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Winter Logging for Mechanical Harvesting and Fuel Treatment Operations

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Cover photo—Stacking logs during a winter logging operation.

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Executive Summary

The U.S. Department of Agriculture, Forest Service and the National Technology and Development Program (NTDP) synthesized existing literature, collected data, and summarized information on winter logging using mechanical harvesting and fuel treatment operations on National Forest System lands. Proper winter logging can improve harvest options while protecting soil and water resources, particularly in areas where forest land managers rely heavily on winter operations for sustainable forest management. Winter logging operations occur to maintain winter timber inventory for lumber mills, reduce impacts on summer wildlife, and minimize soil degradation. During the winter, site conditions can be quite different than other times of the year. These conditions provide opportunities for lower impact logging and can decrease detrimental effects on underlying mineral soil compaction, forest floor ecology, hydrology, and water quality.

Winter logging may reduce damage to residual trees and may lessen the risk of the spread of disease to injured trees. Harvesting during winter (dormancy) months can be favorable in areas that support vulnerable native plant species by protecting the plants and their habitats. The amount, degree, and extent of damage resulting from winter logging depends on ambient environmental conditions, such as climatic regime, organic horizon depth and integrity, mineral soil properties and conditions, as well as harvest operation-related parameters, like traffic levels, load hauling, and snowplowing. Snowplowing roads for timber hauling is an appropriate practice that increases frost penetration. It allows for a longer harvest window while reducing ground impacts. As new innovations and technologies emerge, technical solutions to reduce soil damage are not limited to snowplowing.

States often outline best management practices (BMPs), and the Forest Service uses BMPs in national forest contract language. They are effective techniques that provide foresters, sale administrators, contractors, and operators with methods to meet ecological management objectives. Better management of winter logging opportunities will improve natural resource management efforts. The benefit of winter logging operations aligns with the National Forest System's soil resources program objectives. Furthermore, the use of the Forest Soil Disturbance Monitoring Protocol (FSDMP) before and after harvest can help each national forest determine the extent and severity of winter logging impacts and the effectiveness of applying mitigation efforts. Forest land managers may revise, update, or improve mitigations and BMPs as needed.

Introduction

There are about 303 million hectares (ha) of forest lands in the U.S. (Oswalt and Smith 2014). National forests comprise 58 million ha (or roughly 145 million acres). Conducting silvicultural maintenance and restoration on these lands is important in correcting the current degraded state of overstocking or excess downed woody debris (Reinhardt et al. 2008). Overstocked trees and understory competition can induce physiological stress, and trees may become more susceptible to wildfire, insect pests, and disease (Weatherspoon and Skinner 2002). These conditions ultimately increase the collective amount of biomass fuels that forest land managers may need to remove.

The Forest Service currently treats a greater area for hazardous fuels than the agency has at any other time in the past 20 years to accomplish its restoration goals (U.S. Department of Agriculture, Forest Service 2018). Harvesting and removing excess timber is more cost effective than suppressing wildfires (Ager et al. 2010; Reinhardt et al. 2008). In addition, the restoration efforts of forested sites need to address both watershed health and site resilience (Reinhardt et al. 2008; Stone et al. 2008).

Reducing timber stand volume and improving structure are methods of correcting overstocked stands. However, forest land managers cannot manage these types of harvest opportunities as one-time projects. Because of the dynamic nature of forest ecosystems, ongoing reconnaissance and active stand maintenance are important management strategies (Agee and Skinner 2005; Reinhardt et al. 2008). Extending the duration of forest harvesting operations throughout the year, particularly in the northern tier states, is important to maintain progress. For example, in Wisconsin, where operators can remain active for three and a half seasons, loggers harvested an equal volume (44 percent) during the winter season (December to February) as both the summer (June to August) and fall seasons (September to November) combined (Conrad et al. 2018).

Forest land managers may encourage winter logging as a mitigation tool to reduce disturbances that may be detrimental to soil quality, hydrologic function, forest floor ecology, and understory vegetative growth. There are many important considerations to evaluate before winter logging, such as ensuring the ground is frozen, designating permanent skid trails, using slash mats, and excluding riparian areas (Stone 2002). Ninety-one percent of national forests are located in the western and northern U.S. (Oswalt and Smith 2014), but not all of these areas have climates conducive to winter logging.

Soil scientists and silviculturists have recently explored different harvest and mechanical treatments that meet soil resource objectives and promote forest soil health. Many national forests have initiated processes to examine winter logging operations. This report focuses on locations where the climate and associated environmental conditions are conducive to winter logging.

The intent is to determine whether winter logging reduces soil disturbance impacts, such as erosion, rutting, and compaction compared to traditional, nonwinter harvest practices. When carried out under specific prescribed regional conditions, winter logging can have fewer impacts on the soil, but in some cases, logging methods or site trafficking must include any updated BMPs (Stone 2002).

Objectives

The objectives of this document are to:

- Summarize the impacts of winter logging on soil types, hydrology, vegetation, and forest floor ecology.
- Recommend best management practices (BMPs) to meet newer soil resource objectives, promote forest health, and help reduce current impacts.
- Present current standards for winter logging methods gathered from available literature; personal communications; and data collection methods, results, and outcomes on various national forests in North America.
- Present State BMP recommendations toward common goals.
- Recommend methods for evaluating site readiness and for collecting soil property and site condition data.

Soil Properties and Site Conditions

Forest harvest operations have a large impact on soil properties, stand composition, and future site productivity (Powers et al. 1990; Tiarks et al. 1993). Since the passage of the National Forest Management Act in 1976 (and related legislation), the Forest Service manages all national forests to maintain their productive potential. On public lands in the U.S., maintenance of site productive capacity is a common objective. To ensure continued productivity, forest land managers must consider the soil properties and should determine when and why disturbance occurs, specifically when soil is saturated (figure 1). Winter logging may be a practical solution in areas where forest land managers might expect considerable impacts from nonwinter logging.

Figure 1—Soil rutting is indicative of the low load bearing capacity of soils resulting from soil with high moisture content.

Soil disturbance from typical harvest operations can result in soil erosion, runoff, and reduced vegetative growth (Sipes 2010). Furthermore, other soil impacts, such as soil compaction, soil mixing or displacement, and rutting can have long-term site effects on forest productivity (Corns 1988; Curran 1999; Grigal 2000; Kolka et al. 2012). The degree of impact depends on a number of factors and can occur on the first pass of heavy equipment (Aust et al. 1993).

Soil Disturbance Terms

Forest soils, often characterized by biologically active top horizons rich in organic matter, are particularly prone to compaction (Horn et al. 2007). Soil compaction results in reduced water infiltration and hydraulic conductivity, which contributes to greater waterlogging on flat terrain and runoff and erosion on hillslopes (Agherkakli et al. 2010). With the exception of coarse-textured (well-drained) soils, compaction reduces oxygen and water availability to roots and terrestrial microorganisms (Startsev and McNabb 2000). A consequence of compaction is depressed forest productivity (Agherkakli et al. 2010).

Wet-site harvest operations can also cause rutting or puddling (see figure 1). A rut is a depression or groove worn into a road or path by the travel of wheels or skids from heavy equipment. The tracks left behind are an indication of soil deformation, and rutting usually occurs under saturated soil conditions (but can also occur on dry soils depending on soil texture). Puddling refers to the destruction of soil aggregates into ultimate soil particles (discrete particles) and can result from mechanical manipulation (Sharma and DeDatta 1986). Puddling occurs when soils experience shear failure and results from limited infiltration and churning (Aust et al. 1993). Driving on snow can reduce soil rutting and puddling (figure 2).

Figure 2—Snow cover protects mineral soil and roads from machine traffic.

Soil Moisture Regimes

Soil moisture regimes (SMR) are some of the best indicators of compaction potential (Greacen and Sands 1980; McNabb et al. 2001; Soane 1990). There is a wide range of soil moisture and temperature conditions in areas where winter logging is an option. Regional climate, water table depth, and presence or absence of available water (water that plants can use) define SMRs and are based on data from over 20,000 climatic stations. According to the U.S. Department of Agriculture, Natural Resources Conservation Service's "Soil Survey Manual" (2017), the five SMRs are:

- Aquic
- Udic
- Ustic
- Aridic
- Xeric

SMRs range from aquic, fully saturated soils, to xeric, soils that are extremely dry. The level of soil moisture depends largely on geography but also varies based on other factors, such as clay content, texture, and presence of a hardpan. SMRs are useful because they group similar soils and indicate how climatic regime can influence soil formation and soil management. Different SMRs support different vegetation communities, and each situation requires a specific determination on how and when to apply management practices to limit soil disturbance.

Soil Texture, Soil Organic Matter, and Rock Fragment Content

Soil is a mix of soil particles, organic matter, pore (air) space, and water. The distribution of different sizes of clay, silt, and sand particles in the soil make up the texture. Soil texture, soil organic matter (SOM), and rock-fragment content largely influence soil moisture holding capacity. Therefore, these factors affect how easily traffic causes compaction, puddling, or rutting.

Soil Texture

Soil texture is the relative percentage of sand, silt, and clay. In fine-textured soils, smaller particles allow for more pore space. When the pore spaces fill with water, a fine-textured soil generally has greater water holding capacity than a coarse-textured soil, which has larger pore spaces. Water held in pore spaces, either seasonally or permanently, affects the soil's ability to withstand forces exerted on it by heavy equipment. As moisture content increases, frictional resistance between particles decreases, reducing the load bearing capacity (Cambi et al. 2015).

When wet, fine- and medium-textured soils are more susceptible to compaction than coarse-textured soils (Corns 1988; Greacen and Sands 1980; Kolka et al. 2012; Page-Dumroese et al. 2006). For example, in boreal forests (Alberta, Canada), compaction only occurred when soil moisture was at or wetter than field capacity (McNabb et al. 2001). To minimize compaction, logging companies in Canada schedule winter harvest operations on fine-textured, poorly drained soils because of the increased likelihood that the soils will be frozen (McNabb et al. 2001).

Kabzems (1996), Stone (2002), Stone and Elioff (1998), and Stone et al. (1999) examined relationships among harvest seasons, soil textures, and landscape positions, and the effects of these conditions on soil bulk densities and surface soil strengths for harvest sites in the Ottawa NF and the Northeastern Research Station. Researchers observed greater bulk densities and greater surface soil strengths following harvesting compared with adjacent and similar but unharvested stands (Stone 2002, Stone and Elioff 1998, Stone et al. 1999).

Soil Organic Matter

The role of soil organic matter (SOM) is wide ranging. Organic matter:

- Increases available water holding capacity
- Regulates nutrient cycling
- Sustains microbial diversity
- Limits soil compaction

In the mineral soil, SOM absorbs water as it moves into the soil profile. Increased SOM decreases the impact of mechanical stresses during harvesting, and it takes greater amounts of water to reach maximum compaction (Lull 1959). Water and nutrients in SOM attract fungi and bacteria, which bind mineral particles and SOM together into larger aggregates. Both surface and subsurface organic matter affect aggregate stability (Tisdall and Oades 1982). Soils with high aggregate stability are less susceptible to compaction (Soane 1990). SOM also promotes plant growth and soil health, and therefore the maintenance of SOM should be a long-term management objective (Jurgensen et al. 1997) (figure 3).

Figure 3—Soil organic matter accumulated on topsoil can protect mineral soil and roads from machine traffic during logging operations.

Rock Fragments

Rock fragments within soil can help reduce the compaction forces of heavy equipment (Page-Dumroese et al. 2006). Rocks within and on the surface of mineral soil act like armor to prevent packing, keeping soils porous and allowing water to continuously infiltrate. Generally, rockier soil is less susceptible to compaction.

For trafficked soils containing more than 15 to 20 percent rock content, Liechty et al. (2002) found no difference between soil bulk density for harvests during the dry season and the wet season. Comeau et al. (1982) and Lewis et al. (1989) suggested that severe compaction risk still existed when the soil contained less than 15 to 20 percent rock fragments throughout and had loamy or clayey texture. Studies have indicated that soils containing 20 to 40 percent rock fragments throughout, with a loamy or clayey texture, showed moderate compaction (Brais 2001; Comeau et al. 1982; Gomez et al. 2002; Lewis et al. 1989; Liechty et al. 2002; Powers and Alves 1998). Gomez et al. (2002) and Lewis et al. (1989) found that heavy machine traffic had slight impacts when the snowpack was deeper than 3 feet and/or the depth of frozen ground was greater than 20 inches.

Landscape and Hydrology

Landscape position is important when assessing the impacts of logging operations. Harvest unit topography plays a role in the redistribution of moisture (Block et al. 2002). Steeper sloping areas shed water, whereas adjacent flatter areas receive water. Soils in depressions may receive subsurface inflow (figure 4) and are more susceptible to soil compaction and rutting, because they tend to remain wet for relatively long periods compared with the rest of the landscape (Block et al. 2002).

To limit changes to site hydrology, both surface and subsurface soil conditions require consideration during winter logging. Although winter logging may not appear to impact surface conditions, forest land managers should monitor changes in infiltration, interflow rates, saturated hydraulic conductivity, and surface and subsurface flow paths. As snow begins to melt in the spring, snow-packed trails and roads can inhibit water movement and may result in temporary ponding or flooding. Using cross culverts or cutting cross drainages in roads following harvest operations can minimize this impact (Aust et al. 1993; Clinton 2011; Comeau et al. 1982).

Forest Floor

Forest floor development depends on local climatic conditions, the amount and quality of litterfall, and litter decomposition rates (Sayer 2006). The forest floor (litter layer) plays a role in soil nutrient cycling and soil chemistry dynamics and has other ecosystem functions (Sayer 2006), including:

- Contributing to plant and microbial community interactions
- Protecting and regulating microclimatic conditions
- Providing refuge for invertebrates
- Mitigating erosion

Adding slash mats or increasing litter cover can mitigate ground disturbance (figure 5). Preserving the forest floor during winter logging operations is key because it reduces ground disturbance and supports continued ecosystem functioning. Harvesting can result in forest floor disturbances (e.g., soil displacement or mixing with mineral soil) that may produce multiple mixed layers (figure 6), which can then influence the depth and type of freezing (MacKinney 1929).

Figure 4—An assessment of site conditions for frozen soil. The ground under the snow is not always frozen. Subsurface inflow tends to remain wet for relatively long periods.

Figure 5—Using slash mats or plant litter when operating logging equipment during winter harvests can mitigate ground disturbance.

Figure 6—Combining woody residues with organic matter creates two distinct snow layers—an upper layer mixed with logging debris and a frozen lower layer. Greater bulk density was observed in the frozen lower layer because of compaction.

Snow and Frozen Ground

Exploitation of regional winter conditions (a large snowpack, freezing temperatures, and frozen ground) can be a convenient way to effectively protect soil and trees from disturbance or damage, but forest land managers must monitor snow and soil conditions regularly to avoid soil impacts.

Snow

Winter logging can be beneficial because a snow layer can protect the forest floor (figure 7). In interior Alaska, Zasada et al. (1987) found that snow physically protected the forest floor from disturbance and seedlings from damage during logging. Snow also provides thermal protection to organisms that are active under the snow (Zasada et al. 1987). Alternatively, on a winter-logged, central hardwood site in Connecticut with no snow cover, only 29 percent of the site remained undisturbed after the logging operation (Martin 1988).

Snow properties and the amount of water the snow contains (snow water equivalent) vary depending on snow crystal structure, windspeed, air temperature, and other factors during and after snowfall. Dry snow can have a water content of 1 to 15 percent (figure 8), whereas wet snow can have water content ranging from 20 to 40 percent (figure 9). Freshly fallen snow has a density between 100 to 200 kilograms per cubic meter (kg/m^3) (Blackford 2007), and the amount of water plus snow density affects the snow compactibility and ice formation. Snow properties can affect equipment mobility, soil disturbance, and soil armor.

Figure 7—Snow can act as a protective layer to reduce soil disturbance.

Figure 8—A dry snow field.

Figure 9—Wet snow around the base of a tree.

There are many measurement techniques available for measuring snow strength properties. Selecting the appropriate method depends on the required degree of reliability and available resources. The most reliable method for determining traffic-support capacity is to simulate actual loading conditions, but this requires specially constructed equipment and may be best for research and development use. Abele (1975) defines the more practical measurement techniques, which include:

- **Measuring the surface load—**A vertical load is applied to the snow surface.
- **Measuring sample strength—**A core sample is removed from the snow and subjected to a strength test.
- **Probing—**A probe is penetrated into or through the snow.

As snow ages, it naturally densifies (also called sintering). Sintering results from exposure to solar radiation and wind, temperature cycling, and the introduction of free water and pressure which allows snow particles to bond (Flatten 2002). These bonds result in increased snow strength (Blackford 2007). Sintered snowpack becomes a cohesive mass that can provide greater support than freshly fallen snow (Flatten 2002).

Logging can alter the snowpack by changing snow depth, density, and strength (Zasada et al. 1987). Thus, logging activities may reduce the protective capacity of snow in terms of thermal and structural properties if forest land managers do not consider the local snow properties during harvest site layout and operations.

Creating a snow road within a harvest unit can enable the use of bulldozers, vibrating compactors, SnowPavers, sheep foot rollers, or other heavy equipment. Building a snow road is as easy as plowing or packing the snow cover in place during the day and letting it solidify during the night. SnowPaver stemming is another method forest land managers may consider (figure 10). Researchers

Figure 10—An unloaded SnowPaver machine.

have used this applied technology successfully in Antarctica (Shoop et al. 2016). Because the machine can mill, level, and compact snow in one pass (saving both labor and equipment costs) this equipment may be a good alternative for building snow roads in winter logging operations (Shoop et al. 2013). However, using a SnowPaver in winter logging operations has not yet been tested.

Taking advantage of time and temperature is important in creating effective skid trails and haul roads for trafficking on snow (Abele 1990). Relative fluctuation of ambient temperatures during snow disaggregation and compaction results in greater snow density and the maximum rate of age hardening. A decrease in temperature during the snow-aging process further increases snow strength (Abele 1990) and leads to ideal conditions for heavy trafficking (figure 11).

Figure 11—Operating equipment on a frozen, compacted road minimizes soil disturbance.

Frozen Ground

The appropriate depth of frozen mineral soil for safe harvest practices depends on the equipment type. To summarize various guidelines for suitable winter harvest conditions, some national forests in the Eastern Region determined that the depth of frozen mineral soil should be about 4 inches for small equipment, 6 inches for medium-sized equipment, and more than 6 inches for large logging equipment. Other national forests have developed their own criteria for the depth of frozen soil. For example, some forests use National Environmental Policy Act (NEPA) design criteria that include the guidance of 6 inches of frozen soil or 12 inches of frozen or compacted snow. Most literature concludes that more than 3 inches of solid frozen ground is sufficient to support logging equipment. It is important to note that these guidelines are designed for solidly frozen mineral soil—the interior matrix of mineral soil is completely saturated, free of cavities, or hollow. This condition occurs when the mineral soil is completely saturated before freezing conditions begin.

Winter Logging Impacts

Winter logging can help protect forest floor ecology, tree health, and stand regeneration compared to summer harvesting. However, performing the logging operations under less-than-ideal conditions can have long-term negative impacts.

Impacts on Soil and the Forest Floor

In a study on multiple sites in Saskatchewan, Canada, Block et al. (2002) showed greater increases in bulk density following harvest from the winter-logged sites than for summer-logged sites. The authors acknowledged that the reasons for these results was unclear and described the winter-logged sites as having a “relatively permanent moist soil condition.” Studies by Labelle and Jaeger (2011) and Stone et al. (1999) indicated that freeze-thaw cycles and biological activity did not ameliorate compaction and soil bulk density. Labelle and Jaeger (2011) monitored soil density at locations pre- and post-logging and found no natural rehabilitation (decrease) of soil density down to pretreatment levels after 5 years. Winter logging on aspen tree (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) stands resulted in severe soil disturbance and reduced stand regeneration by almost half (Stone 2002). The logging operation caused severe rutting and other types of soil disturbance. There is abundant literature on the lasting effects of soil compaction, rutting, and other types of soil disturbance (Cambi et al. 2015), and an assessment by Grigal (2000) rates compaction and rutting as high-certainty, medium-severity activities with medium to long durations. The importance of knowing the condition of winter soil (if it is frozen and to what depth) before operations occur is a critical component of implementation.

As part of the North American Long-Term Soil Productivity study, researchers tried to compact soil to within 20 percent of the root-limiting bulk density by compacting many soil textures at (or near) field capacity (Page-Dumroese et al. 2010). Results indicated that fine-textured soils had the greatest increase in bulk density with most of the impact occurring after just one equipment pass (Page-Dumroese et al. 2006). Others also confirm that most adverse impacts to the soil occur within the first few passes of equipment (Brais and Camiré 1998; Han et al. 2006; McDonald and Seixas 1997; Williamson and Nielsen 2000). Hillel (2004) reported that one harvest machine pass on wet soil caused an equivalent reduction in infiltration rate to four passes over dry soil. Though many of these studies were not during winter logging operations, the research does indicate the important role that soil moisture plays in how quickly equipment can compact soil or cause rutting.

Maintaining the forest floor is important for many biological and physical processes, so it is favorable to coordinate harvest operations to minimize impacts to both the forest floor and mineral soil (Powers et al. 2005). Because of the protective nature of snowpack or snow roads, winter logging can minimize impacts to the forest floor and mineral soil (figure 12).

Figure 12—Operating equipment on a frozen, compacted road covered with snow can reduce logging impact.

Following a winter harvest operation with snowpack and frozen soil in an eastern Oregon ponderosa pine forest, Williams and Buckhouse (1993) noted minimal evidence of soil disturbance. There was some reduction in forest floor depth between the harvested and nonharvested plots but no signs of tracks, trails, compaction, or change in infiltration. The authors indicated that even with a reduced forest floor depth, there was also no increase in soil erosion.

In a seasonal comparison of harvesting effects on the Chippewa National Forest (NF) in northern Minnesota, soil bulk densities were greater at summer-logged sites compared to winter-logged sites (Kolka et al. 2012). Although harvest operations on both fine- and coarse-textured soils significantly increased resistance to penetration and bulk density, both measures of soil physical properties changed less during the winter operation. The frozen ground and compacted snow were effective in limiting compaction when the load-bearing capacity was greater than the pressure applied by the harvest machinery (Kolka et al. 2012).

Impacts of winter logging on soil and the forest floor are site specific, and results from studies vary. Stone and Elioff (1998) concluded that winter logging operations on frozen loamy sand in northern Minnesota hardly changed the physical properties. Researchers in Saskatchewan used a systematic grid system to evaluate forest floor disturbance and noted greater incidences of forest floor disturbance for the summer-harvested sites (Block et al. 2002). On the Hiawatha NF (Upper Peninsula of Michigan), a post-treatment evaluation of winter logging during frozen soil conditions using the Forest Soil Disturbance Monitoring Protocol (FSDMP) showed the amount of change was not considerable, and the forest had met its soils standards for both units treated (Townsley et al. 2010).

In contrast, Stone (2002) found that severe soil disturbance (primarily rutting) on 38 percent of a well-drained site from larger felling and skidding equipment reduced the number and height of aspen suckers. Furthermore, Stone and Elioff (2000) indicated that machine traffic in deep snow can affect soil even when there is no visual evidence. Snow depths in their study ranged from 76 to 90 centimeters (about 30 to 35 inches) at one site and 90 to 100 centimeters (about 35 to 39 inches) at another. Soil compaction may occur even when there are no visible tracks, and vegetation and slash can conceal disturbance from view.

The discrepancies in the impacts of these winter operations emphasize the importance of understanding ideal conditions for logging as well as matching proper equipment to individual sites.

Operating guidelines in British Columbia, Canada require serious consideration of the snow condition. Forest land managers must test snow compressibility and mineral soil moisture content before harvesting activities can occur. These simple test results govern the appropriate number of logging equipment passes given the specific conditions to limit the amount of soil disturbance (Curran 1999).

Impacts on Species Composition and Stand Regeneration

In the northeastern U.S., Tubbs and Reid (1984) studied regeneration success of various tree species after winter and summer harvest seasons in the Green Mountain NF in Vermont. The disturbance type, distribution, and amount common to summer logging (e.g., scarification exposure of the mineral soil) favored birch (*Betula* species) regeneration. However, the disturbance type, distribution, and amount common to winter logging (over frozen ground and snow cover) favored regeneration and establishment of beech (*Fagus* species), sugar maple (*Acer saccharum*), red spruce (*Picea rubens*), eastern hemlock (*Tsuga canadensis*), and white ash (*Fraxinus americana*). In addition, although there were differences in species composition, winter logging resulted in greater stocking levels of desirable commercial species (figure 13).

Figure 13—A winter logging stacking/decking operation.

In stands with advanced regeneration in the understory, winter logging may be the best option to ensure successful growth of future forests. When trees return to a dormant state in the winter, they store nutrients in their root systems, and their bark holds tighter against the bole, which reduces the likelihood of stem damage during operations (Schira 2013). Harvesting trees in the winter may encourage healthy tree and stand conditions because the nutrients remain in the root system and become available to promote hardwood sprouts in the spring (Schira 2013). With winter snowpack, seedlings have better protection; therefore, fewer are uprooted, broken, or killed (Tubbs and Reid 1984). Furthermore, shielding of the root systems by frozen ground ensures future growth and regrowth.

Impacts on Understory Vegetation

Preserving the ecological integrity of understory plant communities is important because of the role they play in the structure and function of ecosystems (Kern et al. 2006). Understory plants provide wildlife habitat, decrease invasive species promotion, and lessen the impacts of erosion and runoff from heavy precipitation. Logging can negatively affect understory growth by crushing or uprooting plants, and thus, increases the risk of severe erosion events (Meier et al. 1995; Stone 2002; Wolf et al. 2008). Winter logging preserves the ecological integrity of understory plant communities (figure 14).

Harvest operations in nonwinter months modify surface organic horizons (by mixing, compacting, or displacing), which can result in less-than-optimal conditions for herbaceous reproduction and nutrient cycling (Meier et al. 1995). There are several mechanisms responsible for the decline of understory plant species following logging operations. The reduction in understory plant populations in eastern deciduous forests have altered competitive interactions, favoring early successional species. According to Meier et al. (1995), at particular disturbance intensities, recovery rates of overwhelmed species and the recolonization of certain microsites can exceed natural herbaceous population recovery.

Disturbance and exposure of mineral soil in the harvest unit after a logging event can increase the amount of invasive species, which tend to be better dispersers and more adaptable (Battles et al. 2001). Wolf et al. (2008) used a paired plot study method to

Figure 14—Winter logging preserves the ecological integrity of understory plant communities.

compare the effects of winter and summer logging on understory vegetation. They found greater plant counts and ground cover of ecologically vulnerable native plant species in the winter-logged sites compared to the summer-logged sites.

Short growing seasons coupled with slow growth and snow cover in northern areas may protect understory plants from harvest activities. In Wisconsin, researchers attributed minimal differences in vegetation response to the negligible impacts from winter logging (Kern et al. 2006). Differences in the seasonally logged sites became most apparent 2 to 4 years after the timber management activities. Forest land managers should conduct long-term monitoring of site impacts.

Plant biodiversity, particularly of vulnerable species, may benefit from harvest operations under winter conditions (Meier et al. 1995; Wolf et al. 2008). The limited disturbance to the soil and its environment during winter logging means less disruption to the biological communities, including mycorrhizal associations, which are essential for the maintenance and regeneration of woody, herbaceous, and nonvascular understory plants (Grigal 2000). Figure 15 shows an understory population of native northern-climate bryophytes.

Winter Logging Planning

Although forest management activities are necessary, these activities alter soil physical properties and forest production, are extensive and immediate, and have well-documented effects (Grigal 2000). Furthermore, minimizing negative effects can be difficult given the constraints of the site and timing of operations (Grigal 2000).

While managers cannot predict how changing climatic regimes may affect the winter logging season, winter operations can generally be successful with planning and insight into local conditions. Effective implementation of forestry operations depends on the skill, awareness, and sensitivity to soil disturbance of planners and operators (Lewis et al. 1989; Stone 2002; Stone and Elioff 2000; Stone et al. 2001). Managing winter logging will improve effective resource management capabilities, particularly in areas that rely heavily on winter logging operations for sustainable forest management. Incorporating BMPs is the most effective process, but this also involves preparation (Curran 1999; Shaffer 2009). Knowledge and understanding of the soil, climate, and precipitation (timing and type) among other variables, will help ensure the success of the planned operation and will limit unintended impacts to site resources.

Figure 15—Winter logging may benefit native ground cover species survival.

Limited Operating Periods and Best Management Practices

The concept of limited operating periods (LOPs) to protect or reduce impacts on resources and ecosystem services is one management strategy. Corns (1988), Curran (1999), Kolka et al. (2012), and Sharratt et al. (1998) suggested that many forests should have LOPs to protect or reduce impacts on resources and forest ecosystem services. In Wisconsin, the most cited seasonal harvest restriction is soil/hydrologic disturbance and requires limiting operations to "frozen conditions" or to "frozen or dry conditions" (Demchik et al. 2016). Interestingly, despite restrictions and LOPs, logging capacity in Wisconsin is at its highest (80 percent) during the winter (Demchik et al. 2016).

Using existing winter conditions to the benefit of stands, soil, and effective operations is a good strategy for BMPs. Goychuk et al. (2011) found that working with environmental conditions to improve operations in northern Minnesota can be advantageous. Harvest productivity increased during winter harvest operations when adhering to strict BMPs. The frozen soil depth can vary depending on forest floor depth, soil texture, and rock fragment and soil organic matter content. Promoting the freezing of skid roads and landings by plowing snow, packing snow, or delaying skidding of felled trees until trails and landings have frozen adequately are critical BMPs (Stone 2002). In addition, clearing roads of snow and allowing them time to freeze led to a decrease in time spent working in difficult conditions that ultimately resulted in rutting and compaction.

Favorable operating conditions are also economically advantageous because they increase efficiency and productivity while reducing machinery repairs and fuel costs (Stone 2002). A survey of industry foresters in Wisconsin found that soil disturbance restrictions were one of the top two benefits that exceeded their costs (Conrad et al. 2017). The recognition that there can be a balance between preserving the soil resource and its functions and successfully conducting winter logging operations that have minimal impacts without unnecessary constraints is an important compromise (Flatten 2002).

Timing of Operations

The timing of operations is crucial to the success of a winter logging operation. The three most important decisions are:

- When to begin operations
- When to end for the season
- When to temporarily stop due to unseasonably warm weather

Part of harvest scheduling is to identify suitable winter logging guidelines to begin, continue, or end the harvest period as well as suitable winter logging guidelines for extending the harvest period (Stone 2002; Townsley et al. 2010; Williams and Buckhouse 1993; Wolf et al. 2008). Forest land managers should carefully decide when to start operations. Quantifying sufficient soil frost depth and satisfactory snow conditions can alleviate damage to the soil. Starting operations too early can also negatively affect snowpack conditions and can further delay the harvest. Fluctuations in site temperatures can change soil and snowpack condition quickly, and the decision to stop operations must occur before soil and snow strength dissipate and mud or slushy conditions develop. Snow with a high moisture content over unfrozen soils may increase soil compaction and cause irreparable damage. Restarting operations can follow if weather conditions restore the snow and soil to BMP benchmarks.

As noted previously, logging equipment can easily compact wet or moist soil, and the susceptibility of disturbance decreases with lower water content (McNabb 1999). Winter harvest operations are only effective in limiting soil compaction when the frost layer depth is adequate to resist the pressure applied by the logging equipment (figure 16).

Contract modifications can raise operator awareness to disturbance impacts while validating the need to meet the necessary environmental conditions to keep forest operations ongoing (Flatten 2002). This method can be useful in achieving desired outcomes (Stone et al. 2001).

Soil and Snow Conditions

Shoop (1995) mentioned that frozen soil can make vehicle and equipment operations possible on ground that is otherwise nontrafficable, including some sensitive soils. The frost depth needed to support equipment relates to the static ground pressure of the machine and the forces exerted while the equipment is under load. The static ground pressure is a starting point for classing and understanding vehicle impacts. It does not account for all the forces which are in play during vehicle operation and movement (Cambi et al. 2015) but can guide recommendations (Stone 2002).

For example, in the northern Lake States, Stone (2002) suggested that a minimum of 3 inches (7.5 centimeters) of frozen mineral soil is sufficient for operating smaller equipment, whereas 6 inches (15 centimeters) of frozen soil is more appropriate for operations that used larger equipment (with sensitive soil BMP consideration as well).

Figure 16—Two photos showing a worker performing a field inspection to determine the depth of frozen soil.

Compaction of the snow layer under certain ambient conditions and with simple equipment can produce snow densities of 70 percent or greater (solid ice is 90 percent). Snow compaction results in better thermal conductivity because it pushes air out of the snow mass and thus promotes soil freezing (Abele 1990). A compacted snow layer will bond very quickly under the right conditions to form "snow pavement." If this "pavement" is sufficiently thick, it will support heavy vehicle loads.

Temperature and moisture are two factors which further strengthen the snowpack (Diemand et al. 1996). Older snow, which has experienced a warming period before refreezing, will be strongest (Abele 1990; Flatten 2002). Snow density and strength increase over time with decreasing temperatures (Abele 1990). For sites without long winters or sustained temperatures below freezing, snowpack will not harden to the degree that it does in colder locations.

Lundquist et al. (2013) found that snow in open areas remained on site longer than snow under tree cover, and establishing a forest management plan that incorporates open areas may have implications for extending harvest operations as well as other benefits.

The incorporation of logging residues (slash mats) into existing snow can contribute additional fortification. Combining woody residues with organic matter creates two distinct snow layers—an upper layer mixed with logging debris and a frozen lower, compacted layer (figure 17). Both of these layers may act to protect vegetation, the forest floor, and mineral soil from damage (Zasada et al. 1987).

Figure 17—Snow covered organic material reduces logging impacts.

Constructing temporary roads out of snow may solve some access issues within the logging areas and could allow access over previously-disturbed or sensitive soils, under varying snow conditions (Utterback et al. 1995), and in areas where maintaining winter access via traditional roads is operationally challenging. Snow compaction with readily available equipment is relatively easy compared to other methods in which constructing durable snow roads requires specialized equipment, such as the SnowPaver (Alger 1994; figure 18).

Figure 18—Using a SnowPaver to reduce damage to mineral soil.

Current Standards for Winter Logging

The following are examples of current standards developed by national forests for (low detrimental impact) winter logging, within their respective regions:

- **Okanogan-Wenatchee NF, Eastern Washington (Pacific Northwest Region)—**8 inches (20 centimeters) of snow and frozen ground or a combination of frozen soil and compacted snow/ice.
- **Idaho Panhandle NF, Idaho (Northern Region)—** 24-inch (60-centimeter) snow layer, or 18 inches (45 centimeters) of settled snow, or a slash mat in combination with 12 inches (30 centimeters) of settled snow, or frozen ground to a depth of 4 inches (10 centimeters).
- **Chequamegon-Nicolet NF, Wisconsin (Eastern Region)—**Operate heavy equipment only when soils are not saturated or when the ground is frozen (no actual measurements are taken to determine frozen ground).
- **Hiawatha NF, Michigan (Eastern Region)—** Equipment operations will only occur when the soils are capable of supporting equipment without incurring detrimental compaction, puddling, or rutting. NEPA design criteria (based on Stone 2002) include the guidance of 6 inches (15 centimeters) of frozen soil or 12 inches (30 centimeters) of frozen/compacted snow.

Specific Conditions

When planning and managing winter logging operations, forest land managers must consider specific conditions, which include skid trails, temporary roads, snow over unfrozen ground, shallow soils, and cold and dry conditions.

Skid Trails

During summer or winter logging operations, skid trails experience the most ground disturbance because of the high density of traffic. Plowing snow off the trails and allowing the mineral soil to freeze for at least 48 hours (at or below freezing temperatures) can reduce the impacts by maximizing soil strength to support the logging equipment. Before allowing equipment to operate on the trails, the depth of frozen ground should exceed the minimum depth indicated for each equipment type and load.

Temporary Roads

Using snow to construct temporary roads may solve some access issues within the logging areas. Temporary snow roads can provide access over previously disturbed or sensitive soils, on steep grades, in varying snow conditions, and in areas where maintaining winter access via traditional roads is operationally challenging (Stone 2002; figure 19).

Figure 19—A temporary access road covered with organic materials and snow.

Snow Over Unfrozen Ground

A proper assessment of site conditions will verify whether or not the soil is frozen. If the soil is not frozen, forest land managers should employ regional BMPs for determining soil moisture content, and snow type, condition, and ability to form a sufficiently protective layer. Forest land managers should delay operations until compacted snow has hardened and operations can occur with a high degree of certainty that the soil resource is buffered from impacts (figure 20).

Shallow Soils

Forest land managers should take caution before operating on shallow mineral soils unless there is sufficiently packed, frozen snow present. Operations become risky when the snow starts to melt or becomes loosened by equipment.

Cold and Dry Conditions

In areas with a cryic soil temperature (cold soils) and a xeric (dry) moisture regime, there is often a shallow forest floor with poor mineral soil structure, low SOM, and susceptibility to compaction and displacement (U.S. Department of Agriculture, Natural Resources Conservation Service 2017). Frozen, dry soil may be somewhat less susceptible to compaction. Cold and dry conditions may require extra attention to local BMPs and snow and soil testing before operations commence.

Figure 20—An assessment of site conditions for frozen soil. The ground under the snow is not always frozen.

Best Management Practices

Minnesota, Wisconsin, and Michigan have long histories of conducting winter logging operations. These states have developed BMP guidelines and recommendations that address various aspects of winter harvesting based on scientific evidence. The BMPs serve to protect site, soil, and water quality but may also conserve rare species and limit the spread of diseases and invasive plant species (Conrad et al. 2017). Many of these guidelines should be applicable to similar sites throughout North America.

The following are recommendations for ecosystem protection during winter logging operations (Han et al. 2006; Page-Dumroese et al. 2010; Poltorak et al. 2018; Stone 2002):

- Design and layout a minimum number of roads, trails, and landings to restrict the area affected by logging.
- Use progressive (back-to-front) harvest operations to concentrate vehicle traffic and protect advance regeneration and reserved growing stock.
- Plow or pack the snow on roads and skid trails to enhance soil freezing before the operation.
- Operate equipment on slash mats, and use low ground pressure equipment.

The recommendations vary somewhat from state to state, but all have common goals of minimizing residual stand and site damage and maintaining long-term forest productivity, soil health, and water quality. BMPs are an educational and extension tool available for land managers and specialists to use when discussing harvest method, season, and equipment with logging contractors or equipment operators.

Evaluation of Soil Impacts after Winter Logging

Before assessing postwinter logging impacts, it is imperative to define and compare the existing soil conditions with postharvest soil conditions. As noted in the "Soil Disturbance Terms" section, compaction is one of the most common results of winter logging. Forest land managers can use bulk density and soil resistance to penetration (the capacity of the soil to withstand pressure or compression) techniques to evaluate soil compaction. There are also visual disturbance tools available to national forest soil scientists, timber sells specialists, and NEPA specialists that provide a systematic method of assessment (Page-Dumroese et al. 2009).

"Before assessing postwinter logging impacts, it is imperative to define and compare the existing soil conditions with postharvest soil conditions."

Methods to Evaluate Frozen Soil and Snow Conditions

There are higher and lower level technology approaches for making sound determinations about site conditions and the ability to harvest with little disturbance. Local experience regarding seasonal and historical site characteristics is an important and valuable resource for planners and managers, but additional tools and equipment can help inform management decisions.

Measurement methods should fulfill the project objective of identifying and testing robust indicators of snow compaction, frozen soil depth, soil temperature, soil moisture, air temperature, and surface ground temperature. There is a wide variety of equipment that can provide low-cost, quantifiable methods for determining when ground conditions are adequate to support winter logging operations without detrimental impacts on soils.

Snow Compaction

Research has shown that snow depth is not the driving factor in successful winter logging, but rather success is determined by how well the snow will compact. Soil scientists in the Pacific Northwest are looking to standardize the process of snow compaction in the field.

Curran (1999) used the depth of snow remaining under a boot print as the criterion for outlining traffic limits. This “boot compression” method to gauge snow compaction in the Pacific Northwest is neither consistent nor reliable and does not have associated standards. This method also does not consider moisture content of the soil, which is related to trafficability. Curran’s (1999) method can be useful to predict whether equipment should be allowed initial entry for snow plowing the existing snow (with little disturbance or impact) in order to encourage greater frost penetration.

Frozen Soil Depth

Forest land managers use techniques similar to soil resistance to penetration (RTP) to evaluate the strength of soils during the winter before the onset of operations.

Frost Probe

A frost probe—a ½-inch (1.3-centimeter) steel rod with one end sharpened to a 30-degree cone—detects the depth of frost within the mineral soil by pounding it into the soil until it breaks through the frozen zone. This technique requires some practice to gauge how it feels when the rod passes into frost-free soil. This method does not work well in rocky soils (Flatten 2002). Sampling about 30 locations distributed across the planned travel area provides a statistically defensible number of points (Stone 2002).

Frost Tube

A frost tube is another tool for measuring the frozen soil depth (figure 21) and is easy to construct. A frost tube consists of a piece of 6- to 8-millimeter-diameter clear plastic tubing (inner tube) with markings at 5-cm increments and a sealed bottom (figure 22). The inner tube is placed inside a 12-millimeter-diameter polyvinyl chloride (PVC) pipe with an open end. The inner tube is filled with dyed water or a low osmotic solution, and the top is sealed. A wire or bolt protrudes from the top of the inner tube to enable extracting the tube from the outer PVC casing. The pipe is installed vertically into the soil profile with some length sticking out above the soil surface to facilitate access during periods of snow cover. To measure the frost depth, a field worker extracts the inner tube from the pipe and determines the depth of ice in the tube relative to the soil surface (McCool 1984).

The University of Alaska, Institute of Northern Engineering provides instructions on how to make, install, and operate a frost tube <http://ine.uaf.edu/werc/projects/permafrost/howto.pdf>.

Figure 21—A field worker taking field measurements and observations of snow and frozen soil depth.

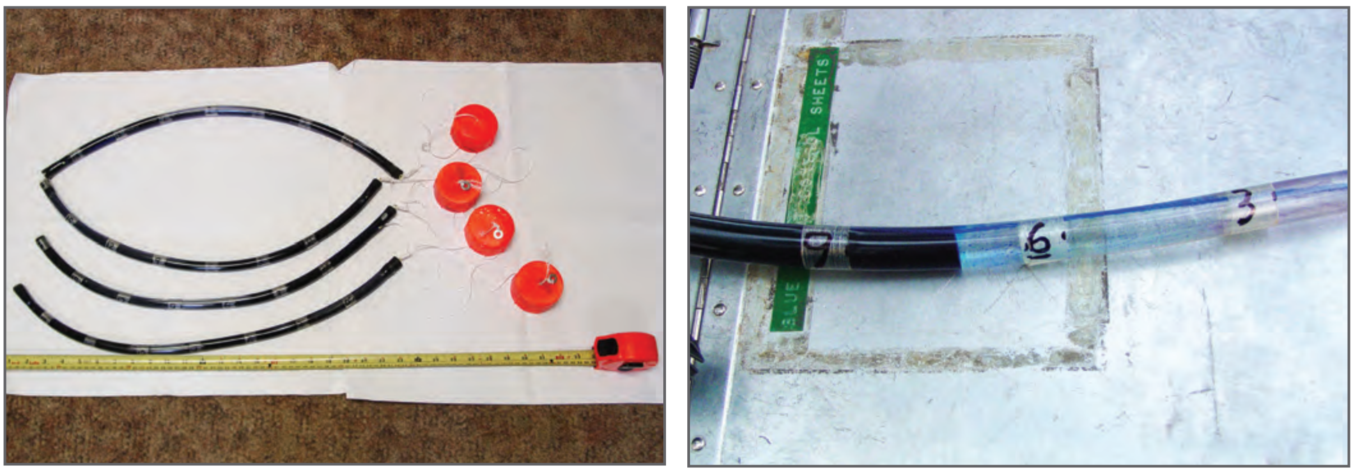

Figure 22—A frost tube is comprised of an outer PVC pipe (not shown) and an inner flexible tube (left). A closeup of the inner flexible tube of a frost tube (right).

Using multiple frost tubes ensures better accuracy. Forest land managers should consider the traffic patterns when placing tubes in the harvest units. Researchers often place four frost tubes at different locations throughout the test site. Because frost tubes are inexpensive, provide a rapid assessment, and are easy to use, they are a widely accepted tool and efforts to refine them for better performance are in progress.

Rebar Method

Forest land managers can use rebar to determine frozen soil depth (figure 23) by simply pounding the rebar into the soil until it breaks through the frozen layer. This method takes some practice and calibration, and most of the time, measurements are not repeatable. However, the rebar method can be extremely fast and inexpensive to use for the initial study of an area.

Soil Temperature and Soil Moisture Sensors

Forest land managers can install equipment to measure and record the soil temperature and soil moisture within the harvest unit.

There are many soil temperature data loggers available that are similar in function. In many areas, the average soil temperature remains relatively constant throughout the year. Temperatures near the soil surface fluctuate more than temperatures at greater depth; therefore, it is important to collect soil temperatures at multiple soil depths.

Figure 24 shows a soil moisture smart sensor, which is compatible with any data logger, such as a weather station. Placing several soil moisture sensors at different locations within the harvest unit and at multiple soil depths ensures adequate soil condition information.

Figure 23—A field worker using rebar to determine the depth of frozen soil.

Figure 24—A local weather station and a data logger. The white device on the left of the tree is a radiation shield for accurate air temperature monitoring.

Road Monitoring Data Loggers

Forest land managers can install equipment to monitor the number of vehicle passes over a skid trail. This data is important for understanding soil impacts and designing BMPs.

Weather Information

To determine harvest operation readiness, forest land managers should monitor the local and site-specific weather conditions. Weather information is available from many resources, such as National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Agriculture, and others.

There are many ways to monitor air temperature, which is fundamental to predicting site conditions. Air temperature determines if skid trails and roads are frozen enough to begin operations. One method to track and record air temperature and other weather variables for your specific site is to install a remote automated weather station (RAWS). It is also beneficial to know if the soil is frozen before a snowfall. Soil that is not frozen can be problematic. Snow acts as an insulator and can prevent the ground under the snow from freezing for an extended period (Curran 1999). Logging operations that occur on top of snow and unfrozen soil may result in muddy conditions.

Winter Logging Technologies

Advances in engineering along with appropriate methodologies for measuring soil conditions and snow properties provide tools to explore forestry operations options during the winter. With the application of the latest equipment, land managers may continue logging operations under safe conditions that limit impacts associated with shoulder season operations, such as rutting, puddling, and compaction.

SnowPaver

The Michigan Technological University, Keweenaw Research Center developed and designed the SnowPaver—a single-unit machine consisting of leveling blades, a milling unit, and a vibratory compactor—to make snow roads (figure 25). Forest and mining industries in Canada, Finland, and Russia have used extensive snow road systems (Abele 1990). Using the same concepts that facilitate fine-textured soil compaction, the SnowPaver mills snow into a very fine granular state that responds well to vibratory compaction (figure 26). Researchers have successfully used the SnowPaver (Ernst et al. 2016; Shoop et al. 2013).

The SnowPaver smooths, grades, mills, and compacts the snow. It first smooths the snow surface with a drag, and then a transversely mounted miller cuts and crushes the snow crystals. The SnowPaver maximizes the mixing of the existing snowpack by using a miller drum (Alger 1994). After the equipment completes smoothing, mixing, and cutting, the snow passes under the vibrating compactor. The optimal frequency of vibration depends on air temperature. The equipment operator can tune the vibration frequency of the compactor to optimize the snow compaction based on temperature. At temperatures colder than -10 °C (14 °F), high vibration frequencies work best to compact snow (Wouri 1965). The resulting material is a high-density snow layer that encourages sintering, binding, and hardening processes (Shoop et al. 2013). Alger (1994) indicated that a mixture of finely milled snow (1 millimeter or smaller in size), compacted to a

Figure 25—The SnowPaver machine.

Figure 26—The front of a SnowPaver machine used to compact snow on an existing road.

density of 0.55 grams per cubic centimeter (34 pounds per cubic foot) or higher, hardens very rapidly (within one hour) to produce a durable surface.

Tests using this machine on fresh snow and snowmobile trails in Houghton, MI, resulted in snow compressive strengths ranging from 3,400 to 6,900 kilopascals (kPa) (50 to 100 pounds per square inch (psi)) immediately after passage through fresh snow, and over 13,800 kPa (200 psi) on trails (Alger 1934). The SnowPaver can build strong snow roads quickly and operators can repair small sections if needed. Across many locations where winter logging is viable, extended autumn and earlier spring weather may require the use of this type of technology to limit soil impacts.

Geocells

Geocells are another technological advancement that allow land managers to use snow in a novel way to form trafficable surfaces. Geocells are expandable plastic webs (available in different sizes) that engineers originally designed for soil confinement and stabilization. However, when conditions permit, they can be filled with snow for use in winter logging operations (figure 27).

Diemand et al. (1996) tested this web system and found that they could use the geocells immediately after snowfall to extend the useful life of snow, facilitate the crossing obstacles (e.g., seeps or streams), and allow for parking of heavy equipment without damage to mineral soil. The military has also tested the technology.

Geocells appear to be a promising option where there is adequate snowfall and favorable temperatures to construct this type of surface. Field crews can easily install the geocells just before the start of winter logging activities. The resulting surface is hard and stable enough to hold heavy truck loads over repeated passes, and the bearing strength of the constructed geocell surface increases as the snow sinters within the cells.

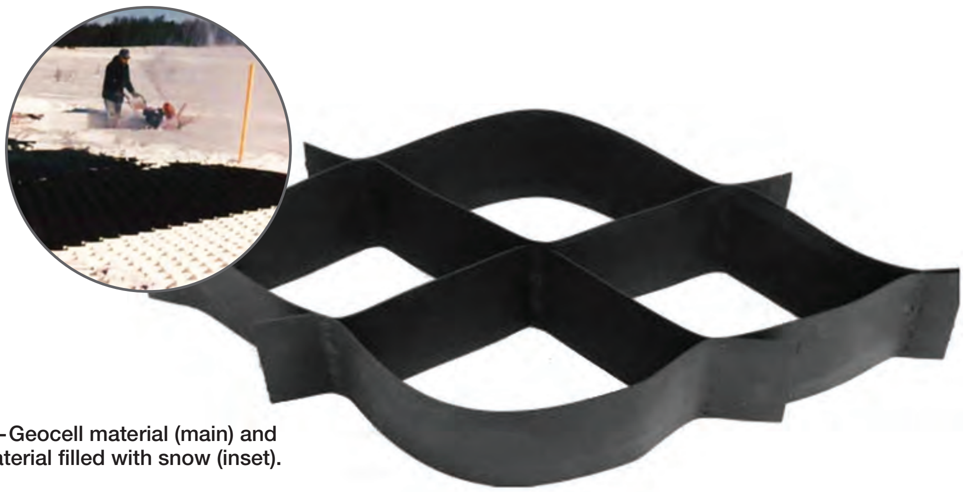

Figure 27—Geocell material (main) and geocell material filled with snow (inset).

Mat Technology

Forest land managers can use temporary surface road covers to protect roads from logging equipment damage (figures 28 and 29). These temporary, portable surfacing systems, commonly called mat systems, improve access and can bridge across soft, wet, and sensitive areas (similar to the geocell technology described above).

Mat systems can be one solution to deal with soil and weather conditions, particularly during shoulder seasons or for summer logging operations in wet areas. Mat systems enable site access when otherwise impossible because of soft and weak subgrade, and they protect native surface road and water resources during required activities.

In addition, mat systems can alleviate rutting on low-volume roads in areas that are unstable. Ruts reduce vehicle access, impact local streams and their hydrology, increase maintenance, and accelerate the loss of surficial material due to erosion. Mat systems can reduce the cost and time involved in reconstructing crossings, improving road access, or maintaining culverts.

The Forest Service determined that mat systems provide several benefits for timber harvesting and resource extraction on Federal lands. Using mat systems can enable more efficient timber hauling by providing a suitable bearing surface for heavier loads than the designed roads. Despite the usefulness of the mat technology, Forest Service land managers underuse them.

Figure 28—A closeup of a temporary road surface cover (left). Heavy equipment driving over a temporary road surface cover (right).

Figure 29—A forest road covered with construction wood mats used to reduce winter logging heavy machine traffic impact (top). A closeup of the road surface cover (bottom).

Mat systems can be a potential solution in areas that have repeated, unpredictable freeze-thaw periods but still have snowpack. In general, mat systems that perform well on loose material, or are flexible, will likely perform best on snow.

The simplicity of this technology makes it ideal for use by many land management agencies. This technology meets the basic objective of load distribution and ease of equipment and/or timber resource transfer while preserving forest resources by providing a stable surface. Rushing and Howard (2011) developed a decision matrix to help potential users make informed decisions when selecting a mat system.

Some advantages of using temporary road mat systems are:

- Readily available
- Easy to install
- Scalable and reusable (therefore, cost-effective)

Some disadvantages of using temporary road mat systems are:

- Cost
- Net weight of the mats
- Manageability by personnel
- Storage needs when they are not in use

Description of Mat Systems

NTDP and the U.S. Army Engineer Research and Development Center (ERDC) tested two mat systems—DURA-BASE mats (DBM) and ACEMat—on two national forests (Allegheny NF and Apalachicola NF) using the different materials and designs.

Engineers designed the DBM system for reinforcing soil to support vehicular and pedestrian traffic as well as serving as a foundation for equipment and temporary buildings. The DBM system <https://www.newpark.com/durabase-mats> is a high-density polyethylene mat consisting of 14- by 8-foot (4.3- by 2.4-meter) and 4.25-inch (10.8-centimeter) thick panels. Each panel weighs about 1,000 pounds. Individual panels interlock by aligning holes on the mat edges and securing them with metal pins enclosed in plastic. The "DBM 00 series" mat features an overlapping lip on all four sides. The lip contains 16 slots, allowing the fastening of adjacent mats with the respective pins. The installer turns the pins to lock them in place and secure the panels (figure 30). The panel surface features a tread pattern that improves traction of vehicles and heavy equipment (figure 31). Panels tend to be forgiving to contours on the ground surface, but they are heavy and require a forklift for transport and installation. NTDP performed demonstrations of the DBM system at both national forests.

Figure 30—Workers installing DURA-BASE and ACEMat systems on a low volume road at Apalachicola NF.

Figure 31—A section of DURA-BASE mats. The overlapping design and pin fasteners ensure mats remain secure and will not separate.

The ACEMat system was a U.S. Government-designed mat made of thin (1/2-inch), fiberglass panels with a 6- by 6-foot (1.8- by 1.8-meter) surface. Holes in the overlapping portions of the square panels align, and 4-foot (1.2-meter) long helical anchors hold the panels together while securing them to the soil. Each panel weighs about 120 pounds (54 kilograms) and requires two people to place them (see figure 30). The installer uses a hydraulic impact drill and a portable power pack to set the anchors. NTDP performed demonstrations of the ACEMat system only at the Apalachicola NF (figure 32).

Figure 32—Workers installing an ACEMat system on a low volume road at Apalachicola NF.

The Future of Winter Logging

Rittenhouse and Rissman (2015) pointed out that foresters, loggers, and others in the industry understand that frozen ground is the middle ground: "frozen ground enables harvest and also facilitates compromise between economic and environmental forest management goals." Managing forests for snowpack may aid in creating conditions favorable for continued winter logging. Equipment, such as the SnowPaver, geocells, and mat systems, may be practical tools for extending the winter logging season, but further testing is needed to evaluate the use of the SnowPaver for winter logging operations. Adherence to BMPs and harvest prescriptions is essential to maximizing the efficiency of operations while minimizing long-term impacts to forest resources.

A changing climate may result in fewer weeks where the ground is frozen (Rittenhouse and Rissman 2015). The continued shift to a warmer climate and the associated regional changes in air temperature, precipitation, soil temperatures, and extent and depth of snow cover will impact harvest operations, soil conditions, and plant species (Rittenhouse and Rissman 2015). Relying on a specific set of cold weather conditions to ensure minimal soil disturbance may become more challenging in the future.

Concluding Remarks

Forest management practices should minimize soil and understory impacts. Forest land managers must couple careful application of BMPs with mitigation of undesirable consequences of land management activities. The Forest Soil Disturbance Monitoring Protocol provides a tool for soil scientists to monitor soil conditions before, during, and after winter logging. The following are some considerations and recommendations:

- BMPs encourage favorable conditions for winter logging, but this can be variable depending on climatic regime and seasonal conditions.
- Ideally, mineral soil should be completely saturated before the onset of freezing conditions. However, in cold, dry areas, soil will freeze when ambient conditions reach subzero. Soil classifications and soil survey data are useful for distinguishing soils mapped as being in the cryic soil temperature regime.
- Mineral soil should be frozen to minimum of 3 inches for winter logging with the use of light equipment. For heavier operating equipment, the mineral soil should be frozen to a minimum of 6 inches. Snow should be compacted and allowed to freeze before equipment is allowed to operate.
- Once the frost is 3 inches (7.5 centimeters) deep in the mineral soil, harvest skid trails will generally not be deformed.
- Forest land managers should delineate and mark poorly drained soil, wetlands, or stream side inclusions during sale preparation to ensure heavy equipment does not impact these areas.
- Marking both sides of trees makes them more visible and easier for the equipment operators to follow.
- Forest land managers should install monitoring equipment near the harvest unit to track frozen ground or employ other methods to stay abreast of site conditions.
- Logging unit boundaries must exclude riparian areas following State and Federal guidelines.
- Interdisciplinary teams consisting of soil scientists, silviculturists, timber sale administrators, and corporate managers must make sure everyone is aware of BMPs, issues, and needs before beginning harvest operations. In addition, active supervision and monitoring of snow and frozen soil quality during harvest operations is critical to ensure proper plan implementation and to minimize soil disturbance.

Glossary Resources

United States Permafrost Association's Permafrost Glossary
<http://www.uspermafrost.org/glossary.php>

Plant & Soil Sciences eLibrary, Soil Genesis and Development, Lesson 6—Global Soil Resources and Distribution
<https://digitalcommons.unl.edu/passel/112/>

References

Abele, G. 1990. Snow roads and runways. Monograph 90-3. [Place of publication unknown]: U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory. Prepared for: Division of Polar Programs, National Science Foundation. https://apps.dtic.mil/dtic/tr/fulltext/u2/a231490.pdf. (7 May 2020).

Agee, J.K.; Skinner, C. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83–96.

Ager, A.; Valliant, N.M.; Finney, M.A. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management. 259(8): 1556–1570.

Agherkakli, B.; Najafi, A.; Sadeghi, S.H. 2010. Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. Journal of Forest Science. 56(6): 278–284.

Alger, R.G. 1994. A new concept in trail grooming—the KRC groomer. Contract report. Lansing, MI: Michigan Department of Natural Resources.

Allen, B.L.; Pikul, J.L.; Waddell, J.T.; Cochran, V.L. 2011. Long-term lentil green-manure replacement for fallow in the semiarid northern Great Plains. Agronomy Journal. 103: 1292–1298. DOI: 10.2134/agronj2010.0410.

Aust, W.M.; Reisinger, T.W.; Burger, J.A.; Stokes, B.J. 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. Southern Journal of Applied Forestry. 17(1): 22–25.

Battles, J.J.; Shlisky, A.J.; Barrett, R.H.; Heald, R.C.; Allen-Diaz; B.H. 2001. The effects of forest management on plant species diversity in a Sierran conifer forest. Forest Ecology and Management. 146: 211–222.

Blackford, J.R. 2007. Sintering and microstructure of ice: a review. Journal of Physics D Applied Physics. 40(21): R355.

Block, R.; Van Rees, K.C.J.; Pennock, D.J. 2002. Quantifying harvesting impacts using soil compaction and disturbance regimes at a landscape scale. Soil Sciences Society of America Journal. 66(5): 1669–1676.

Brais S. 2001. Persistence of soil compaction and effects on seedling growth in northwestern Quebec. Soil Science Society of America Journal. 65(4): 1263–1271.

Brais, S.; Camiré, C. 1998. Soil compaction induced by careful logging in the clay belt region of northwestern Quebec (Canada). Canadian Journal of Soil Science 78(1): 197–206.

Cambi, M.; Certini, G.; Neri, F.; Marchi, E. 2015. The impact of heavy traffic on forest soils: a review. Forest Ecology and Management. 338: 124–138.

Clinton, B.D. 2011. Stream water responses to timber harvest: riparian buffer width effectiveness. Forest Ecology and Management. 261: 979–988.

Comeau, P.G.; Comeau, M.A.; Utzig, G.F. 1982. A guide to plant indicators of moisture for southeast British Columbia, with engineering interpretations. Land Management Handbook No. 5. Victoria, B.C.: British Columbia Ministry of Forests. 130 p.

Conrad, IV, J.L.; Demchik, M.C; Vokoun, M.M. 2018. Effects of seasonal timber harvesting restrictions on procurement practices. Forest Products Journal. 68(1): 43–53.

Conrad, IV, J.L.; Vokoun, M.M.; Prisley, S.P.; Bolding, M.C. 2017. Barriers to logging production and efficiency in Wisconsin. International Journal of Forest Engineering. 28(1): 57–65.

Corns I.W. 1988. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in the Alberta foothills. Canadian Journal of Forest Research. 18(1): 75–84.

Curran, M. 1999. Harvest systems and strategies to reduce soil and regeneration impacts and costs. In: Morland, B.; Corradini, S. (compilers). Impact of machine traffic on soil and regeneration. Proceedings of FERIC's Machine Traffic/Soil Interaction Workshop. FERIC Spec. Rep. SR-133. Edmonton, Alberta: Forest Engineering Research Institute of Canada. 75–111.

Demchik, M.C.; Conrad, IV, J.L.; Vokoun, M.M. 2016. The scale and cost of seasonal timber harvesting restrictions in Wisconsin. Stevens Point, WI: University of Wisconsin. 52 p.

Diemand, D.; Alger, R.; Klokov, V. 1996. Snow road enhancement. Transportation Research Record: Journal of the Transportation Research Board. 1543(1): 1–4.

Ernst, E.; Alger, R.; Kane, E.; Wagenbrenner, J. 2016. Impacts of the installation and use of snow-paved roads on forest soils [Poster]. In: Michigan Technological University graduate student colloquium. [Place of publication unknown]: [Publisher unknown].

Flatten, B. 2002. Determining appropriate winter logging conditions for protection of the soil resource. Presented to: SALHI-W (Sale Area Layout and Harvesting Institute–West) Ground-based Systems Session; Moscow, ID. 14 p.

Gomez, G.A.; Powers, R.F.; Singer, M.J.; Horwath, W.R. 2002. Soil compaction effects on growth of young ponderosa pine in California's Sierra Nevada. Soil Science Society of America Journal. 66: 1334–1343.

Goychuk, D.; Kilgore, M.A.; Blinn, C.R.; Coggins, J.; Kolka, R.K. 2011. The effect of timber harvesting guidelines on felling and skidding productivity in northern Minnesota. Forest Science. 57(5): 393–407.

Greacen, E.L.; Sands, R. 1980. Compaction of forest soils: a review. Australian Journal of Soil Research. 18(2): 163–189.

Grigal D.F. 2000. Effects of extensive forest management on soil productivity. Forest Ecology and Management. 138(1): 167–185.

Han, H.-S.; Page-Dumroese, D.S.; Han, S.-K.; Tirocke, J. 2006. Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. International Journal of Forest Engineering. 17: 11–17.

Hillel, D. 2004. Introduction to environmental soil physics. Amsterdam: Elsevier Academic Press. 494 p.

Horn, R.; Vossbrink, J.; Peth, S.; Becker, S. 2007. Impact of modern forest vehicles on soil physical properties. Forest Ecology and Management. 248(1-2): 56–63.

Jurgensen, M.F; Harvey, A.E.; Graham, R.T.; Page-Dumroese; D.S.; Tonn, J.R.; Larsen, M.J.; Jain, T.B. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. Forest Science. 42(2): 234–251.

Kabzems, R. 1996. Boreal long term soil productivity study. Forest Research Note #PG-06. Prince George, British Columbia: British Columbia Ministry of Forests, Prince George Forest Region. 4 p.

Kern, C.C.; Palik, B.; Strong, T.F. 2006. Ground-layer plant community responses to even-age and uneven-age silvicultural treatments in Wisconsin northern hardwood forests. Forest Ecology and Management. 230: 162–170.

Kolka, R.; Steber, A.; Brooks, K.; Perry, C.H.; Powers, M. 2012. Relationships between soil compaction and harvest season, soil texture, and landscape position for aspen forests. Northern Journal of Applied Forestry. 29(1): 21–25.

Labelle, P.K.; Jaeger, D. 2011. Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. Soil Science Society of America Journal. 75: 2314–2320.

Lewis, T.; Carr, W.W.; Timber Harvesting Subcommittee. 1989. Developing timber harvesting prescriptions to minimize site degradation—interior sites. British Columbia Ministry of Forests Land Management Handbook—Field Guide Insert. Land Management Report 62. Victoria, British Columbia: British Columbia Ministry of Forests.

Liechty, H.O.; Sawyer, V.L.; Shelton, M.G. 2002. Alteration of nutrient status by manipulation of composition and density in a shortleaf pine-hardwood stand. Gen. Tech. Rep. SRS-GT-48. Asheville, NC: U.S. Department of Agriculture, Forest Service: 10–15.

Lull, H.W. 1959. Soil compaction on forest and range lands. Misc. Publ. 768. [Place of publication unknown]: U.S. Department of Agriculture, Forest Service. 33 p.

Lundquist, J.D.; Dickerson-Lange, S.E.; Lutz, J.A.; Cristea, N.C. 2013. Lower forest density enhances snow retention in regions with warmer winters: a global framework developed from plot-scale observations and modeling. Water Resources Research. 49: 6356–6370.

MacKinney, A.L. 1929. Effects of forest litter on soil temperature and soil freezing in autumn and winter. Ecology. 10(3): 312–321.

Martin, C.W. 1988. Soil disturbance by logging in New England-review and management recommendations. Northern Journal of Applied Forestry 5(1): 30–34.

McCool, D.K.; Molnau, M. 1984. Measurement of frost depth. In: Proceedings of the 52nd Annual Western Snow Conference. 33–42.

McDonald, T.P.; Seixas, F. 1997. Effect of slash on forwarder soil compaction. Journal of Forest Engineering. 8: 15–26.

McNabb, D.H. 1999. Compactibility of forest soils and its effects on soil physical properties. In: McMorland, B.; S. Corradini (compilers). Impact of machine traffic on soil and regeneration. Proceedings of FERIC's Machine Traffic/Soil Interaction Workshop. FERIC Spec. Rep. No. SR-133. Edmonton, Alberta: Forest Engineering Research Institute of Canada. 118 p.

McNabb, D.H.; Startsev, A.D.; Nguyen, H. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Science Society of America Journal. 65: 1238–1247.

Meier, A.J.; Bratton, S.P.; Duffy, D.C. 1995. Possible ecological mechanisms for loss of variable-herb diversity in logged eastern deciduous forest. Ecological Applications. 5: 935–946.

Oswalt, S.N.; Smith, W.B. 2014. U.S. forest resource facts and historical trends. FS-1035. U.S. Department of Agriculture, Forest Service. https://www.fia.fs.fed.us/library/brochures/docs/2012/ForestFacts_1952-2012_English.pdf. (8 May 2020).

Page-Dumroese, D.S.; Abbott, A.M.; Rice, T.M. 2009. Forest soil disturbance monitoring protocol: volume I: rapid assessment. Gen. Tech. Rep. WO-GTR-82a. Washington, D.C.: U.S. Department of Agriculture, Forest Service. 31 p.

Page-Dumroese, D.S.; Jurgensen, M.; Terry, T. 2010. Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western United States. Western Journal of Applied Forestry. 25(1): 5–11.

Page-Dumroese, D.; Jurgensen, M.; Tiarks, A.; Sanchez, F.; Fleming, R.; Kranabetter, M.; Powers R.; Ponder, Jr., F.; Stone, D.; Elioff, J.; Scott, A. 2006. Soil physical property changes on the North American Long-Term Soil Productivity (LTSP) study sites: 1 and 5 years after treatment. Canadian Journal of Forest Research. 36: 551–564.

Poff, R. 2014. Wet-weather management of OHV trails on national forests in California. Report. Contract AG-91S8-C-10-0027 and work agreement U30-12-15. [Place of publication unknown]. Submitted to: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Vallejo, CA. 82 p.

Poltorak, B.J.; Labelle, E.R.; Jaeger, D. 2018. Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats. Soil and Tillage Research. 179: 96–104.

Powers, R.F.; Alban, D.H.; Miller, R.E.; Tiarks, A.E.; Wells, C.G.; Avers, P.E.; Cine, R.G.; Fitzgerald, R.O.; Loftus, Jr., N.S. 1990. Sustaining site productivity in North American forests: problems and prospects. In: Gessel, S.P.; Lacate, D.S.; Weetman, G.F.; Powers, R.F., eds. Sustained productivity of forest soils. Proceedings, 7th North American forest soils conference. Vancouver, British Columbia: Forestry Publications, Faculty of Forestry, University of British Columbia: 49–79.

Powers, R.F.; Alves, T.M.; Spear, T.H. 1999. Soil compaction: can it be mitigated? Reporting a work in progress. In: Proceedings of the twentieth annual forest vegetation management conference. Redding, CA: [Publisher unknown]: 47–56.

Powers, R.F.; Scott, D.A.; Sanchez, F.G.; Voldseth, R.A.; Page-Dumroese, D.; Elioff, J.D.; Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. Forest Ecology and Management. 220(1–3): 31–50.

Reinhardt, E.D.; Keane, R.E.; Calkin, D.E.; Cohen, J.D. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management. 256: 1997–2006.

Rittenhouse, C.D.; Rissman, A.R. 2015. Changes in winter conditions impact forest management in north temperate forests. Journal of Environmental Management. 149: 157–167.

Rushing, T.W.; Howard, I. 2011. Matting solutions for low-volume roads. Transportation Research Record: Journal of the Transportation Research Board. 2204: 92–101.

Sayer, E.J. 2006. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. Biological Review. 81(1): 1–31.

Schira, M. 2013. Winter weather conditions may be the ideal time for timber harvest activities. East Lansing, MI: Michigan State University Extension. https://www.canr.msu.edu/news/winter_weather_conditions_may_be_the_ideal_time_for_timber_harvest_activiti#:~:text=Winter%20weather%20conditions%20may%20be%20the%20ideal%20time%20for%20timber%20harvest%20activities,-Mike%20Schira%2C%20Michigan&text=Logging%20when%20ground%20is%20snow,an%20opportunity%20for%20spreading%20disease. (7 May 2020).

Shaffer, R.M. 2009. A logger's guide to forest planning. Publication 420-088. Petersburg, VA: Communications and Marketing, College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University.

Sharma, P.K.; DeDatta, S.K. 1986. Physical properties and processes of puddled rice soils. Advances in Soil Science. 5: 139–178.

Sharratt, B.; Voorhees, W.; McIntosh, G.; Lemme, G. 1998. Persistence of soil structural modifications along a historic wagon trail. Soil Science Society of America Journal. 62(3): 774–777.

Shoop, S.A. 1995. Vehicle bearing capacity of frozen ground over a soft substrate. Canadian Geotechnical Journal. 32(3): 552–556.

Shoop, S.A.; Knuth, M.A.; Alger, R.G. 2013. Evaluating a new snow miller/paver for snow roads. In: 10th international symposium on cold regions development. Anchorage, AK: [Publisher unknown]. DOI: 10.1061.9780784472978.003.

Shoop, S.A.; Phetteplace, G.; Wieder, W.L. 2010. Snow roads at McMurdo Station, Antarctica. Arlington, VA: National Science Foundation Office of Polar Programs. 112 p.

Shoop, S.A.; Uberuaga, J.; Wieder, W.L.; Melendy, T.D. 2016. Snow-road construction and maintenance. Prepared for: National Science Foundation, Division of Polar Programs. Hanover, NH: U.S. Army Engineer Research and Development Center and Cold Regions Research and Engineering Laboratory. 65 p.

Sipes, J.L. 2010. Sustainable solutions for water resources: policies, planning, design, and implementation. Hoboken, NJ: John Wiley and Sons. 369 p.

Soane, B.D. 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil and Tillage Research. 16: 179–201.

Startsev, A.D.; McNabb, D.H. 2000. Effects of skidding on forest soil infiltration in west-central Alberta. Canadian Journal of Soil Science. 80(4): 617–624.

Stone, D.M. 2002. Logging options to minimize soil disturbance in the northern Lake States. Northern Journal of Applied Forester. 19(3): 115–121.

Stone, D.M.; Elioff, J.D. 1998. Soil properties and aspen development five years after compaction and forest floor removal. Canadian Journal of Soil Science. 78: 51–58.

Stone, D.M.; Elioff, J.D. 2000. Soil disturbance and aspen regeneration on clay soils: three case histories. The Forestry Chronicle. 76(5): 747–752.

Stone, D.M.; Elioff, J.D.; Potter, D.V.; Peterson, D.B.; Wagner, R. 2001. Restoration of aspen-dominated ecosystems in the Lake States. In: Shepperd, W.D.; Binkley, D; Bartos, D.L.; Stohlgren, T.J.; Eskew, L.G., (compilers). Sustaining aspen in western landscapes. Proceedings RMRS-P-18. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 137–143.

Stone, D.M.; Gates, J.A.; Elioff, J.D. 1999. Are we maintaining aspen productivity on sand soils? In: ZumBahlen, B.; Ek, A.R., (compilers). Proceedings: Improving forest productivity for timber—a key to sustainability. [Place of publication unknown]: [Publisher unknown]: 177–184.

Stone, J.J.; Nichols, M.H.; Goodrich, D.C.; Buono, J. 2008. Long-term runoff database, Walnut Gulch Experimental Watershed, Arizona, United States. Water Resources Research. 44: 1–5.

Tiarks, A.E.; Powers R.F.; Alban D.H.; Ruark G.A.; Page-Dumroese, D.E. 1993. USFS long-term soil productivity national research project: a USFS cooperative research program. In: Kimble, J.M., ed. Proceedings of the 8th international soil management workshop: utilization of soil survey information for sustainable land use: Oregon, California, and Nevada. [Place of publication unknown]: U.S. Department of Agriculture, Soil Conservation Service: 236–241.

Tisdall, J.M.; Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. European Journal of Soil Science. 33(2): 141–163.

Townsley, J.; Tepler, R.; Flatten, B. 2010. Development of science-based winter guidelines for mechanical and fuels treatment operations. In: WSA currents and profiles, winter/spring issue. 1025 1801–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, Watershed, Soil, and Air Technology and Development Program: 2–4.

Tubbs, C.H.; Reid, B.D. 1984. Logging season affects hardwood reproduction. Northern Journal of Applied Forestry. 1(1): 5–7.

U.S. Department of Agriculture, Forest Service. 2018. Toward shared stewardship across landscapes: an outcome-based investment strategy. FS-1118. https://www.fs.usda.gov/sites/default/files/toward-shared-stewardship.pdf. (8 May 2020).

U.S. Department of Agriculture, Natural Resources Conservation Service. 2017. Soil survey manual. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054262. (28 May 2020).

Utterback, P.; Moore, T.I.; Kestler, M.A; Affleck, R. 1995. The effects of winter haul on low volume forest development roads. 9577 1207– SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, Technology and Development Program. 48 p.

Weatherspoon, P.C.; Skinner, C.N. 2002. An ecological comparison of fire and fire surrogates for reducing wildfire hazard and improving forest health. Association for Fire Ecology Miscellaneous Publication. 1: 239–245.

Williams, J.D.; Buckhouse, J.C. 1993. Winter logging and erosion in a ponderosa pine forest in northeastern Oregon. Western Journal of Applied Forestry. 8(1): 19–23.

Williamson, J.R.; Nielsen, W.A. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Canadian Journal of Forest Research. 30: 1196–1205.

Wolf, A.T.; Parker, L.; Fewless, G.; Corio, K.; Sundance, J.; Howe, R.; Gentry, H. 2008. Impacts of summer versus winter logging on understory vegetation in the Chequamegon-Nicolet National Forest. Forest Ecology and Management. 254: 35–45.

Wouri, A. 1965. Testing of a vibratory snow compactor. Special Report No. SR 55. 11. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Zasada, J.C.; Slaughter, C.W.; Teutsch, C.E.; Argyle, J.D.; Hill, W. 1987. Winter logging on the Tanana River flood plain in interior Alaska. Northern Journal of Applied Forestry. 4:11–16.

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Nash, M.; Napper, C.; Page-Dumroese, D.; Tirocke, J.; Amman, A.; Wagenbrenner, J.; Alger, R.; Courtney, A.; Gries, J. 2020. Winter logging for mechanical harvesting and fuel treatment operations. Tech. Rep. 2025–2806–NTDP. San Dimas, CA: U.S. Department of Agriculture, Forest Service, National Technology and Development Program. 44 p.

The U.S. Department of Agriculture, Forest Service and the National Technology and Development Program (NTDP) synthesized existing literature, collected data, and summarized information on winter logging using mechanical harvesting and fuel treatment operations on National Forest System lands. Proper winter logging can improve harvest options while protecting soil and water resources, particularly in areas where forest land managers rely heavily on winter operations for sustainable forest management. Winter logging operations occur to maintain winter timber inventory for lumber mills, reduce impacts on summer wildlife, and minimize soil degradation. Winter site conditions can provide opportunities for lower impact logging and can decrease detrimental effects on underlying mineral soil compaction, forest floor ecology, hydrology, and water quality.

Keywords: detrimental soil impact, dry and wet snow, forest floor ecology, forest health, frost tube, frozen ground, geocells, organic matter, road cover mat, rock fragments, SnowPaver, snow depth, soil moisture regimes, soil quality, soil rutting and puddling

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The U.S. Department of Agriculture, Forest Service, National Technology and Development Program provides Forest Service employees and partners with practical, science-based solutions to resource management challenges. We evaluate, design, and develop new technologies, products, and systems to solve problems and deliver solutions.

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