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Identifying Soils Trafficability: Soils Operability Conditions for Machine Traffic

Cover photo—Exposing soils with high soil moisture content may result in disturbances such as deep rutting.

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Executive Summary

The U.S. Department of Agriculture, Forest Service, National Technology and Development Program (NTDP) performed a comprehensive review to summarize the impacts of machine traffic on soils and to describe current monitoring approaches. When soil is exposed to machine traffic, three main factors determine the degree and extent of soil compaction:

- Soil moisture content
- Soil type (soil texture and rock fragment content)
- Soil organic matter

The process of soil compaction can vary within a short distance because of natural soil variability. This directly affects soil porosity, which in turn impacts gas exchange and water transmission.

Machine traffic can compact soils to a degree that the soils no longer function, and compaction can lead to several negative consequences for soil ecology and forest productivity. Severely compacted soils can result in offsite effects, such as soil erosion and runoff.

Soil bulk density and penetration resistance are soil strength measures that describe the degree of compaction that impacts soil function based on known thresholds. Soil moisture content governs threshold values for soil trafficability—the capacity of the soil to support machine traffic. When soil moisture is high, compaction will deform the soil. Soil scientists use several methods to assess soil trafficability—shear strength, critical moisture content for maximum penetration resistance, bulk density, field capacity, soil trafficability at optimum moisture content, and residual water content in the soil after rainfall. Each of the listed attributes for different soil types and soil moisture contents have different threshold values.

This report introduces methods for determining soil moisture and soil strength thresholds as they relate to soil operability for machine traffic and describes devices used for measuring these factors. NTDP found that site-specific techniques were effective when measured before and after operations. The risk of compaction from machine traffic can be highest on fine-textured soils, while a deep organic topsoil and the presence of slash can help reduce the risk of compaction. Soil moisture content can indicate trafficability risk, given the strong relationship between soil moisture and soil strength.

Three fundamental principles for understanding soil penetration resistance versus soil moisture content as they relate to soil trafficability are:

- When soil moisture content is below a threshold value for that soil type, the soil is trafficable.
- When soil moisture content is above a threshold value for that soil type, the soil is not trafficable.
- When soil moisture content is between the threshold values for a given soil type, but within a chosen confidence interval or confidence limit, then soil scientists must decide if harvesting operations should continue. Calculations and statistical methods are presented and available Forest Service-wide.

Objectives

Objectives of this report:

- Demonstrate how to determine threshold values for soil moisture and penetration resistance (PR) relationships as they relate to soil trafficability during timber harvesting or public recreation.
- Evaluate existing harvesting systems and methods that the agency currently uses to manage soil disturbance associated with soil trafficability on National Forest System lands.
- Identify soil attributes that influence soil trafficability (e.g., soil moisture and PR).
- Examine ways to reduce machine traffic impacts.

As a result, this project:

- Presents an easy, reliable, and rapid method for measuring soil moisture and PR
- Quantifies the relationship between soil moisture and soil PR
- Provides direction for obtaining daily year-round data on soil moisture and trafficability from Proctor test data
- Provides soil scientists with required information for interpreting changing soil moisture and PR to determine when to close or open forest roads and trails
- Discusses using slash mats (or other material) as a road cover to protect forest roads and extend the operating season for both recreation and timber harvesting

Introduction

The U.S. Department of Agriculture, Forest Service, National Technology and Development Program (NTDP) reviewed existing literature and collected and analyzed data to summarize information about soil trafficability for ground-based harvesting operations and recreational vehicle use of forest roads and trails on National Forest System (NFS) lands. The U.S. Army defines soil trafficability as “the capability of the soil to support moving vehicles” (U.S. Department of the Army 1994), such as timber harvesting equipment or recreational vehicles. Soil scientists should design and implement harvesting operations to protect soil and water resources while extracting forest products.

Figure 1—Using forest roads during wet periods can damage natural resources.

NTDP (we) collected limited data on soil trafficability for this report, but we include a detailed and intensive literature review. The report focuses on the principal factors that affect soil trafficability and provides information about equipment and procedures to measure these factors. Measuring soil PR under varying soil moisture conditions can help identify soil trafficability critical points or threshold values beyond which the soil will be impacted. However, measuring soil PR under different moisture conditions provides different results. Therefore, it is critical to measure soil moisture during sampling or to calculate bulk density (ρ_b) to assess soil compaction. Roots and rocks also affect soil PR measurements. Machine traffic can affect forest soils (f igures 1, 2, and 3) in many ways, and may lead to decreased porosity and increased ρ_b (Rab et al. 2005).

Figure 2—A sampling plot. Operating equipment under suboptimal moisture conditions can result in soil disturbance.

Definitions of Soil Impacts from Machine Traffic

NTDP received several requests from the field to:

- Introduce new measures to protect wet soil during harvesting or recreation activities.

Figure 3—A timber harvesting operation on National Forest System land.

- Scientifically (and defensibly) explain how heavy machinery associated with timber harvesting—and/or how off-highway vehicles (OHVs) and all-terrain vehicles (ATVs)—can operate with minimal damage to the environment.

Existing literature indicates strong relationships between soil moisture, soil strength, and soil trafficability. Soil moisture is a critical factor influencing soil trafficability because of its effect on soil strength, ρ_b , and porosity. Soil compaction reduces porosity, primarily the gaseous phase, and increases soil ρ_b by reducing interaggregate pore spaces. However, soil ρ_b and PR are not related—ρ_b measures particle consolidation while PR measures the force it takes to push a rod into the soil.

There are six different soil moisture regimes in the United States, ranging from saturated soil to soils that dry for more than 90 days per year. Soil moisture regime classifications depend in part on the presence of water held at a tension of less than 1,500 kilopascals (kPa), which is the permanent wilting point (Soil Survey Staff 2014), but also on the length of time a soil has a deficit of water. Soils with aquic (saturated several weeks each year) or udic (often has a soil moisture surplus) moisture regimes may not need to be measured. Classifying field capacity (water held at a tension of less than 33 kPa) and soil type can help in identifying soil trafficability. Forest managers can refer to local soil survey maps to identify the type of soil and the soil moisture regime, and can use this data to help mitigate soil disturbance during harvesting.

The term "skeletal" describes soils with 35 percent or more rock fragments by volume (Soil Survey Staff 2014). If the soil has less than 15 to 20 percent rock fragments throughout and has a loamy or clayey texture, severe compaction is possible. However, if the soil has 20 to 40 percent rock fragments throughout and has a loamy or clayey texture, then moderate compaction is expected (Brais and Camiré 1998, Gomez et al. 2002, Liechty et al. 2002, Powers and Alves 1995). Soils with a sandy-skeletal texture can dry quickly after rainy or wet periods (Soil Survey Staff 2014); rapid free-water drainage and increased soil cohesion enable longer periods of operability for timber harvesting during rainy periods. For example, in Brazil, an udult soil moisture regime was more susceptible to compaction than aquox and udox soils (Dias et al. 2007).

Compaction, shallow and deep rutting, puddling, smearing, churning, and platy structure are visually distinct, wet-site harvesting disturbances associated with increased soil ρ_b (Page-Dumroese et al. 2006). These impacts often occur on sites with lower organic matter that experience machine traffic during moist to wet soil conditions, but soil physical properties respond differently to each type of impact (Aust et al. 1995). Soil texture or slope are often the controlling factors for rut depth and the degree, extent, and amount of compaction.

However, Najafi et al. (2009) did not find a significant correlation between rut depth and soil texture during skidding operations in loam, clay loam, sandy loam, or sandy clay loam soils in northern Iran, and instead found that slope was the primary factor for rut formation in these soils. In forest soils, rut depth increases with increasing slope because of the vertical force of the load distributed on a smaller surface (Agherkakli et al. 2010, Najafi et al. 2009). Nine passes of an 11-metric ton (12 ton, American units) skidder on a loamy-to-silt loamy soil with 30 percent water content caused 12-centimeter (cm)-deep ruts on slopes of more than 20 percent and 9-cm-deep ruts on slopes of less than 20 percent. Najafi et al. (2009) found significant correlations between increasing slope classes (0 to 15 percent, 15 to 25 percent, and more than 25 percent) and increasing rut depth. On forest soils in Italy, Macri et al. (2017) reported compaction and rutting increased with an increasing number of passes, which also resulted in a significant change in soil structure and water-holding capacity, total porosity, and soil PR.

Ruts

Ruts can damage and mix surface organic horizons and mineral soil during harvesting operations (figure 4). Ruts are a product of machine traffic and result in both vertical and horizontal soil displacement to either the middle or edges of the traffic corridor (Horn et al. 2007). Ruts form during repeated passes of machine traffic along the same route and are particularly pronounced in soft soils because of their high moisture content (figure 5).

Figure 4—Timber harvesting operations can damage surface organic horizons and mineral soil.

Figure 5—Rutting increases as machine traffic increases, often from repeated passes along the same route, and becomes particularly pronounced when the soil is soft due to high moisture content.

Rut bottoms are often highly compacted, and the soil pores may be smeared. Compaction causes water to puddle on the soil surface. Rut formation indicates that vehicles have exceeded the bearing capacity of the soil (Muro 1982). Vehicle weight, ground contact factors (e.g., wheel size, tire width, inflation pressure, semitrack or track), ground slope, and soil properties (e.g., texture and moisture) all influence the depth and extent of rutting (Bygdén et al. 2004). Several authors have demonstrated that the intensity of machine traffic (number of passes) is a primary factor affecting rut depth, and rut depth tends to be about equal to half the rut width (Bygdén et al. 2003, Eliasson 2005, Eliasson and Wästerlund 2007, Jakobsen and Greacen 1985, McNabb et al. 2001, Nugent et al. 2003, Rab et al. 2005). Beyond a critical moisture content, tire or track forces cause soil displacement and rut formation rather than simple compaction (Hillel 1998, Horn et al. 2007, Vossbrink and Horn 2004, Williamson and Neilsen 2000).

Cambi et al. (2015) found that ruts created by a wheeled tractor during harvesting operations in the silt loam soil of a coppice oak forest in Italy tended to have other visible damage as well, including broken roots, soil displacement, and compaction. They concluded that ruts and compaction induce anoxic conditions in the top layer when the soil compaction is extreme or pores are smeared and water pools on the soil surface. Ruts become preferential flow paths during the rainy season (figure 6), resulting in erosion and water standing on the soil surface instead of infiltrating the soil for use by vegetation. Lack of infiltration on slopes means that water moves downslope, potentially increasing erosion.

Figure 6—During the rainy season, ruts become preferential flow paths and result in erosion.

Displacement

Poorly planned skid trails constructed for harvesting operations are a concern, particularly in steep terrain. Trails and roads can be a source of erosion and sedimentation, and creating them displaces a significant amount of topsoil and surface organic matter. Williamson and Neilsen (2000) found that machine traffic on wet soils displaced soil rather than compacting it (figures 7 and 8). Displacement also results on a smaller scale when equipment turns, when bulldozer blades lower to move trees or downed wood, and wherever equipment removes the surface organic horizons.

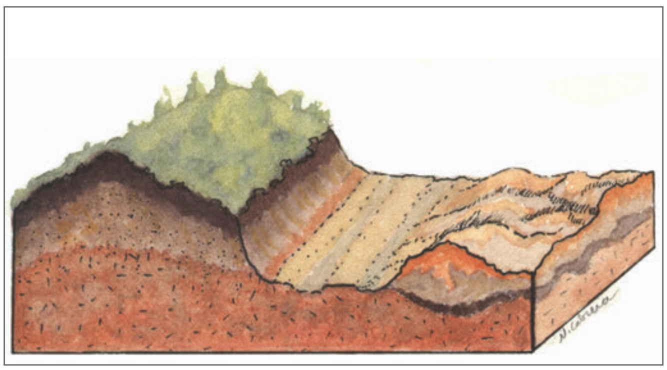

Figure 7—On wet soils, machine traffic forces displacement of topsoil.

Figure 8—Topsoil displacement due to machine traffic.

Topsoil displacement by machine forces exposes low-fertility subsoil with higher soil ρ_b and poor soil structure. This may slow subsequent revegetation of these areas (Williamson and Neilsen 2000), and often releases a buried seed bank consisting of weeds and woody shrubs.

Compaction

Ampoorter et al. (2012) found that soil compaction occurs when equipment destroys soil pores (especially macropores) and breaks down surface aggregates (figure 9). Soil compaction can develop alone or after rutting (Etter and Plummer 2021), and can occur after the initial few passes (Reeves et al. 2012), as shown in figure 10. Hillel (1998) found that soil compaction occurs when traffic from wheeled or tracked heavy machinery exerts instantaneous forces on soil particles under unfavorable soil conditions. Forest soil compaction reduces porosity, decreasing air and water supplies to soil microorganisms and plants (figures 11, 12, and 13). Limited air and moisture have negative consequences on soil ecology and forest productivity. The compaction of topsoil also increases the risks of runoff and erosion. Topsoil is vital to soil-air exchange, water infiltration, organic matter accumulation and decomposition, soil microbial activities, and plant root movement.

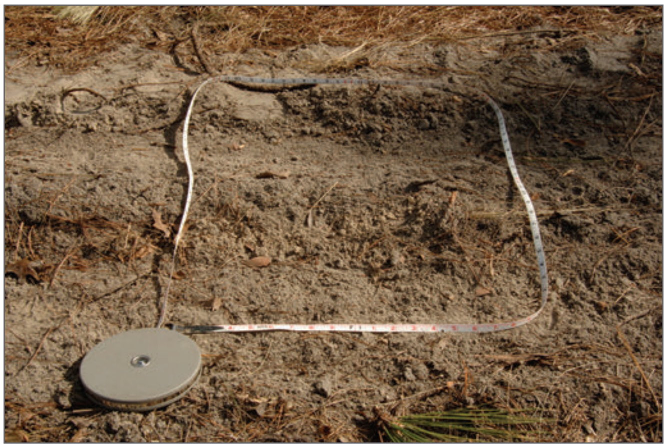

Figure 9—Soil compaction occurs after one pass of machine traffic when the soil pores (especially macropores) are destroyed and surface aggregates are broken down.

Figure 10—Soil compaction after a few passes of machine traffic over the same path.

Figure 11—Compacted soil becomes hard to dig through.

Figure 12—Compacted soil loses its pore space and macropores are destroyed.

Figure 13—Soil bulk density and penetration resistance increase with increased compaction.

Makineci et al. (2007) found the herbaceous understory and organic matter content on a skid road decreased considerably with increased compaction. Compaction changes soil aeration (Gaertig et al. 2002), soil water retention, and hydraulic conductivity (Reicosky et al. 1981). Increased compaction can induce a shift in the composition of understory vegetation (Zenner and Berger 2008), and has also been detected up to 0.5 meters (m) from the main trail in some soils (Solgi et al. 2019).

Soil ρ_b and PR both increase with increased compaction (Aust et al. 1998, Cullen et al. 1991). Macri et al. (2017) evaluated the changes in soil PR, water content, ρ_b, and porosity after different numbers of passes—0 (control), 1, 5, 10, and 15—with the same farm tractor. They found a significant correlation between the degree of compaction and the amount of traffic. Majnounian and Jourgholami (2013) reported increases in soil ρ_b at shallower depths when comparing uphill skidding and downhill skidding.

Puddling

Sharma and De Datta (1986) found that soil puddling occurs when soil aggregates break down into ultimate (individual) soil particles (figure 14). Puddling alters soil structure because these soils are at their liquid limit and have a liquid response to external forces (figure 15). The destroyed aggregates turn into plastic mud (Beacher and Strickland 1955, Ghildyal 1982, Swanson et al. 1955). Once aggregates break down, continued machine traffic forms ruts. An additional impact of aggregate loss is that the soil organic matter that holds aggregates together becomes available for microbial decomposition, resulting in an overall loss of soil carbon.

Figure 14—Soil puddling is the destruction of soil aggregates into ultimate soil particles.

Figure 15—Puddling alters soil structure because soils are at the liquid limit and have a liquid response to external forces.

Platy and Massive Soil Structures

Platy soil structure occurs when soil pores become elongated. These alterations form thin fissures parallel to the soil surface that resemble plates (Pagliai 1987). Massive soil structure occurs when there is no arrangement of soil particles into aggregates. If machine traffic continues, the soil structure becomes cemented together into uniform particle sizes with little pore space and no cracks. Both platy and massive soil structures can limit tree growth and reduce long-term site productivity (Lister et al. 2004) (figures 16, 17, and 18). Platy structure often causes roots to follow a plate parallel to the soil surface, preventing the roots from penetrating deep into the mineral soil profile. Because of this, trees growing on platy soils are particularly susceptible to windthrow and drought conditions.

Figure 16—Platy soil structure formed on the main skid trail. Notice there are few roots within the soil.

Figure 17—Platy soil structure formed on the main skid trail. Notice there are few roots within the soil.

Figure 18—Soil sample showing soil compaction.

Measures for Trafficability

Efforts to minimize soil compaction impacts require reliable forecasting of soil trafficability. This can be challenging because soil and machine use conditions may vary daily and by location. Soil scientists can use remote or handheld equipment to monitor soil moisture as needed during harvesting operations. Daily soil moisture readings may be necessary to protect the surface organic horizons and mineral soil from mixing, displacement, rutting, and compaction. Knowing how soil texture, depth to a restricting layer, organic matter, slope, and rock-fragment content vary across a harvest unit is critical for limiting soil disturbance. In shoulder seasons (fall or spring), soil trafficability varies with freezing and thawing, especially when traffic turns thawing soils into mud (Jones and Arp 2017). Cambi et al. (2015) noted that abundant rainfall can saturate the soil contiguous to the ruts, and can consequently cause mudflows or landslides. Ruts become preferential flow paths for water in steep terrain and may be dangerous foci for erosion, such as gullies. Significant soil disturbance (e.g., compaction, displacement, rutting) is more likely with harvesting activities on steeper slopes (Johnson et al. 2007). Steep slopes that are compacted or rutted also have more runoff and erosion (Jansson and Johansson 1998, Cambi et al. 2015).

Active vegetation management using heavy equipment can compact soils, degrade soil quality, and reduce long-term productivity. Parkhurst et al. (2018) found that skidder traffic changed the visual appearance of the soil surface and altered the physical properties of soil on skid trails. Larger equipment caused more obvious ruts and resulted in greater increases in soil ρ_b and decreases in macroporosity. Using slash mats is one way to reduce surface horizon and mineral soil impacts on skid trails. Slash mats can reduce the compaction effects and rutting from heavy equipment. Parkhurst et al. found with three high soil moisture contents that a slash mat did not effectively prevent soil PR increases after equipment made 12 passes and broke the slash into smaller pieces. However, slash mats can be an effective tool if they are replaced when residues become crushed. Moderate soil moisture treatment at a depth of 5 to 15 cm had the greatest increase in soil PR, but dry soils had the smallest increase in soil PR (Han et al. 2006).

The most common design feature for timber sale projects is to restrict operations to times when soils are relatively dry and have higher bearing strength to support equipment. Frozen soils or soils with a deep snowpack provide similar conditions. Forest managers may schedule ground-based harvesting operations to protect wildlife, reduce fire danger, or to address other resource concerns. For socioeconomic reasons, forest managers may schedule harvesting operations when soil moisture conditions are high. In these situations, the manager directs harvesting crews to avoid unwanted impacts and directs employees to monitor soil moisture content to maintain soil quality (figure 19).

Figure 19—Soil disturbance from operating machinery under wet conditions.

Factors Affecting Soil Operability

Several variables influence the effectiveness of soil operability by machine traffic:

- Soil moisture regimes (SMR)
- Soil PR or ρ_b
- Soil type (texture, gravel, and rock fragment content)
- Organic matter content of mineral soil
- Depth of the surface organic horizons
- Duration of machine traffic

Soil Moisture Regimes and Compaction Forces

Soil moisture influences soil PR (Hillel 1998). Dry soil may be trafficable by any vehicle. Soil PR is lower at high moisture contents, which indicates that wet soils cannot support heavy traffic (Cambi et al. 2015). The SMR can help forest managers understand how traffic may affect soil. SMR refers to the cumulative and consecutive periods of dryness and moistness in the soil moisture control section at different periods of the year. The soil moisture control section can be from 10 to 30 centimeters below the soil surface when the particle size class is fine-loamy, coarse-silty, fine-silty, or clayey; from 20 to 60 centimeters below the surface when the particle size class is coarse-loamy; or from 30 to 90 centimeters below the surface when the particle size class is sandy. Laboratory tests indicate that soils are dry when the water potential is less than -1,500 kPa (-15 bars), which is the permanent wilting point. Most plants cannot survive when soil moisture is this low. Laboratory tests indicate that soil is moist when water potential is higher than -1,500 kPa. Soil scientists classify soil moisture control sections based on moisture held in the soil during certain periods of the year (Soil Survey Staff 2014).

Different SMRs support different vegetation types and biomass production. The U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff (2014) defines five soil moisture regimes to describe soil taxonomy:

- Aquic
- Aridic and torric
- Udic and perudic
- Ustic
- Xeric

The regimes range from saturated most of the year to very dry. SMRs incorporate information about local climatic regimes and soil temperature. Given the wide variety of soil moisture and temperature regimes throughout the country, it is essential for forest managers to understand when to restrict machine traffic in order to maintain soil health.

Understanding the relative importance of applied pressure and water content during the compaction process is essential when developing and implementing practical guidelines for managing soil compaction for a wide range of machinery types and forest soils. It allows forest managers to make decisions that minimize soil compaction based on the moisture content of a particular soil and the equipment load. Smith et al. (1997) evaluated the relative importance of soil moisture content when they applied pressure to four different forest soils in South Africa: sandy loam, silty clay, sandy clay loam, and clay soils. Interestingly, compacting the sandy loam soil had little to do with moisture content and resulted almost entirely from increasing ground pressure. Because sandy loam soil was relatively insensitive to moisture content, there is likely no benefit to restricting harvesting operations to a particular season for this type of soil. Additionally, applied pressure was also the principal factor influencing compaction of the silty clay soil, where a doubling of ground pressure (from 200 to 400 kPa) substantially increased soil compaction.

Clayey soils were sensitive to both moisture content and vehicle pressure. The study by Smith et al. (1997) indicated that forest managers should restrict harvesting operations on clay-textured soils to dry periods and should use low-ground-pressure equipment. Soils with more than 25 percent clay are more sensitive to machine traffic, especially during wet seasons (figure 20).

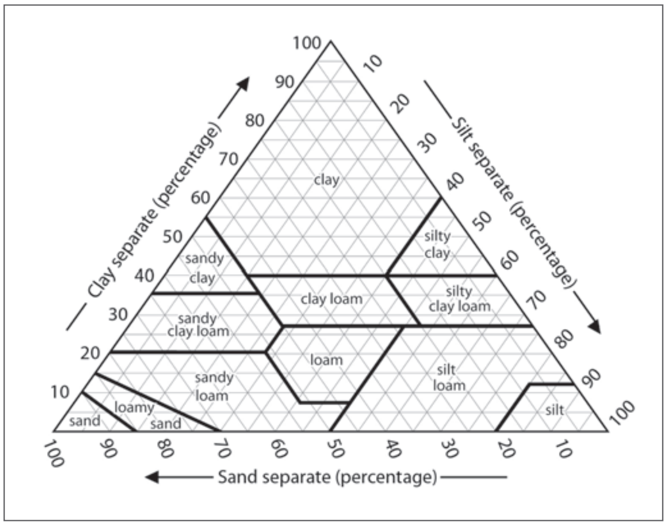

Figure 20—U.S. Department of Agriculture soil texture triangle.

Ash-Influenced Soils

Volcanic ash material dominates soils in many forests of the Western United States. These soils have high organic matter content and low natural ρ_b and, in the absence of machine traffic, they have a very rapid water infiltration rate and little runoff or erosion (Heninger et al. 2011). In the Inland Northwest, andisols and andic subgroups account for 37 percent of the soils. In some soils influenced by volcanic ash, forest productivity has declined because of soil displacement, compaction, puddling, and loss of surface or mineral soil organic matter (Heninger et al. 1997). Additionally, andic soils are susceptible to both pressure and vibratory compaction, and their recovery is slow, particularly deep (10 to 30 cm) in the soil profile (Page-Dumroese et al. 2006). When ash-influenced soils are at field capacity (free water has drained), just four equipment passes can compact them to a depth of 30 cm (Page-Dumroese 1993). In an extensive study of soil disturbance recovery on the Kootenai National Forest, 86 percent of harvest units had substantially less detrimental soil disturbance after 20 years, but the recovery rate was not constant. Most recovery occurred during the first 3 to 5 years after harvesting operations, but displacement, erosion, rutting, and compaction are still detectable and may be long-lived (Gier et al. 2018).

Soil Penetration Resistance

Soil scientists have known for years that the first few passes of heavy equipment cause the most impacts (e.g., compaction, rutting, displacement) to the soil (Abdi et al. 2017, Amir et al. 1976, Williamson and Neilsen 2000). Changes in soil PR result from the cohesive forces between individual soil particles and their frictional resistance, and this affects soil-bearing capacity (Rab et al. 2005). A cone penetrometer can easily and rapidly measure soil PR.

Examining both PR and ρ_b and their relationships to soil moisture content in one plot is helpful. Soils with high rock fragment content, dry soils, or soils with many roots near the surface may provide inaccurately high PR readings, reducing the value of the data (Rab et al. 2005).

Soil PR is the capacity of soil to withstand pressure or compression. Lal and Shukla (2004) described it as either resistant to volumetric compression or resistant to linear deformation or shear strength. For a given soil bulk density, PR decreases as soil moisture content increases. In general, fine-textured soils with low soil moisture content exhibit high strength. Soil compactability provides an example of how moisture content, PR, and land management can interact. Soil resistance to rutting is directly proportional to the ratio between tire footprint pressure PR (Affleck 2005, Jones and Arp 2017, Saarilahti 2002, Sakai et al. 2008). Etter and Plummer (2021) used a cone penetrometer to evaluate the shear strength of soil and soil moisture content to assist OHV and ATV off-road recreational activities. The penetrometer has a 30-degree circular stainless steel cone. A dial ranging from 0 to 300 kPa indicates the force necessary to push the cone slowly though the soil. A force of 150 pounds results in a measured value of 300. The measured value, a dimensionless, number-termed cone index, provides an index of soil strength (U.S. Department of the Army 2003).

As noted, traffic on wet soils results in more severe compaction than traffic on dry soils. Abdi et al. (2017) found that one pass of harvesting equipment over moist soil caused a reduction in the infiltration rate and a strong, negative relationship between infiltration, PR, and ρ_b. They also found an increase in ρ_b of 57 percent and 31 percent (moist soil compared with a dry control) in wheel ruts and centers of skid trails respectively. NTDP recommends using a protective layer of slash and logging debris on skid trails to reduce soil compaction and to mitigate the destructive impact of logging equipment. Jones and Arp (2017) used hydrological and geospatial modeling to interpret the results when using PR and soil moisture. They then transformed this modeled data into rut-depth estimates of temporal changes in PR after multiple passes of off-road ATV traffic.

Examining agricultural soils, Kirby and Blunden (1990) studied the relative importance of PR and machinery ground pressure on soil compaction. They found PR to be more critical than ground pressure when managing wet soils. Sakai et al. (2008) reported that an increase in soil contact pressure of 100 kPa decreased soil porosity by 5.7 percent at a depth of 10 to 15 cm after 24 passes using a maximum PR of 85 kPa. They concluded that it is more important to operate on dry soil than to choose a different (lighter) machine or wider tires. On a forest site in the Southeastern United States, however, Aust et al. (1995) found that sites with better drainage and aeration had the greatest changes to compacted and rutted skid trails. Furthermore, compaction resulting from site preparation may be easier to mitigate than compaction from rutting because compaction during site preparation occurs closer to the soil surface.

It is essential for forest managers to know when to begin and end harvesting operations because of concerns over high soil moisture content and soil disturbance. Having soil trafficability parameters in place can enable forest managers to determine when to continue or discontinue harvesting operations to reduce impacts to the soil and ensure that best management practices are met.

Equipment Ground Pressure

Equipment ground pressure is the pressure exerted on the ground by the tires or tracks of a motorized vehicle. It is a measure of the vehicle's potential mobility over soft terrain (U.S. Department of the Army 2003). Ground pressure *(P)* is the unit loading produced by vehicle suspension components that contact the ground. It is based on total vehicle weight *(F)* divided by the track or tire contact area *(A)*—ground pressure is measured in Pascals (Pa), which corresponds to pounds per square inch (psi).

To calculate the average ground pressure in pounds per square inch:

$P = F \div A$

Where: P = average ground contact pressure (psi)

F = total vehicle weight (lb)

A = contact area (in^2) = length (in) × width (in)

The U.S. Army (1981) calculated the ground pressure for a wheeled vehicle by determining ground pressure at each wheel and dividing the load at each wheel by the contact area of the tire. They calculated the nominal ground pressure for tracked vehicles as follows:

$P_n = (W \div 2bL) \times 98.06$

Where: P_n = nominal ground pressure (kPa)

W = vehicle weight (kg)

b = overall track width (cm)

L = length of track between projected centerlines of front and rear road wheels (cm)

98.06 = conversion factor to metric

Jones and Arp (2017) reported that rutting increases as vehicle weights and loads increase and tire footprints decrease. Consequently, rutting decreases with lighter weights and loads, wider tire footprints, and reduced tire pressure. Rutting increases further from multiple equipment passes and on slopes that cause tires to spin to gain traction (Han et al. 2006). These impacts are similar for other types of soil disturbance associated with equipment traffic. Using full, extended tracks on tracked equipment substantially reduces equipment pressure on the soil surface, and adjusting the load and tire pressure on wheeled vehicles provides the same results. The actual contact pressure in pounds per square inch is equal to the tire inflation pressure plus the number of plies (Lull 1959).

Triplat et al. (2015) presented a method that the European Union uses to develop a protocol for ecofriendly wood harvesting. The method integrates guidelines for selecting the most appropriate harvest equipment to reduce soil disturbance while still maintaining the cost-effectiveness of harvesting operations.

Soil Texture, Organic Matter, and Rock Fragments

Soil texture, soil organic matter (SOM), and rock fragments on the soil surface and in the mineral soil significantly influence the moisture-holding capacity and compactibility of soil. The size of soil particles also plays a significant role in soil compactibility. Smaller particles compact tighter and bond more than larger particles, such as coarse sand. Soil ρ_b increases with increasing soil compaction and water content, up to a maximum point or threshold, before the soil deforms. Rab et al. (2005) presented the relationship between bulk density and soil water content for one type of soil and found that ρ_b increased with soil water contents below a threshold value for that particular soil. They found that soil ρ_b did not increase as quickly after the water content rose above a threshold value. With the water content at the threshold value, soil compaction had little impact on soil bulk density. Above the threshold value, machinery formed ruts or sank into the muddy soil.

Soil Texture

Rab et al. (2005) noted that soil texture affects soil susceptibility to compaction and also relates to soil moisture content. Subsoils appear to be more susceptible to compaction than topsoil because subsoils often have a higher clay content. On the other hand, soils with a coarser texture (e.g., sands or skeletal soils) exhibit a positive relationship between maximum ρ_b and sand content (Howard et al. 1981, Ohu et al. 1989, Stone and Ekwue 1993). Additionally, Froehlich et al. (1980) observed similar soil textural influences where soil bulk density increased with increasing soil water content until it reached a maximum density. After reaching maximum density, soil density decreased as the soil water content increased because, as soil ρ_b increases, the soil becomes more resistant to additional compactive forces.

Soil Organic Matter

SOM is an essential factor for increasing the available water-holding capacity of soil. Organic matter in the mineral soil acts as a sponge to absorb water as it moves into the soil profile. It also helps to limit compaction and regulate nutrient cycling and microbial diversity. Consequently, SOM is critical for promoting plant growth and soil health. Soils high in organic matter content don't compact as easily as soils with low organic matter content (Greacen and Sands 1980, Rab et al. 2005, Sands et al. 1979). In New Zealand, Murphy and Robertson (1984) found considerable differences in bulk density and soil moisture content based on SOM content. Surface and subsurface organic matter creates soils with high aggregate stability that are less susceptible to compaction.

Free et al. (1947) and Bodman and Constantin (1965) found that adding organic matter to soil increased the water content at which the soil achieves maximum ρ_b. Soane (1990) reviewed the role of SOM on compactibility extensively and noted that compactibility is sensitive to even small changes in SOM. Increases in SOM may reduce compactibility by increasing resistance to deformation or by improving elasticity (rebound effects). Sands et al. (1979) reported that sandy soils low in organic matter are especially sensitive to compaction. Maintaining both surface organic horizons and SOM in the mineral soil are critical for reducing the compactive effect of equipment during logging operations, while also maintaining the critical soil functions of water storage and plant growth. Rocks both within and on the mineral soil surface act as armor, helping maintain soil porosity and improving water infiltration.

Rock Fragments

Comeau et al. (1982) and Lewis et al. (1991) presented a key to soil disturbance hazards, finding that texture and rock fragment content are the most critical factors for reducing equipment impacts on mineral soil. Rockier soil is generally less susceptible to compaction.

Depth of Surface Organic Horizons and Slope

Before harvesting operations begin, forest managers must understand how deep the surface organic horizon is and must also perform a field evaluation or use a contour map to determine the steepest slope and dominant grade of the harvest unit.

Surface Organic Horizon Depth

A deep surface organic horizon can buffer much of the trafficking effects to mineral soil during harvesting operations. Rab et al. (2005) studied the relationships between the depth of surface organic horizons and changes in soil bulk density resulting from compaction and water content. They noted that a decrease in the thickness of the organic horizon and an increase in water content resulted in an increase in mineral soil ρ_b. In mineral soil, the maximum bulk density in the subsoil occurred at a lower critical value of soil water content than in topsoil because subsoil has a lower SOM content than topsoil. The maximum PR of subsoil is also usually higher than for topsoil.

Slope

A steep slope often has a stronger effect on soil disturbance than seasonal conditions, and increased slope also tends to increase rutting. Forest managers usually avoid slopes of more than 35 percent for ground-based harvesting operations, but may use tethered logging for these slopes to reduce soil impacts and increase logger safety. Agherkakli et al. (2010) found that harvesting operations on skid trails with slopes of more than 20 percent caused higher soil bulk density, more rutting, and removed more of the surface organic horizon than operations on slopes of less than 20 percent. After nine passes with a tracked skidder, bulk density increased by 35.2 percent on skid trails with slopes of more than 20 percent, compared with 24.4 percent on skid trails with slopes of less than 20 percent. Agherkaki et al. also found that slope did not significantly affect the removal of the surface organic horizon, with most of the loss occurring after the first equipment pass.

Timing of the Harvest

The degree and extent of soil disturbance depends on the method of logging, the equipment used, the slope, the soil, and the season. The timing of harvesting operations influences the success and speed of harvesting and can minimize soil disturbance. To maximize machine operability on a site, the forest manager must determine the mean and range of soil moisture conditions and understand when soil is at a reference level (such as field capacity). The two most important decisions are when to begin operations and when to end them temporarily or for the season. Deciding when to begin can be tricky. Impatience can lead to operations before soil conditions are sufficient. Ending operations may be a quick decision. When weather conditions quickly become unfavorable for machine traffic, operations must end before soil trafficability declines and mud begins to develop (figure 21). Harvesting operations must then wait until soil moisture falls below the soil trafficability threshold before resuming.

NTDP developed remote soil-sensing technology and a simplified, field-based process for determining the soil moisture/strength relationship (figure 22). When installed, this combined remote wet weather management system enables forest managers to make decisions about trail or road closures based on changing soil conditions. Managers can make decisions quickly and easily based on repeatable data. Precipitation-based methodologies that are responsive to user access needs can also better protect natural resources (Etter and Plummer 2020).

Figure 21—Soil disturbance from operating machinery during wet conditions.

Figure 22—A remote soil sensing station installed on an off-highway/all-terrain vehicle trail system (Tahoe National Forest).

Measurement Methods

Bulk Density

Forest managers traditionally use dry soil ρ_b measurements to determine the amount of compaction caused by machine traffic. This method requires sampling, drying, and weighing a known volume of soil. The total ρ_b is the weight of the entire volume of soil, including rocks. Soil fine-fraction (less than 2 mm) is the weight of only the mineral soil fraction with the rocks removed (and weighed). Both total and fine-fraction ρ_b provide information about pre- and post-harvest soil compaction levels. Collecting soil cores is difficult if the soil has a lot of rock fragments or roots. There are other methods for collecting a known volume of soil, such as using plastic in the ground and filling it with a known volume of water (Page-Dumroese et al. 1999). It is also critical to know the size of rock fragments in the soil in order to use the proper tools and methods (Page-Dumroese et al. 1999; Jurgensen et al. 2018). Soil scientists can plot measured values of soil ρ_b, coupled with soil moisture content, to develop a relationship of compactibility. Agriculture uses this ρ_b-optimum moisture content (Proctor 1933), or critical moisture content (CMC), but it can also be used for forest soils (Froehlich et al. 1980, Howard et al. 1981, Murphy and Robertson, 1984, Smith et al. 1997). ρ_b is one of the best methods for collecting data on soil compaction before and after harvesting operations, but it is time-consuming to collect accurate samples and one drawback is the need for an oven to dry the samples. If an oven is not available, samples can air dry.

Cone Penetrometer

A cone penetrometer is the equipment used to determine PR. The U.S. military used the Proctor test and a penetrometer to determine soil trafficability for military vehicles (U.S. Department of the Army 1981). Forest managers may apply similar principles to determine the trafficability for harvesting machines or ATV use on forest roads. A cone penetrometer has an aluminum or stainless-steel shaft 20 mm in diameter that can range from 10 to 60 cm in length. Some types of penetrometers also have a proving ring, a micrometer dial, and a handle. The penetrometer shown in figure 23 is a recording penetrometer that stores data from specific depths (i.e., every 2.5 cm). The operator must insert the rod into the soil using steady pressure. When the operator pushes the cone tip into the soil, a sensor or proving ring measures the force applied. On dial penetrometers, the gauge indicates the amount of force. As noted earlier, the amount of force required to push the cone into the soil varies considerably, depending on the soil moisture content. To minimize the effect of varying soil moisture on data, the American Society of Association Executives (ASAE 1999a, 1999b) recommends that operators take soil cone penetrometer measurements when soil moisture content is near field capacity.

Figure 23—Typical cone penetrometer for field characterization of soil strength.

Although the military developed the following PR trafficking ranges for their vehicles, these ranges also apply to logging equipment. For example, most military vehicles require a PR measurement between 69 and 2,068 kPa (10 to 300 psi) in the critical (surface soil) layer for support (U.S. Department of the Army 1981). Except for a few vehicles, the U.S. Army considers a PR reading of less than 69 kPa (10 psi) to be nontrafficable, and deems above 2,068 kPa (300 psi) to be trafficable for 50 passes (U.S. Department of the Army 2003).

The cone penetrometer offers several advantages:

- It is a simple device
- It is relatively easy to use
- It has been used widely for other purposes, including soil compaction and root growth studies
- It is relatively inexpensive (about $250)

The Forest Service has tested handheld versions of the cone penetrometer (Amacher and O'Neill 2004). The disadvantage of the cone penetrometer is that it provides different readings for the same soil tested at different moisture contents. Therefore, NTDP recommends taking all readings on the same day or when soil moisture conditions are the same. This may be difficult because compacted areas may have different soil moisture than neighboring uncompacted soil.

Penetrometer resistance decreases exponentially as soil moisture content increases. Heavy equipment can compact soil with lower moisture contents, while lighter equipment does not compact the soil as much until soil moisture contents are higher.

Soil penetrometers measure compaction quantitatively, objectively, and in realtime, presenting a distinct advantage over conventional measures for both monitoring soil quality and making decisions about trafficability. Soil scientists can synchronize the soil-strength measurements with field soil moisture samples to model the relationships, and can predict the value of a "threshold" from soil strength-moisture curves (figure 24). Figure 24 presents results from a recent study the Forest Service conducted in the Sierra National Forest measuring soil strength using a handheld cone penetrometer and soil moisture content using a handheld time domain reflectometer (TDR). Soil scientists consider the inflection point between the positive and negative relationships of PR and soil moisture a threshold. Soil strength has a maximum value of 1,586 kPa (230 psi) at a soil moisture content of 42 percent. The graphed data shows maximum soil strength at certain soil moisture levels (the soil-strength moisture curve) used to quantify a threshold.

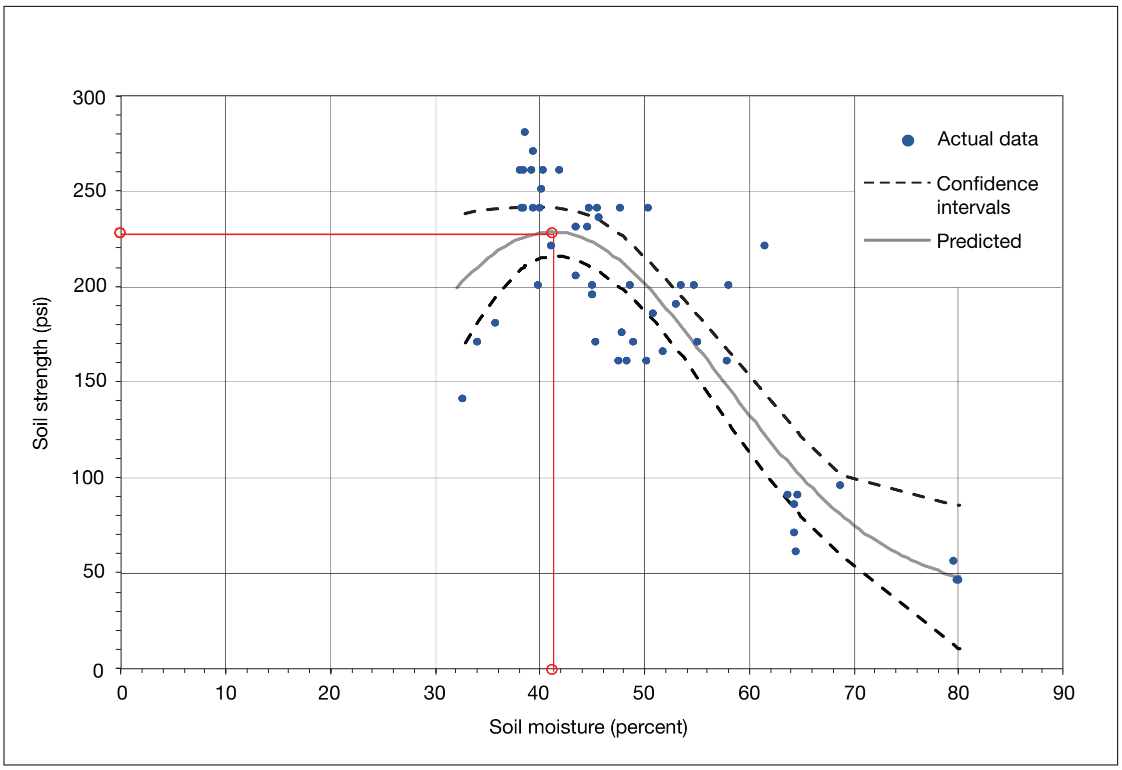

Figure 24—Soil strength-moisture curve. The red horizontal and vertical lines intersect at the predicted threshold.

For the data collected from the Sierra National Forest for different soil depths—0 to 2 inches (0 to 5 cm) and 2 to 4 inches (5 to 10 cm)—and for both depths combined, the best model fit was nonlinear with an R^2 of 0.935. Soil scientists can use this model to produce a graph of PR across the site at any soil moisture content (see figure 24).

Batey (2009) and Ohu et al. (1989) found that knowing water content in relation to soil compaction for a particular soil can help with scheduling routine mechanical operations on that soil. Rab et al. (2005) recommended the use of a cone penetrometer matched with soil moisture content on a timber harvesting operation in New South Wales, Australia. Many commercially available handheld soil moisture meters (e.g., Field Scout Digital Moisture Sensor, Spectrum Technologies, Aurora, IL) measure soil moisture for different types of soil. These meters come with interchangeable probes for measuring moisture at different depths and can be upgraded to collect Global Positioning System (GPS) coordinates to map soil moisture. Roger Poff (2014) plotted soil moisture versus soil strength data on an X and Y axis using a handheld soil moisture meter (figure 25).

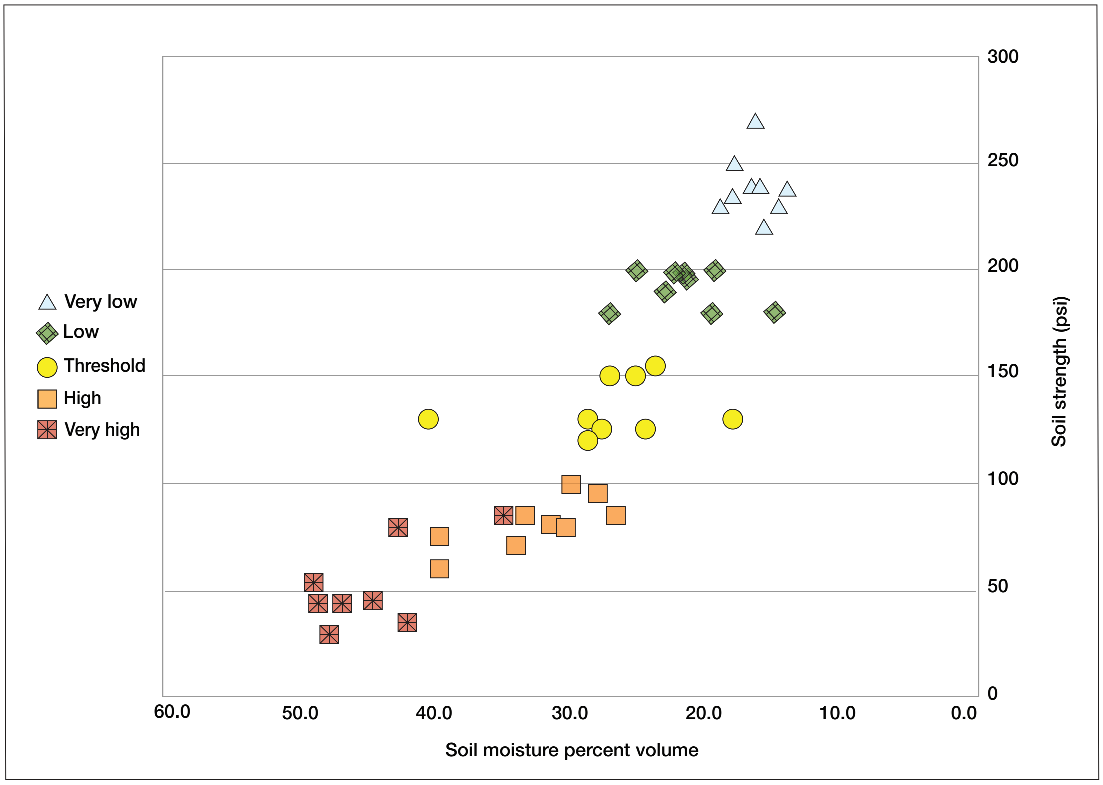

Figure 25—Example of threshold determination (adapted from Poff 2014). psi = pounds per square inch.

Threshold Values Criteria for Soil Trafficability

Droogers et al. (1996) defined soil trafficability as "the soil moisture content at which machine traffic is possible without causing detrimental soil impact or compaction." Soil scientists use various criteria to assess the trafficability of soils, including:

- Shear strength
- Critical moisture content for maximum bulk density
- Plastic limit
- Water balance and field capacity
- Direct penetrometer measurement

Soil scientists use different threshold values for different soil types, vehicle configurations, and soil moisture content.

Soil Shear Strength and Compaction

A shear vane device measures soil shear strength. Data from this device can help forest managers determine when soil is suitable for machine traffic. Managers should not allow machine traffic on the soil if the measured soil shear strength is below the threshold. Both soil type and moisture content significantly influence the bearing capacities of soil and snow. Clay soil may have a ground bearing capacity of 800 kPa when dry during the summer, but the soil's capacity may fall as low as 100 kPa when wet during the winter (Rab et al. 2005).

Owende et al. (2002) classified soil bearing capacity into three categories:

1. Low (assumed less than 40 kPa)
2. Medium (assumed 40 to 80 kPa)
3. High (assumed more than 80 kPa)

The parameters used to classify soils are PR, shear strength, and deformation modulus (elasticity). Soil scientists can measure each of these easily in the field using portable equipment (Owende et al. 2002). Rab et al. (2005) and Owende et al. (2002) classified soil into bearing capacity categories based on the "least common denominator." They presented the equations below for determining nominal ground pressure.

For wheeled machines:
Nominal ground pressure (NGP) = $W \div rb$

Where:

NGP = nominal ground pressure (kPa)

W = wheel load (kilonewtons, kN)

r = wheel radius (m)

b = tire width (m)

For tracked machines:

NGP = $W \div b\,(1.25 + L)$

Where:
NGP = nominal ground pressure (kPa)

W = track load (kN)

L = length between the wheel centers (m)

b = track width (m)

Moist sandy soil and moist clay have similar average bearing capacity.

Forest managers can use NGP values to minimize soil surface rutting if they match the values to soil bearing capacity. (Owende et al. 2002, Rab et al. 2005).

From comprehensive field measurements, PR lower than 0.5 MPa appear insufficient to support traffic, while values higher than 0.7 MPa are sufficient (Droogers et al. 1996, Rab et al. 2005). Note that Ehlers et al. (1983) reported root-limiting PR from 2 to 3 MPa (2,000 to 3,000 kPa). The Forest Service established North American Long-Term Soil Productivity (LTSP) plots with a range of soil compaction, but soil compaction did not reach “severe” levels on many coarse-textured soils with an inherently high soil ρ_b. In many cases, the soil did not reach the root-limiting ρ_b described by Daddow and Warrington (1983). However, during periods of drought, many LTSP plots have a PR higher than 2,000 to 2,500 kPa, indicating the likelihood of reduced root growth. After 5 years, compaction in the moderate and severely compacted plots on the LTSP sites was still evident in surface soils across North America. However, after 20 years the surface (0 to 10 cm) was largely mitigated, but deep soil compaction is still evident. Additionally, the Forest Service observed that compaction on the LTSP plots was relatively uniform after 5 years, and there was more variability in PR after freeze-thaw cycles, root growth, and invertebrate or animal tunneling.

The ratio of cone index (CI) to NGP defines operational limits for machine traffic. Operational limits lie in the CI/NGP range of 3 to 7. Owende et al. (2002) considered a rut 10 cm deep to be the threshold for economic and ecological consequence. Ruts this deep can occur at a CI/NGP of 5. Owende et al. proposed a CI/NGP value of 5 as the criteria for establishing the required NGP of a given operating vehicle.

Prediction Models

There are several models for predicting the risk of soil compaction from machine traffic:

- Terranimo International provides a model for predicting soil compaction that results from agricultural field traffic <www.soilcompaction.eu>.
- EFFORTE is a research and innovation project for the European forestry sector <https://www.luke.fi/efforte/>.

Critical Moisture Content

As noted throughout this report, soil moisture content is the most critical influence on soil compactibility, so it is vital that forest managers schedule harvest and site preparation activities for when soil is dry. Understanding CMC helps managers determine the best times for causing the least impact.

Managers can also determine the CMC at which penetration resistance or shear strength values decline from the maximum. Hillel (1998) and Rab et al. (2005) found that the maximum penetration resistance and shear strength occurred at a lower soil moisture content than the content that produced the maximum soil ρ_b, and the shape of the soil strength-water content curve was flat or close to the CMC. Others observed this phenomenon (Ohu et al. 1985, 1987, 1989). With soil water content below the CMC, bulk density has more influence on PR and shear strength than the soil water content. When the soil moisture content is near the significant value CMC, the effect of PR is higher, resulting in a flatter curve. When the soil water content is above the CMC, both PR and shear strength decrease more rapidly than soil ρ_b due to a reduction in soil bulk density and an increase in soil water content.

Plastic Limit

The plastic limit is the soil moisture content at the boundary between the plastic and semisolid states. Soil scientists use the plastic limit to evaluate soil trafficability for heavy machinery. A soil’s plastic limit is the water content at which undrained shear strength is about 170 kilonewtons per square meter (kN/m^2) (Sharma and Bora 2003). A rapid and practical method for defining the plastic limit is the water content at which a person can roll the soil into a “worm” about 3 mm in diameter without it breaking, but this method is only useful if the soil has enough clay to roll it (Rab et al. 2005). As noted for other changes in soil physical properties, soil trafficability relates to moisture content at the plastic limit (Rab et al. 2005, Smedema 1993). The higher the soil plasticity, the more severe the effect of soil “stickiness” on machine traffic. The plastic limit affects the speed and control of moving equipment. The soil must have sufficient bearing capacity—the ability of a soil to support a vehicle without undo settlement—to prevent the machine traffic from sinking when tractive capacity is not enough for the wheels to move forward. The U.S. Army (2003) reported that bearing capacity and tractive capacity are primary functions of the shearing resistance of soil. In contrast, tractive capacity is the ability of a soil to provide sufficient resistance between the moving wheel or track of a vehicle and the soil to provide the necessary thrust to move the vehicle forward. A soil is trafficable when it has an adequate bearing capacity to support a vehicle and sufficient tractive capacity to enable the vehicle to move.

Soil Trafficability and Water Balance

Soil scientists can generally take two approaches to understanding soil trafficability. The first approach involves predicting and measuring PR, and the second approach uses soil moisture content in a water balance model or in field capacity measurements. It is important for scientists to consider climate in any soil moisture relationship. Several scientists have used soil moisture content at field capacity to determine the trafficability of agricultural and forest soils. The moisture content criterion for soil trafficability in the spring is thought to be 90 percent of field capacity in the top 12 cm of soil, whereas in the autumn it is 95 percent. Rab et al. (2005) and Rounsevell (1993) used a soil moisture content of more than 95 percent of field capacity as the criterion to determine when the soil on a Mississippi forest site was unsuitable for machine traffic.

Babeir (1984) and Babier et al. (1985) developed a simulation model (TRACTMOD) to predict the available field operation time for machinery in relation to weather and soil moisture conditions in the top 30 cm of the soil. Rab et al. (2005) tested and validated TRACTMOD by comparing its output with 11 years of observed workdays in central Iowa. The model had a satisfactory agreement between observed and predicted soil trafficability conditions, and may apply elsewhere (Rab et al. 2005).

The Sierra National Forest Hemlock Restoration Project demonstrated that a soil scientist or hydrologist can use the soil water balance method to determine soil moisture content empirically. The amount of water remaining in the soil after rainfall depends on evapotranspiration, runoff, drainage, and changes in soil moisture content over time. The project used the empirical method developed by Thornthwaite and Mather (1957) to calculate water retention in the soil profile under a tree canopy. The project also used monthly climatic variable averages between 1989 and 2012 to demonstrate the water balance over 12 months. For example, Thornthwaite and Mather used the monthly average of rainfall, potential evapotranspiration (PET), and temperature datasets to develop empirical equations to determine a water balance (figure 26). The Forest Service used the soil moisture storage values from Thornthwaite and Mather at the Sierra National Forest to a depth of 300 mm. The water balance components presented in figure 26 show the soil water surplus, soil water deficit-utilization, and recharge, and their periods over the year. Soil scientists can use water availability in soil profiles to more accurately determine the depth of soil and available moisture on a finer scale than typical map units. These water balance components closely reflect soil moisture content.

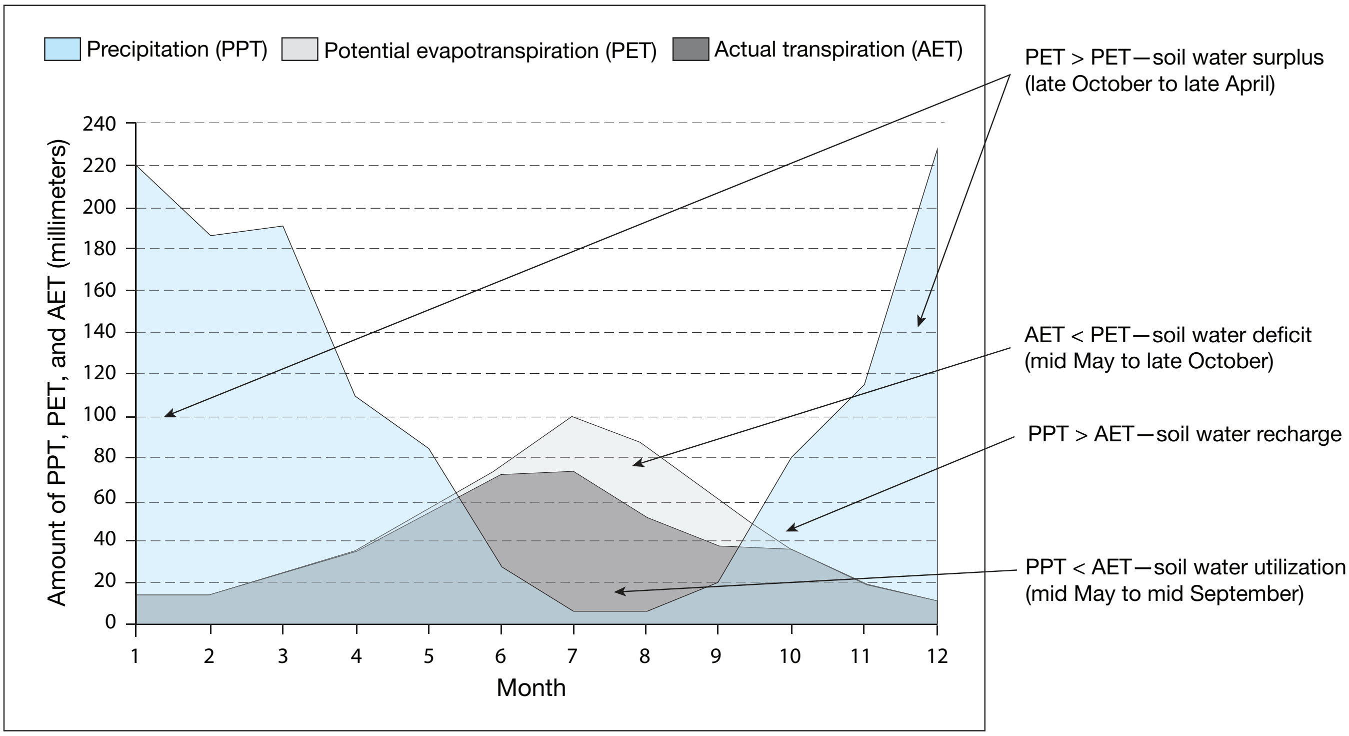

Figure 26—Precipitation, potential evapotranspiration, and actual evapotranspiration for the Sierra National Forest Hemlock Restoration Project.

Stephenson et al. (1998) defined climate water deficit (D) as the difference between PET and actual evapotranspiration (AET), or D = PET – AET, and assumed that AET is equivalent to precipitation (PPT) in millimeters when PPT is less than PET. If the result of PET – PPT is less than 0 it is a surplus, if it is more than 0 it is a deficit (Stephenson et al. 1998). A soil scientist or hydrologist can also use the ratio between water deficit and surplus. If the result of PPT ÷ PET is more than than 1 it is a surplus, if it is less than 1 it is a deficit. Thus, the value of PET becomes critical to soil moisture content (see figure 26).

Several studies used the combination of soil moisture content and the amount of rainfall as a threshold for determining soil trafficability (Babeir et al. 1985; Cornish 1981, 1985; Cornish et al. 1981). Babeir et al. (1985) used a combination of soil moisture content in the top 30 cm of the soil, the amount of daily rainfall, the amount of snow on the ground, and the daily air temperature as criteria for determining soil trafficability. Soil puddling is most severe when soil moisture contents are higher than field capacity because moist soil aggregates have low strength (Braunack and Dexter 1978). Several researchers have used the degree of saturation at which maximum bulk density occurs as a threshold value. Hillel (1980) presented methods for calculating the degree of saturation that Aragon et al. (2000) also used in Argentina to determine the maximum bulk density and corresponding critical SMC content for 30 soil types.

Direct Penetrometer Measurement

PR is a physical attribute of soil that soil scientists use to monitor and evaluate soil quality (Islam and Weil 2000), and it influences the growth of roots and can indicate the effects of tillage or decompaction on the rooting zone (Abrougui et al. 2012). Soil scientists can also use PR to predict the traction force needed to prevent the formation of a compacted area that reduces plant root growth (Rab et al. 2005). Root growth is significantly inhibited at higher penetrometer readings of 2,000 to 2,500 kPa.

Tylor and Burnett (1964) indicated that no roots penetrate the soil when PR is more than 2,068 kPa (300 psi), but root growth is inversely proportional to PR when penetrometer readings are less than 2,068 kPa (Duiker 2002). The effect of compaction on root and aboveground growth is dependent on both weather and climate; where soil moisture deficits are large, restricted rooting depth may have severe effects on vegetation. However, where moisture soil deficits are small, the effect is likely negligible.

Discussion

Soil Moisture Content

Soil moisture is critical for plant growth and is an integral component of the plant-soil-atmosphere continuum. Knowing when a soil is at CMC is also important for knowing when maximum soil compaction will occur. When CMC is lower than the maximum/threshold value, harvesting operations can proceed without excessive soil disturbance. Soil scientists often use a Proctor compaction test to determine CMC for maximum compaction. The CMC value for the Sierra National Forest is 42 percent, but varies depending on soil conditions and the equipment used (with CMC ranging from 15 to 50 percent). Soil scientists can determine CMC values where penetrometer readings for shear strength start to decline from the maximum (figure 27). Maximum PR and shear strength occur at lower soil moisture content than the content that produces the maximum soil ρ_b. Ohu et al. (1985, 1987, 1989) found that the shape of the soil strength/water content curve is flatter at or close to critical soil moisture content. Others observed this phenomenon. At a soil moisture content below the critical value, soil ρ_b influences PR and shear strength more than the soil moisture content. When soil moisture content is at or near the critical value, PR is higher, resulting in a flatter curve. At soil moisture contents above the significant value, both PR and shear strength decrease more rapidly than soil ρ_b due to a reduction in soil ρ_b and an increase in soil moisture content (Rab et al. 2005).

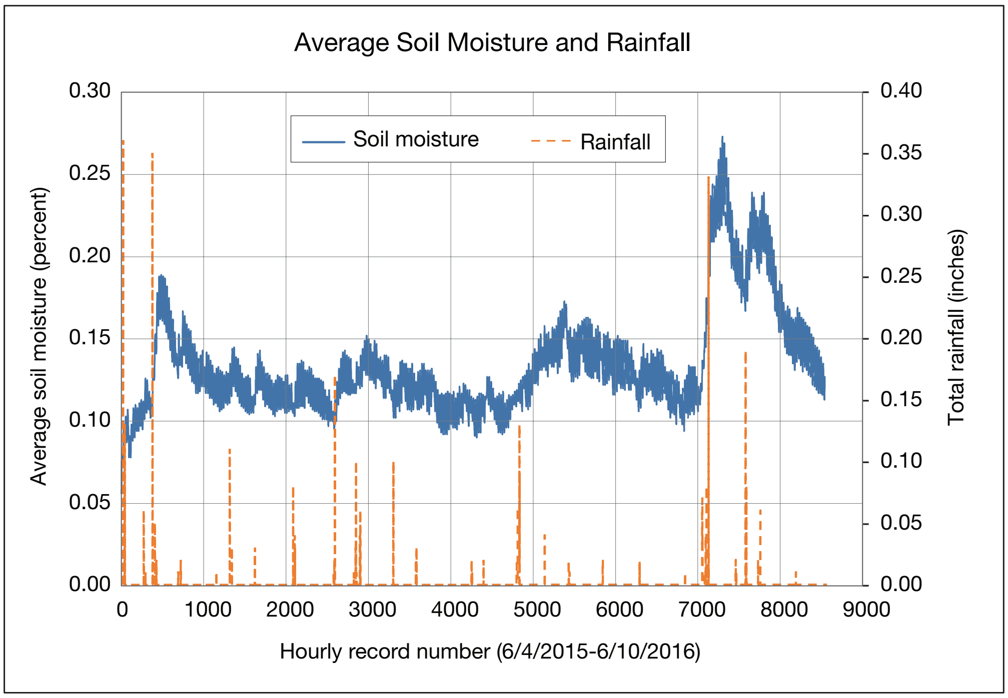

Figure 27—Hourly measured soil moisture content and rainfall data from a remote soil sensing station installed on an off-highway/all-terrain vehicle trail system (Tahoe National Forest).

Changes in soil moisture content and, consequently, changes in soil trafficability depend on weather conditions, especially rain. Increases in soil moisture content result in sticky soil and decreased PR. Dry periods produce the opposite effects. The exception is loose sands, where soil trafficability improves through an increase in cohesion when soil is wet, and returns to a loose, less trafficable state when dry (Rab et al. 2005). Because of spatial and temporal variability, soil scientists may need to reevaluate measured trafficability characteristics for changes in PR and soil moisture content.

Effect of Gravel Content on Soil Trafficability and Compactibility

In general, soil with a high rock fragment content has a higher total soil ρ_b. However, the fine-fraction (less than 2 mm in size) soil ρ_b may be similar to other soils with the same textural classes in the less-than-2-mm size fraction. Because total soil ρ_b increases with increasing rock fragment content, this likely means an increase in the bearing capacity and, in turn, improved soil trafficability (Rab et al. 2005). Rock fragment size is an important consideration when evaluating trafficability.

Several researchers have studied the effects of rock fragment content on soil compactibility and rutting (Whitford 2001, Whitford et al. 2005, Wronski 1984). Soils with high rock fragment content are generally more resistant to rutting and soil mixing under moist conditions than soils that have a loamy texture with less rock fragment content (Whitford 2001, Wronski 1984). Wronski (1984) reported that when rock fragment content of a sandy clay declined below 55 percent by weight, the soil was more susceptible to developing ruts. Traditionally, soil scientists used mined gravel on road surfaces to improve road trafficability. However, there is little information on the threshold values of rock fragment content within the soil profile that would help determine when a soil compacts or ruts (Wronski 1984). Rab et al. (2005) found that 15 to 20 percent (by volume) of soil rock fragment content can protect the fine-earth fraction from compaction, and recommended a rock fragment content of 60 percent for dragging logs along the ground during spring and winter periods.

Effect of Organic Matter Content on Soil Trafficability and Compactibility

Organic matter plays an essential role in soil compactibility (Adams 1973, Howard et al. 1981, Saini 1966). Soils rich in organic matter are more difficult to compact than soils with poor organic matter (Greacen and Sands 1980, Mulqueen 1973, Sands et al. 1979). De Kimpe et al. (1982) reported that the most important physical properties influencing compaction behavior were water retention properties at high matric potentials. Rab et al. (2005) found that both clay and SOM content primarily influenced water retention properties.

Subsoils are prone to more compaction because they are low in SOM, and they recover more slowly because there are fewer roots and fauna moving through the soil. However, PR, shear strength, and CMC also govern subsurface soil compaction. Higher SOM in the topsoil may be beneficial for reducing soil compactibility (Ekwue and Stone 1995, Sands et al. 1979, Soane 1990, Stone and Ekwue 1993). Even small changes in the amount of SOM can affect compactibility, and increases in SOM might reduce compactibility by increasing resistance to deformation or by improving elasticity (rebound effects). Sands et al. (1979) reported that sandy soil with low SOM is especially sensitive to compaction. Increases in organic matter increase resistance to heavy machinery impacts. Increases in SOM can loosen the soil and increase its porosity (Soane 1990).

Although not recommended because subsoils have lower productivity than surface soils, Mulqueen (1973) found that mixing subsoil with topsoil can increase soil bearing capacity. Bodman and Constantin (1965) and Free et al. (1947) found that adding organic matter increased the moisture content at which maximum bulk density occurred.

Road Surface Matting Systems

The Forest Service recognizes the need to protect NFS road surfaces by inhibiting or limiting the development of ruts. A simple solution for the Forest Service (and other Federal land management agencies) may be to use road-surface matting systems. These systems can potentially improve the efficiency of hauling timber, and may also provide a suitable bearing surface for heavier loads than a road is designed for, such as roads associated with the energy sector (oil, gas wind turbines, etc.). Matting systems tend to be a low-cost alternative that enable temporary access across short sections of unstable soil while decreasing possible environmental impacts (figures 28, 29, and 30). Matting system components are readily available and are easy to implement. They have been tested and used for other applications, particularly in the energy sector and the military.

As Rushing and Howard (2011) stated, “Roadway matting systems offer solutions to a variety of needs for low volume roads, including temporary roads or construction platforms, stream crossings, bridging of muddy areas, protection of environmentally sensitive areas, military applications, and disaster recovery. However, choosing the right system or system type for a specific application can be challenging. All matting systems are not created equal; construction, economic, logistical, and performance characteristics can vary considerably from one mat to another. Numerous modern matting materials are commercially available.” The U.S. Army Engineering Research and Development Center (ERDC) in Vicksburg, MS, developed a decision matrix to enable potential users to make informed decisions for selecting matting systems (Rushing and Howard 2011).

Figure 28—High-density polyethylene mats (HDPE) are designed to reinforce existing soils, providing support for vehicular and pedestrian traffic and potentially providing a foundation for heavy equipment or temporary buildings.

Figure 29—The United States Government designed this mat using thin panels.

Figure 30—A section of a low-volume road reinforced with mats at the Apalachicola National Forest.

Summary

- Machine traffic causes soil disturbance, particularly when soil moisture is high, soil PR is low, and there are few rock fragments in the soil profile.
- Machine traffic during high soil moisture conditions can result in a variety of soil changes that alter water flow, gas exchange, root growth, and long-term productivity.
- Fine-textured soils are more susceptible to long-lasting compaction than coarse-textured soils, but climatic regimes that have a freeze-thaw cycle may work to reduce compaction.
- The number of equipment passes, soil moisture content, soil type (soil texture, structure, and rock fragment content), and SOM are the main factors that determine the degree of compactibility in the soil.
- Soil with more than 35 percent rock fragment content tends to have less compaction and faster recovery.
- Fine-textured soils (clay loams, clays, silty clay loams) tend to have severe compaction when soil moisture is more than 30 percent by weight and rock fragment content is less than 35 percent. Equipment used on fine-textured soils should have a ground pressure of less than 6 psi. To avoid soil compaction from equipment with a ground pressure of more than 6 psi, the soil should be dry (less than 20 percent moisture by weight), have a high rock fragment content, and/or have sufficient (more than 2 cm and continuous) surface organic horizons. Alternatively, using slash mats will also protect the mineral soil.
- Soil compaction has direct effects on soil physical properties, such as soil ρ_b, PR, and porosity or water moisture; soil scientists use these parameters to quantify soil compaction.
- Soil compaction results in reduced porosity, which results in limited oxygen and water exchange between the soil and the atmosphere, fewer microorganisms, and reduced plant growth. This results in an overall negative consequence for soil ecology and forest productivity and increases runoff and topsoil erosion.
- Increased soil ρ_b and ruts can increase soil erosion and landslide potential.
- Every soil requires a field capacity measurement. Information on the field capacity of soils enables interpretation for land management decisions.
- Soil moisture monitoring should be site-specific to understand disturbance impacts. Specifically, monitoring water content in the field during timber harvest season is crucial.
- The threshold value for soil trafficability (the soil moisture status) is the soil moisture content at which machine traffic is possible without causing unfavorable soil compaction. Soil scientists can use various criteria to assess the trafficability of soils, including shear strength, critical moisture content for maximum soil ρ_b, field capacity, saturation moisture content, and a combination of field capacity and rainfall amount.
- Soil scientists can use inexpensive TDR probes to collect soil moisture data in the field.
- There are simple field methods to measure PR or soil ρ_b to determine soil compaction levels.
- Plotting soil moisture versus PR or soil ρ_b can determine the threshold point. Soil scientists can use penetration resistance meausres to develop site-specific soil data to easily determine the support

capacity of roads and skid trails and to provide a baseline for remote monitoring data.

- Soil scientists can graph PR versus soil moisture content using an empirical model or by drawing a straight line between soil moisture (vertical line) and soil strength (horizontal line). The threshold for PR is the point of intercept.
- Soil scientists can use Excel data files and site-specific models to create data plots to determine the soil moisture and PR inflection point. The first component is the threshold value for soil trafficability, expressed in moisture content, stating whether machine traffic is possible. The second component is the period during which the soil is trafficable, which is a function of the soil moisture regime and the threshold value.
- After developing threshold values for each soil, soil scientists can use these values to predict when roads/trails should be opened with a low risk of damage or closed to avoid damage.
- Thresholds will vary with the types of vehicles, the amount of traffic, and soil moisture content.
- Machine traffic impacts surface organic horizons and mineral soil through topsoil displacement, compaction, puddling, platy structure, and rutting.
- Soil moisture has the most significant effect on the amount of damage machine traffic will cause to both surface organic horizons and the underlying mineral soil.
- Rock fragment content of more than 35 percent by volume can reduce impacts but may affect PR. Soils with high rock fragment content are less impacted by machine traffic, as are sandy soils or soils with high SOM content or plant debris.
- Surface organic horizons and slash can reduce machine traffic impacts.
- NTDP developed a remote wet weather soil monitoring system to monitor forest road conditions. Forest road uses are dependent on weather conditions.
- The fine-earth fraction of forest soil (less than 2 mm in diameter) is more critical for regeneration (i.e., seedling growth) than rock fragment content. It is an essential source of nutrients and water, improving seedling regeneration and root growth. The presence of coarse fragments changes the soil volume and helps reduce soil compaction and improve soil recovery.
- Soil textures with lower compactibility and better trafficability are sand, loamy sand, sandy loam, fine sandy loam, and gravelly sands.
- Soil textures with medium compactibility and medium trafficability are loam, silt loam, fine sandy loam, sandy clay loam, sandy clay, silty clay, silty clay loam, clay loam, and fine sandy clay loam.
- Soil textures with high compactibility and low (very poor) trafficability are sandy clay, silty clay, silty clay loam, and clay (soils with high clay content).
- Analyzing soils with different soil textures separately, rather than lumping them together, is crucial to forest site-specific timber harvesting. This helps soil scientists understand the unique local properties of soil texture, SOM, woody residues, soil moisture, and weather conditions to achieve management objectives.
- Using woody residues as slash mats can reduce the negative impacts of traffic on soil physical properties, and is also an effective method for controlling erosion on skid trails.
- If harvesting crews must skid logs under wet conditions, operations should stop once ruts form.
- NTDP tested lightweight road mat covers that soil scientists can use to avoid skidding and rutting on recreational roads.
- NTDP tested heavyweight road cover mats that soil scientists can use to mitigate damage from heavyweight timber harvesting equipment.
- Daily remote or onsite soil moisture monitoring throughout the year can help determine when soils can withstand machine traffic. This information will help soil scientists achieve management objectives.
- Decisions based on real-time scientific, valid, and defensible data will help protect the native surface of travel routes, protect water resources, and

maximize public access to public lands through trail and road systems.

- Remote sensing monitors (see figure 22) can help soil scientists make scientific judgments by implementing field water capacity as a "favorable" moisture level threshold to control compaction. They can improve access to roads and provide bridging across soft, wet, and sensitive areas during wet conditions to maximize the forest use.
- Coarse-scale, remotely sensed soil moisture estimates (such as data captured from NASA imagery) should not be used for this type of monitoring. The remote sensors we refer to in this document are sensors placed in the ground at specific locations with the capability of recording and transmitting soil moisture data (Etter and Plummer 2021).

Acronyms and Abbreviations

AET—actual evapotranspiration

ASAE—American Society of Association Executives

ATV—all-terrain vehicle

CI—cone index

cm—centimeters

CMC—critical moisture content

ERDC—U.S. Army Engineering Research and Development Center

HDPE—high-density polyethylene

kN—kilonewtons

kPa—kilopascals

LTSP—North American Long-Term Soil Productivity

m—meters

mm—millimeters

NFS—National Forest System

NGP—nominal ground pressure

NTDP—National Technology and Development Program

OHV—off-highway vehicle

ρ_b—bulk density

PET—potential evapotranspiration

PPT—precipitation

PR—penetration resistance

psi—pounds per square inch

SMR—soil moisture regimes

SOM—soil organic matter

TDR—time domain reflectometer

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This report is a desktop guide for techniques to quantify the relationship between soil compaction conditions resulting from timber harvesting. It includes methods for evaluating and preventing compaction.

Keywords: hydrology, penetrometers, soil bulk density, soil compaction, soil disturbance, soil microbes, soil moisture, soil organic matter, soil porosity, top soil

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