount of organic matter will help, but research showed positive effects with a ratio of 25% organic matter to 75% soil by volume (Claassen 2006). Sawdust should not be used because the smaller particles break down quickly which ties up soil nitrogen and can cause yellowing and stunting in plants (Bulmer 2000).

**MULTIFUNCTIONAL SUBSOILING EQUIPMENT**

To further improve excavator subsoiling effectiveness, personnel of the Diamond Lake Ranger District of the Umpqua National Forest in Oregon invented 3 new subsoiling implements. These are patented USDA Forest Service technologies and are commercially available from Savannah Forestry Equipment LLC (see Equipment Availability section). These innovative tools have been used successfully not only in Oregon but this technology has been transferred to the Bitterroot National Forest in Montana and the Clearwater National Forest in Idaho. What is unique is that all 3 implements are interchangeable on an excavator arm and each can perform multiple restoration functions, reducing the need for other types of equipment.
1. Subsoiling Grapple Rake
This implement has been modified (US Patent 7,086,184) to include 2 curved shanks on the underside of the bucket that can rip soils to an effective depth of 50 to 75 cm (20 to 30 in) (Figure 3A). A sharpened coulter blade on the front of the rake is used to cut woody debris into smaller pieces. The subsoiling grapple rake was designed specifically for resolving the severe soil compaction that develops with the repeated heavy equipment use on timber sales. Compaction is particularly bad on landings and haul roads, and the grapple rake is ideal for subsoiling these sites and returning organic debris onto the soil surface. Treating compacted soils before leaving the site has obvious erosion and revegetation advantages, and it is also considerably less expensive than bringing equipment back to treat these sites at a later date.

2. Subsoiling Excavator Bucket
This excavator bucket was designed specifically for watershed restoration projects (US Patent 7,059,072) and also features curved shanks and an optional coulter blade (Figure 3B). On road decommissioning projects, this implement can rip compacted roadbeds and ditch lines before they might be buried with soil during recontouring. One road decommissioning project used the bucket to reclaim gravel from the road surface prior to subsoiling, which resulted in considerable savings not only in materials but also in haul costs. On a Forest Service in-house project, the subsoiling excavator bucket produced a US$ 40,000 savings compared with the lowest contract price.

3. Subsoiling Brush Cutter Hitch
This multipurpose implement was designed specifically for vegetation management projects (US Patent Pending). In addition to the subsoiling Shank and coulter blade, this implement adapts to receive a masticating head for chipping woody vegetation (Figure 3C). The subsoiling brush cutter has proved useful in a variety of projects including pre-commercial thinning, forest health, fuel reduction, forage enhancement, and brush removal.

RE VEGETATING SUBSOILED SITES
Prompt revegetation of subsoiled sites is critical for these 4 reasons (Bagley 1998).

1. Reduce Surface Erosion  Controlling surface erosion is the most important short-term benefit of revegetation. Erosive raindrop impact and surface runoff energies are dissipated by vegetation and organic litter. Plant stems and root channels further reduce surface runoff by providing avenues for water to infiltrate the soil.

2. Improve Soil Structure  Plant roots and substances released by soil organisms bind the soil together, improving soil structure. Soil organic matter and organic debris on the soil surface increase resistance to erosion and improve soil development.

3. Increase Slope Stability  Revegetating with native plants prevents slumps and other slope failures by reducing soil moisture through transpiration and by plant roots binding surface soils together.

4. Enhance Biological Activity  Native plants provide habitat for a wide variety of insects and other small animals, and decomposition of their litter provides an energy source for soil organisms.

Subsoiled sites provide an opportunity to create a unique habitat.

On the Diamond Lake Ranger District, subsoiling is followed immediately by one of two revegetation treatments: direct seeding or outplanting. Subsoiling creates an ideal germination environment for direct seeding source-identified seeds. The seeding mix varies consider-
ably with site conditions but is done promptly to prevent soil erosion and weed growth. For example, much of the area on the Maple Creek road decommissioning project is in heavy shade so the seeding mixture consisted of shade-tolerant grasses (Poaceae) including bromes (Bromus spp.), western fescue (Festuca occidentalis Hook.), and oniongrass (Melica bulbosa Geyer ex Porter & J.M. Coult.). Legumes are particularly good for seeding on subsoiled restoration sites because they are aggressive pioneer species and improve soil fertility. Rhizobium bacteria form nodules on the roots of legumes and fix atmospheric nitrogen into available forms that other plants can use (Figure 4A).

Outplanting nursery stock or transplanting large shrubs and trees helps restore decommissioned roads in several ways. Not only do they provide shade and protection for the natural in-seeding of other local natives but their leaf litter improves soil quality and provides food for soil organisms. Again, nitrogen-fixing woody plants such as alder (Alnus spp. Mill. [Betulaceae]) (Figure 4B) are especially beneficial for restoration plantings. Alder is an example of an actinorrhizal plant that forms root nodules with another genus of nitrogen-fixing bacteria (Frankia spp). More than 200 species of native plants, including Purshia spp. DC. ex Poir. (Rosaceae) and Ceanothus spp. L. (Rhamnaceae), are also actinorrhizal (Steinfeld and others 2008). Finally, a dense outplanting of large woody plants near the start of the road creates a visual and physical screen to discourage four-wheelers and other recreational vehicles.

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