USDA Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Rocky Mountain Research Station | General Technical Report RMRS-421 | January 2021

Soil Sustainability and Harvest Operations: A Review

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Crawford, Leslee J.; Heinse, Robert; Kimsey, Mark J.; Page-Dumroese, Deborah S. 2021. Soil sustainability and harvest operations: A review. Gen. Tech. Rep. RMRS-GTR-421. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39 p. https://doi.org/10.2737/RMRS-GTR-421.

Abstract

Soil productivity is essential to the sustained production of forest ecosystem goods and services. Timber harvests may lead to negative ecological impacts to the soil environment, thus reducing both soil and forest long-term productivity. Impacts caused by timber harvests are site-specific, and soil monitoring at various times post-harvest is critical to understanding both short- and long-term damage. Soil compaction is one of the most important issues that arise from harvest operations because it can alter many soil properties and processes including soil bulk density, gas diffusivity, and water holding capacity. Changes in these factors, and others, can lead to lower plant productivity. Additional impacts from timber harvests include soil displacement, rutting, and puddling (smeared soil pores). Soil and site characteristics influence the degree to which the soil is prone to disturbance, as well as rock-fragment content. Understanding the degree, extent, distribution, and duration of soil disturbance is key to determining how long the impacts may last and whether soil restoration activities are needed. We highlight the literature about long-term soil recovery after timber harvests and review the types of impacts, harvest operation methods, and recovery times.

Keywords: Soil disturbance, timber harvest, soil management, soil recovery

Cover photo

Rut from ground-based timber harvesting on the Malheur National Forest, Oregon. Rut depth averages 30 cm (photo: Leslee J. Crawford, USDA Forest Service).

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Acknowledgments

The authors would like to thank Amy Unthank, Natural Resources and Planning Staff Office, Malheur National Forest, for her support during data collection and writing of the original thesis.

Contents

Introduction

Timber harvests can negatively impact soil and affect long-term productivity due to the use of heavy machinery and harvest operations which can compress the soil (compaction), displace or mix the surface organic matter with the mineral soil, or expose low-productivity subsoil. These soil disturbances are a concern for both foresters and soil scientists, who seek to maintain or increase site productivity. The degree and extent of soil disturbance are often site-specific and the distribution across a site depends on the type of logging system (e.g., ground-based operations, skyline or helicopter harvest systems) and silvicultural prescription (Lacey 1993; Lacey et al. 2003). For forest managers, one goal is to minimize or mitigate soil disturbance and then validate the degree and extent of disturbance on soil properties and site processes (Croke et al. 2001) to reduce the risk of negative impacts (e.g., increased runoff, reduced productivity).

Soil Disturbance

Soil disturbance most commonly occurs as compaction resulting from ground-based harvesting and slash disposal equipment. Soil displacement and erosion, rutting and puddling, and platy structure are some other common forms of soil disturbance. The effects of soil disturbance on site productivity or hydrologic function are related to the degree, extent, distribution, and duration of impact (Craigg and Howes 2007). **Degree** refers to the percent change in a soil property. **Extent** refers to the amount of land surface occupied by the change and is expressed as a percentage of the harvest unit. **Distribution** of soil disturbance within a harvest unit determines whether the change in a soil property is widespread or concentrated. Duration is the length of time that disturbance effects persist (Craigg and Howes 2007; Han et al. 2009).

Compaction

All soils are highly susceptible to compaction except for a few unique, strongly cemented soils. Soil compaction is defined as the “densification of an unsaturated soil body by the reduction of its air-filled porosity, generally resulting from the application of compressive forces (pressure)” (Hillel 2008: 265). Forest soils are prone to compaction due to their loose, friable structure and high porosity. Soil compaction occurs from a variety of natural and human-caused conditions. Although timber harvesting causes the greatest impacts, it is not the sole cause in a forest environment. As Howard W. Lull with the Forest Service, U.S. Department of Agriculture, said, “Whenever you put a foot down on forest or range land, you are—to a degree—compacting the soil” (Lull 1959: 1). Soil can be compacted in concentrated animal trails or due to freeze-thaw and wetting-drying cycles (Cambi et al. 2015; Hillel 1998). However, the most common cause of soil compaction is human activities, such as timber harvesting, that increase the amount of traffic (e.g., off-road vehicles, harvest equipment; Cambi et al. 2015). Despite being a common occurrence and universal process, soil compaction is a concern in forested sites where harvest activities occur (Lull 1959). The degree of soil compaction is related to soil texture (Page-Dumroese et al. 2009), soil moisture (Froehlich and McNabb 1983), harvesting system (Adams and Froehlich 1984), amount of slash on the soil surface (Han et al. 2006; McMahon and Evanson 1994; Wronski 1980), and the number of machine passes (Han et al. 2006; McDonald and Seixas 1997; Soane 1986). Concerns about the effects of compaction extend to reductions in vegetation and root growth, nutrient cycling, and microbial functions (Bodelier et al. 1996; Cambi et al. 2015; Frey et al. 2009; Startsev and McNabb 2000).

Several principles determine where and when soils are at the greatest risk of compaction. These principles are derived from building and road construction research focused on achieving desired levels of compaction (Johnson et al. 2007). In construction, engineers tend to use either kneading compaction (compression) or vibratory compactors to compact the soil to a desired level. These construction methods are also applicable to a forest environment and logging equipment impacts. For example, kneading compaction is typically accomplished by using a sheepsfoot roller that gradually increases the amount of pressure until the desired compression is achieved. In forest operations, this is similar to the effects of rubber-tired skidders, but the pressure exerted is far less than that exerted by a sheepsfoot roller (Johnson et al. 2007). Engineering research also explores soil properties that affect compaction. These properties are soil initial strength and bulk density, particle size distribution, structure, moisture content, organic matter content, and rock-fragment content.

All harvest equipment traffic will lead to an increased bulk density (Han et al. 2006). The extent of impact on skid trails can be variable with bulk density increases in the skid tracks (if present), throughout the skid trail width (up to 5 m in width), and up to 2 m outside the trail (Solgi et al. 2020). Unfortunately, soil compaction occurs within the first few passes of machinery used for skidding or forwarding during a timber harvest operation (Cambi et al. 2015; Han et al. 2006). After timber harvesting and site preparation operations are complete, the extent of compaction within a harvest unit can range from 10 to 70 percent (Cambi et al. 2015; Frey et al. 2009; Grigal 2000; Picchio et al. 2012). In addition to changing soil physical properties, increased compaction can lead to substantial alterations of soil biological and chemical properties (Cambi et al. 2015), such as less gas exchange and water infiltration, reduced root and tree growth, lowered decomposition, altered nutrient cycling, and a general decline in soil microbes. These range from short- to long-term effects, depending on the degree of soil compaction.

For most mineral soils, low initial bulk density values result in a significant amount of soil compaction during harvest and site preparation operations, whereas soils with high initial bulk density have a lower likelihood of compaction (Cambi et al. 2015; Hillel 1998; Page-Dumroese et al. 2006; Powers et al. 2005; Williamson and Neilsen 2000). For example, Powers et al. (2005) found that soils with a bulk density greater than or equal to 1.4 Mg m^{-3} have the lowest capacity for compaction during harvest operations because the soil is already dense. Many forest soils have lower initial bulk densities than 1.4 Mg m^{-3} resulting from high levels of organic matter from litterfall and microfauna and macrofauna incorporation into the mineral soil (Powers et al. 2005). Soils with a low bulk density and a steady input of organic matter form a well-developed crumb structure with high porosity, which are desirable conditions for mineral A horizons. These properties are critical for maintaining vegetation growth, water infiltration, and water storage (Cambi et al. 2015; Corti et al. 2002).

Soil Displacement and Erosion

Once soils reach saturation, soil displacement is often more detrimental than compaction as a disturbance feature (Binkley and Fisher 2013). Soil displacement is the movement of soil from one place to another by harvest equipment and is sometimes confused with soil erosion. Displacement occurs when equipment turns on soft soil or when equipment moves topsoil from one location to another. Displacement can negatively affect numerous site and soil characteristics by altering short- or long-term soil quality or site productivity. For example, organic horizons improve site productivity because they act as a mulch, drive nutrient cycling, and are home to many microorganisms and macroorganisms (Martin 1988), but they can easily be displaced during harvest operations. Perhaps the most important attribute of surface organic horizons and organic matter within the soil profile in seasonally dry forest soils is that they hold a great deal of water; 1 to 6 percent organic matter can hold 5 to 25 percent available water (Hudson 1994).

Erosion (e.g., fig. 1) is defined as the detachment and removal of soil particles from the soil surface by running water or wind (Hillel 2008). It can be exacerbated by displacement because of the piling of loose soil on the soil surface, but it can also be a result of skid trail construction on steep slopes that allows for accelerated water movement downslope (Johnson et al. 2007). On slopes, removal of overstory trees can lead to erosion where ground cover or surface organic horizons are removed due to traffic. Soil disturbance and erosion can further be increased if stumps are pulled for bioenergy or to reduce a threat of disease (Page-Dumroese et al. 1999). Over time all roots decompose and this loss of root structure within the soil profile can exacerbate soil erosion, particularly shallow landslides on steep slopes (Amman et al. 2009). In addition, an increase in the loss of wood (including roots) after harvesting has been attributed to termites on sites where they occur, which could lead to increased erosion after harvesting or wildfire (Jurgensen et al. 2019; Martin 1988).

Rutting and Puddling

Ruts (e.g., fig. 2) are deep tracks created by traffic (Froehlich et al. 1986) and are the consequence of vertical and horizontal soil displacement when the soil is beyond its critical water content (Cambi et al. 2015; Hillel 1998; Horn et al. 2007; Vossbrink and Horn 2004; Williamson and Neilsen 2000). Soils at or near saturation undergo shear failure when a load is applied, resulting in the formation of a rut. Rutting is common during harvest operations on both wet and dry soils and the extent, degree, and duration of the ruts are dependent on soil texture,

Figure 1—Erosion on a skid trail during salvage logging after the Canyon Creek Complex fire on the Malheur National Forest, Oregon (photo: Leslee J. Crawford, USDA Forest Service).

rock fragments, organic matter content, and soil moisture. Ruts form either in the middle or on the sides of skid trails (Cambi et al. 2015; Horn et al. 2007). Further, excessive traffic can move soil from under the wheel into berms along the skid trail.

One concern with ruts is the interruption of water infiltration, which leads to pools or erosion after harvesting. On flat terrain, ruts act as rain collection basins when the water table reaches the surface or pools because of altered

Figure 2—Rutting on the Malheur National Forest, Oregon. Excessive traffic can cause rutting, particularly on skid trails that lead to a log landing and when slopes are greater than 20 percent (photo: Leslee J. Crawford, USDA Forest Service).

pore structure. On slopes, ruts are preferential flow routes for overland flow during and after major rain events or during spring snow melt (Cambi et al. 2015; Christopher and Visser 2007; Startsev and McNabb 2000). Continuous erosion can result, thus making the ruts deeper and longer (Cambi et al. 2015; Schoenholtz et al. 2000). Rut formation has been linked to the volume of timber removed and the mass of the harvest equipment. Ideally, the lightest possible machinery should be used on soils that have a low bearing capacity, are shallow to bedrock, or have low rock-fragment content (Cambi et al. 2015). Not all ruts are formed during equipment traffic, and excessive cattle grazing can also cause ruts (Lull 1959).

Disturbance that causes puddling frequently destroys surface soil structure, resulting in a dense crust that can be similar to a thin, compacted layer (e.g., inhibition of water infiltration; Binkley and Fisher 2013). Soil puddling is "the destruction of soil aggregates into ultimate soil particles" (Sharma and DeDatta 1986: 139) when soils are at the liquid limit and have a liquid response to external forces. Soil aggregates are destroyed and churned into plastic mud (Beacher and Strickland 1955; Ghildyal 1982; Swanson et al. 1955). Puddling, ruts, and compaction are all interrelated when soils are impacted by traffic (Aust et al. 1995). Puddling occurs because water-dispersed soil particles settle at different rates, allowing clay particles to orient parallel to the soil surface. This arrangement of clay particles leads to soil pores that are sealed, reducing infiltration. This condition commonly occurs in ruts following tire slippage.

Reduced water infiltration from puddling can lead to erosion (Cambi et al. 2015; Rab 1996). Additionally, puddling was found to reduce seed germination and increase both loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) seedling mortality rates following harvest operations in the southeastern United States (Binkley and Fisher 2013).

Platy Structure

Platy soil structure is another common result of traffic on forest soils. Platy soil structure is identified as relatively thin horizontal peds or plates that may be found in surface and subsurface horizons (Binkley and Fisher 2013). It is the result of both shearing and compacting forces that destroy the soil's natural structure. A consequence of this action is a reduction of total pore space. Platy soil structure can prevent roots from penetrating these layers. Large roots may be able to penetrate platy layers, but fine or medium roots cannot (Napper et al. 2009).

Soil Properties Influencing Disturbance

Particle Size Distribution

In several laboratory and field experiments, Krynine (1951) demonstrated that during compaction maximum soil densities were related to particle size, optimum soil moisture content, and equipment type. After traffic, soils with a wide range of particle sizes generally had the highest soil density due to soil particle reorientation that allows smaller particles to pack into voids between larger particles (Cullen and Montagne 1981; Li 1956; Miller et al. 2004). Fine-textured soils are more susceptible to compaction than coarse-textured soils (Binkley and Fisher 2013; Cambi et al. 2015; Hillel 1998; Wästerlund 1985). Fine-textured soils that contain considerable amounts of shrink-swell clays can reduce compaction over time through expansion and contraction (Binkley and Fisher 2013).

Soil Structure

Soil structure is a term used to define the ways that individual particles of sand, silt, and clay arrange themselves into aggregates. Aggregates are bound by physical, chemical, and biological processes, and aggregation may be broken by mechanical stresses (e.g., compaction or excessive disturbance). Well-aggregated soils often have a larger amount of soil organic matter and these two factors minimize the impacts of heavy machinery (Cambi et al. 2015; Page-Dumroese et al. 2006).

Soil Moisture

Soil moisture content is an important factor to consider during logging and site preparation operations. Dry soil has a high degree of particle-to-particle bonding, allowing the soil to resist deformation due to friction (Cambi et al. 2015; Hillel 1998). Moist soils often have a greater amount of compaction because water lowers soil resistance to deformation when soil is exposed to shear forces. Soil with less than 15 percent soil moisture content can support higher ground pressure from vehicles, which results in less soil compaction in the surface 10 cm of mineral soil (Han 2005; Johnson et al. 2007). Further, during winter harvest operations soil impacts will be low if the mineral soil is frozen to depths of 10 to 15 cm (Flatten 2002; Johnson et al. 2007). In addition to frozen soil, adequate snow cover (≥15 cm) will minimize soil impacts from ground-based systems (Johnson et al. 2007).

Slope

Soil compaction increases with increasing slope. Tire pressure is not evenly distributed on steep slopes, which generally means that compaction occurs under the load-bearing wheels or tracks (Cambi et al. 2015). Several authors have found that soil bulk density or resistance to penetration is higher post-logging when slopes exceed 20 percent (Agherkakli et al. 2010; Najafi et al. 2009; Solgi et al. 2020). In addition, pulling a load of logs uphill results in greater soil compaction; slope gradients of 0 to 10 percent result in the greatest compaction, followed by slopes ranging from 10 to 20 percent (Jourgholami et al. 2014). Loaded equipment traveling downhill on a 10 to 20 percent slope caused the smallest degree of soil compaction (Jourgholami et al. 2014).

Soil Properties Affected by Disturbance

Soil Porosity and Infiltration

Soil porosity is a measure of open spaces between soil particles. Traffic on forest soil can reduce overall porosity up to 60 percent (Ampoorter et al. 2007; Ares et al. 2005; Cambi et al. 2015; Demir et al. 2007; Frey et al. 2009; Pichhio et al. 2012; Solgi and Najafi 2014) and reduce macropores (>0.08 mm) to the size of micropores (<0.08 mm) (Frey et al. 2009; Seixas and McDonald 1997). Total porosity is the sum of micropores and macropores. Soil physical, chemical, and biological processes depend on pores to move water and gases within the profile or for root penetration. Porosity is expressed as the percentage of the total bulk soil that is not occupied by the solid particles (Sulzman and Frey 2002). When soil is compacted, pore space is reduced as the open spaces are filled with solid particles. Water transport through the soil profile is strongly influenced by macroporosity and less by the total porosity. Thus, macropores are vital for the movement of water and air within the soil. Macropores are formed by roots, worms, and insects, and macropore amount and size depend on soil texture.

Increased micropore space can lead to increased soil volumetric water content. In contrast, air content, water infiltration rate, and saturated hydraulic conductivity all decrease (Binkley and Fisher 2013; Greacen and Sands 1980). Consequently, compacted soils may retain more water than undisturbed soils, but this capacity does not translate to more water available for the plants (Corrao et al. 2016). This relationship (more water, but less available for plants) occurs because more water is held in micropores at high matric potentials and is difficult for root uptake (Cambi et al. 2015).

One method for assessing the interrelationships of porosity, water, and plant growth is the least limiting water range (LLWR; da Silva et al. 1994; Letey 1958). The LLWR calculation is based on soil resistance to penetration and the water release curve to determine when water is no longer available for plant growth. Calculating LLWR can be a useful indicator of soil quality (Lapen et al. 2004; Zou et al. 2000), but it requires monitoring soil water conditions and knowing the field capacity and permanent wilting point of each soil.

Air and Gas Diffusivity

A reduction in macropores from compaction reduces the overall pore space for gas and air exchange between the soil profile and the atmosphere. For soils to sustain aerobic life, oxygen consumed by microorganisms and roots must be replaced and porosity should be such that it facilitates the removal of carbon dioxide and other metabolic byproducts, such as ethylene. Soil respiration maintenance involves a continuous gas exchange between the soil and the atmosphere. The main pathway for gas exchange is through the network of air-filled pores connecting the surface soil to deeper layers. Connectivity of macropores is important for ongoing gas and air exchange (Hillel 1998).

Uncompacted soils usually have increasing levels of carbon dioxide with depth due to a decrease in soil diffusivity (Bekele et al. 2007; Cambi et al. 2015; Certini et al. 2003). If the soil surface is compacted, gas exchange is reduced. However, the amount of soil organic matter also influences air and water flux (Kuncoro et al. 2014). Generally, soil organic matter has a high porosity, resulting in rapid diffusion of air and gases between the soil and the atmosphere (Bekele et al. 2007). Traffic that caused severe soil compaction (i.e., deep ruts, topsoil displacement, altered structure) reduced soil porosity, which resulted in the reduction of air permeability by 96 percent in the top 5 to 10 cm of the profile (Frey et al. 2009). In contrast, moderate compaction (i.e., churned soil churned, moderate compaction, partial topsoil removal) resulted in a permeability decline of 88 percent, and lightly compacted areas had only a 51 percent reduction (Frey et al. 2009).

Machine harvesting has a complex effect on microbial carbon dioxide production and soil diffusivity (Bekele et al. 2007; Cambi et al. 2015; Fernandez et al. 1993; Goutal et al. 2012). In most uncompacted soil there is a lower ratio of carbon dioxide to oxygen relative to compacted soils because of higher diffusivity in undisturbed soils (Cambi et al. 2015; Goutal et al. 2013). The results of a higher ratio of carbon dioxide to oxygen are inhibited root respiration and growth (Qi et al. 1994; Viswanathan et al. 2011). In turn, nutrient uptake is inhibited, resulting in reduced overstory growth (Cambi et al. 2015; Conlin and van den Driessche 2000; Kozlowski 1999). During periods of high rainfall or snowmelt, soil compaction generally leads to anoxic (lacking oxygen) conditions, consequently depressing soil respiration and promoting production and release of the powerful greenhouse gas methane into the atmosphere (Cambi et al. 2015).

Hydraulic Properties

Soil hydraulic properties are fundamentally important to describe water, energy, and carbon exchange processes between the soil and the atmosphere (Ek and Cuenca 1994; Montzka et al. 2017; Xue et al. 1996). These properties are linked to soil disturbance through changes in pore size, amount, and connectivity. Hydraulic properties regulate the relative magnitude of water evaporation, water infiltration, and gas fluxes; monitoring these variables can help managers estimate the amount of water held in the soil at any time (Montzka et al. 2017; Vereecken et al. 2016). These factors are important for describing water flow in variably saturated soils (Hendrayanto et al. 2000).

Reduced hydraulic conductivity, especially in surface soils, may reduce water infiltration rates and increase waterlogging (anaerobic soil conditions), standing water on flat terrain, or surface runoff and erosion on steeper slopes (Cambi et al. 2015; Jansson and Johannson 1998; McFero Grace et al. 2006). Stagnant water or evidence of stagnant water in late summer may indicate compaction and reduced porosity. In mineral soils, features that indicate anoxic conditions include depleted concentrations of iron or manganese (or both) (Cambi et al. 2015; Herbauts et al. 1996), and localized changes in soil color reflect chemical reduction of primarily iron in a low-oxygen environment (Callahan 2015).

Measuring Disturbance

Measuring the level of disturbance of puddling, rutting, displacement, and erosion can easily be done through visual assessment (e.g., Page-Dumroese et al. 2009) that examines the extent and severity of each feature. After disturbance characteristics are described, key soil types in a climatic region can be selected to validate how these features alter soil processes and vegetation. Soil disturbance that removes both the surface organic horizons and topsoil should be considered in the context of site nutrient supply, coarse fragments, slope, climatic regime, and topography.

Bulk Density

Compaction is often measured with a soil core to determine bulk density. Soil bulk density is the dry mass of soil per unit volume (Hillel 2008), and increased soil compaction is expressed as an increase in bulk density (Ares et al. 2005). The bulk density value from the harvested unit is then compared to a reference soil with similar properties (e.g., texture, organic matter content), which is important to properly characterize the level of compaction and potential impacts to plant reproduction or hydrologic function (Håkansson and Lipiec 2000; Zhao et al. 2010). Comparing soil bulk density on a site-by-site basis (disturbed vs. reference) characterizes the change in soil bulk density associated with land management practices (Håkansson and Lipiec 2000).

Resistance to Penetration

Bulk density is a useful method but can be a laborious and time-intensive endeavor. As an alternative, soil strength measurements (Herrick and Jones 2002; Viscarra Rossel et al. 2011) are often used to determine soil resistance to a penetrating probe. Soil strength (or resistance to penetration) reflects the frictional forces associated with root development and, ultimately, vegetation productivity (Smith et al. 1997). Soil strength also defines a soil's ability to resist compaction (Greacen and Sands 1980). A recording penetrometer (0–60 cm depth) is one method for determining soil resistance. Pocket penetrometers are another tool used for measuring the surface 10 cm of soil. They are lightweight and can quickly assess compaction in skid trails or landings (Amacher and O'Neill 2004). Both types of penetrometers have the advantage of being a relatively rapid assessment of compaction, but soil moisture, rock fragments, and roots sometimes limit its use (Bennie and Burger 1988; Spain et al. 1990). Another disadvantage of using a penetrometer is that the level of soil compaction may exceed the limits of the equipment (Amacher and O'Neill 2004). However, if the goal is to measure compaction levels during harvesting or when soil moisture is consistent, then a penetrometer can be an effective tool. Low-tech versions of a penetrometer are a shovel or rod. These can be inserted into the soil to determine the relative level of compaction, but the assessment must be calibrated to a reference soil. Calibration to the physical resistance of each soil type is crucial for accurate assessments with the shovel or rod soil penetration method (Page-Dumroese et al. 2009).

Coarse Fragments

Rock, coarse roots, and steep slopes make the measurement of compaction difficult (Page-Dumroese et al. 1999), but a high rock-fragment content (>19 mm size material) can also provide a buffer for the fine soil fraction (<2 mm size material) to resist compaction (Poesen and Lavee 1994; Rücknagel et al. 2013) (fig. 3). The type and size of the rock fragments (e.g., gravel, cobbles) will determine how susceptible the fine fraction may be to compaction from traffic. A high coarse-fragment content may be one reason soil compaction is less on some soil types (Williamson and Neilsen 2000). Corns (1988) found that coarse-textured, gravelly soil resisted compaction from traffic during timber harvest. When a dynamic load was applied to a soil with a loamy texture, rock fragments decreased compaction of the fine fraction and smaller rock fragments were the most effective for limiting compaction (Poesen and Lavee 1994; Saini and Grant 1980). In a laboratory experiment, Magier and Ravina (1984) determined that clay soils, with a moderate rock-fragment content of 25 to 30 percent by volume, had a positive effect on growth of trees and root system development by preserving a lower soil bulk density and maintaining porosity. However, Magduff and Garti (1971) observed that plant growth was limited by layers of densely packed rock fragments. Generally, greater amounts of rock fragments aid in limiting compaction, particularly in fine-textured soils (Poesen and Lavee 1994). An assessment of the amount and distribution of rocks within the soil profile can help land managers anticipate potential impacts (Ravina and Magier 1984).

Figure 3—Coarse rock fragments on the Malheur National Forest, Oregon. Coarse fragments on or in the mineral soil help buffer the impacts of harvest equipment (photo: Leslee J. Crawford, USDA Forest Service).

Rock-fragment content is also important for estimating soil nutrient pool changes after logging. Bulk density measurements should be adjusted to account for a high rock-fragment content (Jurgensen et al. 2017; Page-Dumroese et al. 1999).

Harvest Systems, Equipment Type, and Soil Disturbance

Soil properties and site characteristics are key components influencing the degree of soil impacts and disturbance. The extent of soil impacts is influenced by the timber harvest method and equipment used during harvesting. Harvest method and equipment also affect the degree, extent, duration, and distribution of soil disturbance (Han et al. 2009).

Harvest System and Equipment

Harvest systems are typically classified by how logs are transported from where the tree was felled to the landing. Harvest transport systems that are commonly used include ground-based logging systems, skyline or cable yarding, helicopter or aerial, and tethered logging (Chase et al. 2019). Ground-based systems drag or carry logs from the stump to the landing by driving over the harvest unit on or off skid trails. Cable or skyline harvest systems use an overhead cable that is attached to a stationary machine. This overhead cable is used to drag or haul the logs to the landings. Helicopter or aerial logging systems lift the logs above the ground and into the air by a helicopter (MacDonald 1999).

On steep slopes logging equipment can be tethered to an anchor near the top of the slope to increase safety and productivity (Sessions et al. 2017).

Ground-based Harvesting

Mechanized ground-based timber harvest systems have the largest disturbance effect on soil as compared to skyline, helicopter, or tethered operations (Bockheim et al. 1975; Chase et al. 2019; Laffan et al. 2001; Miller and Sirois 1986; Miller et al. 2004; Page-Dumroese et al. 2006; Reeves et al. 2013). Ground-based logging is responsible for the greatest extent and degree of soil disturbance in the Northern Region of the U.S. Department of Agriculture, Forest Service (Reeves et al. 2011), and these results are consistent with other studies (Bockheim et al. 1975; Miller et al. 2004).

Harvest equipment used for ground-based logging varies greatly in configuration, soil-wheel contact area, tire pressure, and dynamic shear forces. Most ground-based equipment ranges from 5,000 to 40,000 kg in mass (Cambi et al. 2015; Eliasson 2005; Jansson and Wästerlund 1999) and, of course, greater equipment mass usually translates to greater soil pressure, resulting in greater levels of compaction (Cambi et al. 2015). Ground-based operations are used on slopes that are less than 35 percent. However, some specialized tracked equipment can operate on slopes up to 50 to 60 percent. The slope limitations for ground-based harvest operations are in place because as slopes become increasingly steep, the equipment may become unstable, especially during turning (MacDonald 1999). The extent of compaction from ground-based timber harvests varies. For example, crawler tractors or rubber-tired skidders typically compact soils on 20 to 35 percent of the harvested area (Adams 1990; Steinbrenner and Gessel 1955), but harvest design, using old skid trails, or other site factors may limit soil impacts.

Two common ground-based harvest systems are whole-tree (WT) and cut-to-length (CTL). As the name implies, WT removes the entire aboveground portion of the tree from the site and has been a preferred method for reducing fuels in high-density stands and, thereby, reducing fire hazard (Han et al. 2009). Despite the benefit of reducing fuel loads, there is a high potential for both soil compaction and other types of soil disturbance. Skidders moving trees from stump to landing tend to sweep the organic horizons from the skid trails, exposing the mineral soil and increasing the degree of compaction (Han et al. 2009; Hartsough et al. 1997), but this activity is usually confined to skid trails. A feller-buncher and rubber-tired skidder operation on the Colville National Forest in Washington caused detrimental soil disturbance to 42 percent of the harvest unit; the extent of disturbance is similar to results from the Wenatchee National Forest, also in Washington (Laing and Howes 1988). Skidder systems can disturb a greater area, with more severe soil compaction, than log forwarder systems used for CTL harvesting (Lanford and Stokes 1995).

Cut-to-length systems use a harvester and a forwarder. The harvester has a cutting head attachment that fells the tree and removes the branches and top. The branches and tops, or slash material, are placed in front of the harvester across the skid trails (Hwang et al. 2020). The tree is then cut into logs and left to be retrieved by the forwarder. In a CTL system, the harvester and forwarder use the same skid trails (Hwang et al. 2020). Logging residues may be distributed within the stand after the timber harvest has concluded, thereby recycling nutrients in the needles and twigs back into the soil (Hartsough and Cooper 1999). Because the slash mat can act as a cushion for the soil, CTL operations generally have a lower impact on the soil (Gingras 1994; Han et al. 2006; Kirk 1995; Lanford and Stokes 1996).

Recently CTL harvesting has been becoming even more popular due to the potential to significantly reduce site-related problems. Cut-to-length can limit the amount of compaction typical of skidding or forwarding operations (Hwang et al. 2020). Reducing the amount of land over which heavy machinery drives lessens the extent of soil compaction in the harvested stand. McNeel and Ballard (1992) found that in a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand CTL had little detrimental impact on the soil, and skid trails occupied less than 20 percent of the harvest unit area. During a thinning operation in Oregon, Bettinger et al. (1994) note that the extent of CTL skid trails was 23 percent, but that cumulative effects analyses should be completed to evaluate past, present, and future site effects.

Soil disturbance data from the Kootenai National Forest in northwestern Montana from the early to mid-1990s suggest that past timber harvest operations resulted in more soil disturbance than current practices. In the past, bulldozers would create very large (>0.1 ha) burn piles that also included surface organic horizons and, often, the fertile topsoil. As of recently, however, forwarders and excavators are being used for fuels reduction treatments. Fuels reduction treatments include making smaller burn piles using a grappler; piles are only 0.05 ha or smaller (Gier et al. 2018).

Burning slash piles has been one concern for soil disturbance monitoring. Large piles can have long-lasting effects on the soil with burn scars lasting up to 50 years (Rhoades and Fornwalt 2015). However, jackpot burning, a modified form of a broadcast burning, can reduce the amount of detrimental soil disturbance (Gier et al. 2018). Further, smaller piles (<5 m in diameter) can be rehabilitated with mulches and seeding (Rhoades et al. 2015).

Operator experience is another component of reducing soil impacts (Reeves et al. 2011). Soil scientists may assess soil conditions before harvest operations and prescribe objectives for soil conditions, but logging operators are the key to limiting soil disturbance during operations (Curran et al. 2007). Logging operators' ability to skillfully maneuver on slopes with fully loaded equipment will determine the degree of soil compaction (Cambi et al. 2015). However, cost and efficiency of harvest operations must also be considered (Akay et al. 2007).

Cable Yarding Operations

Timber harvest operations conducted on steep slopes involve felling trees with a chainsaw, attaching them to a cable, and then extracting them by partially or completing suspending them above the soil (Garren et al. 2019). When logs are completely suspended, there is less overall soil disturbance than in ground-based operations (Allen et al. 1999; Cromack et al. 1978; Dyrness 1965; Miller and Sirois 1986; Reeves et al. 2011; Tepp 2002). However, partial suspension means that logs are dragged across the soil, resulting in greater amounts of exposed mineral soil and rutting (Youngblood 2000). This is particularly pronounced on finer-textured or ash-cap soils (Youngblood 2000). Use of a helicopter to remove trees from steep slopes results in little soil disturbance as compared to skyline or ground-based harvest systems (Reeves et al. 2011).

Tethered Logging Operations

Tethered logging operations have been used widely in Europe (Bombosch et al. 2003) and New Zealand (Amishev and Evanson 2010) for the last 15 years on slopes that are greater than 60 percent. In the United States, Sessions et al. (2017) presented a theoretical model for using tethered and untethered feller bunchers that considered soil strength limitations. A tethered assist allows equipment to operate on slopes that would be considered unsafe for equipment or potentially destructive to soils (Sessions et al. 2017). In the Pacific Northwest a study was conducted to examine the effects of tether logging on soils in Washington and Oregon. Chase et al. (2019) compared soil disturbance of tethered logging to cable- and winch-assisted operations on steep slopes. They found that stream-adjacent disturbance and soil disturbance associated with tethered logging on steep slopes is greater than that caused by conventional steep-slope harvesting practices, such as cable logging, but similar to disturbance assessed from untethered equipment (Chase et al. 2019). In general, however, soil disturbances were less than regulatory thresholds and negative impacts were not excessive. Soil disturbance from this type of harvest operations is compaction and displacement from traffic and track slippage (Belart et al. 2019).

Slash Mats and Machine Passes

Soil disturbance can be minimized by using slash mats and limiting the number of machine passes on a skid trail. The maximum amount of soil compaction occurs within the first 10 passes of harvest machinery (Froehlich et al. 1980; Gent and Ballard 1984; Han et al. 2006, 2009); therefore, limiting the impacts by using residual materials produced during harvesting can be important. Slash mats are made using woody residues from harvest operations and the residues scattered across the skid trails (Han et al. 2006). Tree tops and branches are more effective at reducing compaction than wood chips or sawdust because they support the weight of the equipment above the soil (Akay et al. 2007; Cambi et al. 2015). The machine load is distributed over a greater area than the actual equipment footprint, thus lowering the equipment pressure per unit of contact area (Ampoorter et al. 2007; Cambi et al. 2015; Labelle and Jeager 2011), and these materials provide a cushioning layer. The effectiveness of slash mats is dependent on soil moisture, number of passes, terrain characteristics, slash type and density, and soil profile thickness (Akay et al. 2007; Carter and McDonald 1997; Han et al. 2006; Lanford and Stokes 1995; McDonald and Seixas 1997; McMahon and Evanson 1994; McNabb and Boersma 1996; McNabb et al. 2001;

Wood et al. 2003). Slash mats may also be effective in reducing soil rutting on both slopes and flat terrain (Tepp 2002). Further, slash mats reinforce skid trails to alleviate the potential for rutting (Eliasson and Wästerlund 2007; Han et al. 2009).

On wet soils or soils with a low bearing capacity, the use of slash mats is ideal for limiting soil disturbance (Cambi et al. 2015; McDonald and Seixas 1997). For example, in a CTL harvest operation, slash mats can cover up to 70 percent of the skid trail area (Han et al. 2006; Vidrine et al. 1999). It is critical to understand the density and quality of material used so that they provide the greatest level of equipment support (Akay et al. 2007).

Slash mats lose their effectiveness as the number of machine passes increases; effectiveness also depends on equipment type and slash mat material (Akay et al. 2007). Small-diameter slash tends to be crushed into smaller pieces that can no longer distribute the equipment mass or absorb vibration and can result in soil compaction (Han et al. 2006). In addition, the decrease in the support capacity of slash mats with the number of passes was not significant at a soil depth of 20 cm (Akay et al. 2007). In the United Kingdom on a clay loam soil, Hutchings et al. (2002) found that a slash mat lost its effectiveness for reducing compaction after 12 equipment passes. The number of passes of machinery across a harvest stand is an important factor that contributes to the degree, extent, duration, and distribution of soil compaction, but these effects can be limited with slash mats.

The Unique Challenges of Volcanic Ash-cap Soils

Volcanic ash, from the eruption of Mount Mazama in southern Oregon approximately 7,700 years ago, is an important component of many Pacific Northwest soils, and ash-cap soils are a valuable resource for their economic impact and ecosystem services (McDaniel and Wilson 2007). This volcanic ash overlies the residual mineral soil to varying depths, depending on geographic location, topographic position, and vegetation community (McDaniel et al. 2018). In terms of texture, volcanic ash soils are a silt or sandy loam (Johnson et al. 2007) and are known for ample water holding capacity, which enhances site productivity (Brown and Lowenstein 1978; Garrison-Johnston et al. 2007; Mital 1995). Although they are fine textured, clay content is low (0–27 percent clay) and indicative of a soil with very little cohesion and a high risk of soil disturbance. Thus, volcanic ash-influenced forest soils tend to be more susceptible to compaction, rutting, and mixing (Allbrook 1996; Cambi et al. 2015; Cerise et al. 2013; Page-Dumroese 1993; Parker 2007).

Volcanic ash-cap soils, either mixed with mineral soil or in pure deposits, are located in mid- to high-elevation forest soils (Geist and Cochran 1991; Löf et al. 2019; McDaniel and Wilson 2007; Meurisse et al. 1991) and coincide with the location of highly productive forests. Volcanic ash-influenced soils can be compacted across the entire spectrum of soil moisture conditions (Craigg and

Howes 2007). The properties that make volcanic ash-influenced soil susceptible to compaction also make them slower to recover than other mineral soils (Froehlich et al. 1985; Johnson et al. 2007; Page-Dumroese et al. 2006). In central Idaho, Froehlich et al. (1985) found significant compaction of ash-cap soils on and off skid trails as they highlighted the soils' vulnerability to just a few machine passes and equipment vibration. In particular, ash-influenced soils had a 26 percent higher bulk density at a depth of 15 cm within the skid trails, as compared to adjacent undisturbed soil, 20 to 25 years post-harvest (Froehlich et al. 1985; Johnson et al. 2007).

Soil Disturbance Impacts on Plant Growth

Soil compaction has been studied for many years to quantify its effects on forest productivity (Fleming et al. 2006; Grigal 2000). Lower forest productivity associated with soil disturbance has also been found (Agherkakli et al. 2010; Ares et al. 2005; Cambi et al. 2015; Kozlowski 1999). Generally, soil compaction is considered detrimental to forest productivity (Greacen and Sands 1980); however, recent research has shown that moderate levels of compaction on coarse-textured soils can enhance survival and growth of young trees in Mediterranean climates while having little effect in cold northern climates (Fleming et al. 2006; Gomez et al. 2002). These results, along with increasing pressure to accurately predict harvest operation outcomes, mean that there is more work to do to fully evaluate the factors that affect seedling performance in compacted soils (Bulmer and Simpson 2010). Site and soil characteristics, particularly physical properties and water content, affect tree growth. Data collected for these characteristics are also critical for sites that require restoration from compaction. In field studies, where many factors affecting seedling growth are subject to variations over a short time and small distance, results will vary. Therefore, understanding site-specific processes will help land managers better develop prescriptions for managing soil compaction to improve or maintain forest productivity (Bulmer and Simpson 2010).

Soil Productivity

As noted, not all soil disturbances are detrimental to plant growth, ecosystem services, or biodiversity. Although it is clear that soil disturbance can occur as a result of timber harvesting, disturbance can also occur during site preparation and is often not considered within soil disturbance guidelines (Curran et al. 2007). However, whenever disturbance is assessed, the rationale for delimiting when it is detrimental should be soil- and climate-specific and the effects elucidated for both vegetation growth and hydrologic function. Further, the net effect of all soil disturbances should be evaluated against growth-limiting factors. For example, soil compaction may reduce aeration porosity, but it can also produce a concurrent reduction in competing vegetation (Grime 1973). Rehabilitation is also a strategy to ameliorate soil disturbance (Curran 1999).

In coarse-textured soils, compaction may increase water holding capacity and increase tree growth (Ares et al. 2005; Gomez et al. 2002; Powers and Fiddler 1997; Stone et al. 1999) and these soils are generally harder to compact. Rehabilitation of coarse-textured soils indicates that they may be repairable following traffic (Bulmer and Curran 1999). Finer-textured soils may be at greater risk of soil disturbance, particularly compaction, but could also be rehabilitated. In the Oregon Cascades on silty-clay soils, skid trails were rehabilitated, and tree growth was not different from undisturbed soil (Heninger et al. 2002). In western Montana on sites that had been harvested and terraced, changes in mineral soil properties 45 years after harvest operations were no longer detectable and there were no long-term impacts on the establishment and growth of planted ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) seedlings (Cerise et al. 2013). Plantation trees may have a competitive edge over natural regeneration, but the results are likely to be site-specific (Cerise et al. 2013). In addition, altered soil profiles may not result in reduced seedling growth. For example, when logging results in topsoil mixing and soil displacement (Firth and Murphy 1989; Greacen and Sands 1980; Miller et al. 1996; Senyk and Craigdallie 1997), there can be better survival and growth of tree seedlings. When the organic horizons are extremely thick, mixing or displacement to reduce the depth of organic horizons can result in better vegetation growth because seedlings have better access to mineral soil, water, and nutrients (Cambi et al. 2015; Löf et al. 2012; Perala and Alm 1990; Prévost 1997). Identifying soil texture, particularly clay content, depth to water table, coarse-fragment content, and shallow topsoil areas, is one way to guide modification of harvest operations to minimize soil disturbance (Curran et al. 2007). Species and climatic regime also play a role in how vegetation will respond to soil disturbance; therefore, long-term studies and soil monitoring can help managers understand the risks of specific harvest methods.

Forest soil surface horizons are more fertile than deeper soil horizons, and a compacted or displaced surface can lead to reduced plant growth. Severe compaction in the surface mineral soil can negatively impact forest regeneration and root development when the soil penetration resistance exceeds 2.5 MPa, which is commonly reached in skid trails (Cambi et al. 2015; Williamson and Neilsen 2000). Seedling roots have difficulty penetrating compacted mineral soil, leading to seedling death or growth deformities (Greacen and Sands 1980). Seedling survival declines when emerging radicles cannot penetrate dense soil caused by soil compaction (Froehlich et al. 1986). If seedlings do establish on compacted soils, they may have lower growth rates due to the alteration of soil physical properties that influence root penetration, aeration, moisture, and nutrient uptake (Brais 2001; Conlin and van den Driessche 1996; Demir et al. 2010; Froehlich et al. 1986; Gomez et al. 2002; Parker et al. 2007; Pinard et al. 2000; Smith 2003; Williamson and Neilsen 2000). The greatest losses during seedling establishment occur when the surface structure is destroyed by puddling (smeared mineral soil particles that reduce infiltration; Binkley and Fisher 2013).

Soil Biodiversity

Land managers can satisfy forestry objectives while also favorably influencing soil fauna and flora to enhance soil fertility and stand health (Battigelli et al. 2004). Harvesting results in large amounts of woody residues and dead roots that are decomposed by soil biota. The presence and decomposition of organic materials, along with the variety of compaction-induced conditions and displacement or mixing of the organic horizons and topsoil, create a myriad of microsites where biota are either positively or negatively affected. For example, in a boreal aspen (*Populus tremuloides* Michx.) forest, severe compaction of the mineral soil reduced available nitrogen, microbial biomass phosphorus, and acid phosphatase by 53, 47, and 48 percent, respectively, when the forest floor was intact (Tan et al. 2008). Further, soil compaction reduced net nitrification rates in both the forest floor and mineral soil, reduced microbial biomass nitrogen in the mineral soil, and reduced available nitrogen content in both the surface organic horizons and mineral soil (Tan et al. 2005). Soil lightly disturbed after harvesting has had a short-term increase in soil microarthropods (McIver et al. 2003).

Heavily impacted skid trails can result in less aboveground vegetative biodiversity. Pinard et al. (2000) found that skid trails 18 years post-harvest had fewer small woody stems when compared to the surrounding areas. This change in vegetative growth and root proliferation, combined with soil compaction and the removal of the surface organic horizons, can reduce the density of soil mesofauna through the loss of habitat (Battigelli et al. 2004). When surface organic horizons are removed, there can be long-term shifts in microbial populations in response to changes in soil temperature and moisture (Wilhelm et al. 2017). The alteration of soil water and air volume by compaction generally has a negative effect on microarthropods (Radford et al. 2001). Differences in microarthropod populations after using a feller-buncher harvester or single-grip harvester were small off-trail, but on-trail there were reductions in mites and collembolans (Addison and Barber 1997).

Soil is home to a wide array of soil organisms (e.g., mites, collembolans, termites, and worms) which move mineral soil particles and deposit or move organic matter. These combined efforts can help reduce soil compaction if the effects do not limit their survival (Cambi et al. 2015; van Vliet and Hendrix 2007). Therefore, although compaction can be detrimental to the soil biota, some organisms can contribute to soil recovery. The degree and extent to which microfauna and macrofauna can decrease compaction will depend on soil texture, climate, and the degree of initial compaction.

Soil Recovery

Similar to soil disturbances, the recovery of soil processes is related to climatic regime, harvest method, and the degree, extent, duration, and distribution of impacts. Soil is a limited resource which should be protected from disruptive management actions and, where necessary, restored for economic and ecological productivity. The loss of soil porosity and surface organic horizons is now recognized as a North American-wide forestry concern, and the North American Long-Term Soil Productivity (LTSP) study was established in response (Powers et al. 2005). This study has a common experimental design used across the continent that examines a pulse impact (clearcut harvesting, soil compaction, and organic matter removal) across the major forest types in North America. Further, it is evaluating the time it takes for soil recovery and the impacts on stand productivity. It highlights several important soil recovery and resilience results (Page-Dumroese 2020), but key long-term impacts are that surface organic horizon loss often results in a decline in soil carbon and that soil density recovery was slow in soils with a frigid temperature regime.

More research and administrative studies, combined with state-of-the-art reviews, can help define and validate soil monitoring data. This effort includes expanding our understanding of how to make appropriate comparisons of field data. For example, studies that collect data in disturbed and undisturbed soil are at risk of comparing soil characteristics that are not similar. Soil differences such as horizonation, rock-fragment content, texture, or other features can lead to different results and conclusions if these variables are not accounted for in the sample design (Johnson et al. 2007).

Soil recovery can be slow deeper in the profile (Cambi et al. 2015). For example, Page-Dumroese et al. (2006) found that soils had recovered to predisturbance levels in the surface 10 cm of some coarse-textured soils within 5 years of disturbance, but at the 10- to 30-cm depth soil had not recovered from compaction (Cambi et al. 2015; Page-Dumroese et al. 2006). On skid trails, soil recovery can also be slow (Croke et al. 2001). In addition, although traffic has less impact on subsurface horizons, this zone of the soil profile is slower to recover than surface horizons (Rab 2004).

Attempts can be made to reduce the extent of legacy disturbance within a stand. Soil restoration could be as simple as ripping compacted horizons and adding coarse woody residues to prevent recompaction. On sites with displaced organic horizons or erosion, however, this may involve adding compost or biochar. In addition, planting trees and shrubs may be necessary so that invasive species do not become established.

Determining priorities for soil restoration is important and designing restoration plans for rapidly changing climatic and ecosystem conditions will be difficult. Although restoration plans often seek to return to "the way things were," this target is problematic because of changing atmospheric carbon and air temperature, altered disturbance regimes, and other factors (Safford et al. 2012). Under these changing conditions, restoration plans directed at the degree of altered soil and the feasibility of intervention options will interact to drive the design and implementation of soil recovery plans (Hobbs et al. 2014). However, restoration attempts must acknowledge the interactions of soil physical, chemical, and biological properties (soil ecological knowledge, or SEK) and their feedbacks to aboveground and belowground ecosystem processes in order to be successful (Callaham et al. 2008; Heneghan et al. 2008).

Soil quality and dynamic soil processes can also provide a measure of the efficacy of different soil management practices on similar landscape positions with equivalent inherent properties (Karlen et al. 2001). For example, as part of a forest dynamic soil processes study, active carbon, phospholipid-derived fatty acids (PLFA) community structure, and microbial biomass were used to asses soil biological quality in five paired (clearcut and unharvested) forest stands on volcanic ash-cap soils in northern Idaho (Page-Dumroese et al. 2015). This study noted that ash-cap soils in moist ecosystems have highly resilient biological communities, but that soil compaction was still evident 40 years after harvesting.

Soil Monitoring

Understanding soil impacts and recovery of land management systems requires monitoring and validation of disturbance classes. Not all soil disturbance is detrimental to stand growth or hydrologic function, but a rationale is needed for deciding when a disturbance type or severity may result in alteration of soil processes. If disturbance alters soil moisture, temperature, rooting volume, carbon sequestration, nutrient cycling, competing vegetation, invasive species, or disease, then understanding when these changes become tree growth limiting is critical (Curran et al. 2007). The Forest Service is using a visually based soil monitoring protocol (Page-Dumroese et al. 2009) that clearly defines soil disturbance types and levels. These characteristics are easily discernible to scientists and laypersons and can be recognized by equipment operators. This statistically robust protocol can be used to develop best management practices for particular soils and climatic regimes. Initial work on risk-ratings for different types of logging equipment has been done (e.g., Reeves et al. 2012), and a risk assessment model for the Northern Rocky Mountains was developed which uses soil and geology databases to define soil disturbance hazards (Kimsey et al. 2011). Additional research, monitoring, and validation will provide an infrastructure for developing a robust database on long-term effects of soil disturbance.

Conclusions

Soil disturbance is a growing concern that is associated with land management and human use. In forest operations, the heavy machinery used for timber harvests poses a risk to soil productivity, which can subsequently lead to a decrease in stand productivity or other ecosystem services (e.g., water storage, beneficial microbial diversity, carbon sequestration). The degree, severity, and extent of soil disturbance impacts are site-, equipment-, and soil-specific. Changes in soil quality and hydrologic function can be long-lasting and impact seedling establishment and growth, invasive species, and erosion, but can be avoided. On sites that require forest and soil restoration activities, it is critical to understand the ecological relationships between the aboveground and belowground portions of the ecosystem to restore and maintain appropriate functions.

Management Implications

Understanding soil and site characteristics before harvest operations begin is the first step toward maintaining soil properties and processes. These initial characteristics will influence the potential for soil disturbance and contribute to the refinement of harvest operations that will minimize soil disturbance. Limiting soil disturbance is critical as the climate changes and forests experience drought, higher air temperatures, or altered nutrient cycling. Further, changing climates may alter the severity of wildfire or insect and disease outbreaks. Healthy soils can help buffer forests from adverse effects and make them more resilient.

Soil monitoring can detect both the short- and long-term effects of soil disturbances that are a direct result of harvesting. Knowing the disturbance extent, severity, duration, and distribution within a harvest unit will provide insight into current site recovery times and processes. This knowledge also will inform decisions about restoration activities and potential alterations in harvest operations that could reduce disturbance in the future.

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