Soil Disturbance Recovery After Timber Harvests on the Malheur National Forest, Oregon

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Authorization to Submit Thesis

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Abstract

Soil productivity is essential to the sustained production of ecosystem goods and services and monitoring the impacts of land management is critical for ensuring the continuation of productive forests. The National Forest Management Act of 1976 (NFMA) mandates monitoring soil property changes following management practices at all national forests, so they "will not produce substantial and permanent impairment of the land". The Forest Soil Disturbance Monitoring Protocol (FSDMP) was developed by the U.S. Department of Agriculture Forest Service (USFS) to ensure a standard method for collecting pre- and post-harvest soil monitoring data. Data collected following the FSDMP provide temporal and spatial insights into soil recovery rates and alteration of soil processes or hydrologic function following disturbance. The objective of this study was to 1) identify site factors and operational harvest impacts that alter dynamic soil properties, and 2) outline best management practices that account for these site and operational factors.

Prior harvested stands on the Malheur National Forest in northeastern Oregon, USA were identified to reflect a range of soil types, climatic conditions, past timber harvest mechanisms and seasonal timing, as well as topographic position (slope, aspect). Fifty-one stands were selected within a project area approximately 31,000 hectares and monitored retrospectively to evaluate soil disturbance and site characteristics that influence soil recovery from timber harvests completed within the past 5, 10, 20, or 40 years ago.

We found that clay and silt content, spring moisture deficit, fall mean maximum temperature as well as interactions between clay x silt content, depth to restrictive layer x coarse fragment content, and silt x depth to restrictive layer had the most influence on soil disturbance. Important management considerations are (1) harvest operations that occurred during winter months resulted in less soil disturbance, (2) greater clay content (relative to silt content) decreased the amount of soil disturbance, and (3) soils show a trend toward recovery 10-years after harvest operations are complete.

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Introduction

The timber industry is an important aspect of the Pacific Northwest's economy. Despite the importance of this industry it may lead to ecological impacts to the soil environment. Timber harvests can negatively impact soils thus reducing the soils long-term productivity, on either public or private forest lands. For years soil disturbance from such timber harvests has been a growing concern for foresters and soil scientists. The impacts of soil disturbance caused by timber harvest operations is site specific. It is important to ensure these operations will not negatively impact soil productivity at an alarming rate for future timber production. To assess the impacts of timber harvests, soil scientists or forest managers evaluate changes in surface soil properties, soil compaction, and erosion rates (Croke et al., 2001).

Soil Compaction

Soil compaction is one of the most important issues that arises from timber harvests. It 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). Logging equipment used in ground-based timber harvest operations that cause vertical and horizontal stress can inflict soil compaction (Cambi et al., 2015; McNabb et al., 2001). During harvest and site preparation operations, the energy exerted on the soil by vehicular traffic commonly results in soil compaction. This reduces air space and increases the soil bulk density (Johnson et al., 2007).

Soils are matrices that are highly susceptible to compaction, except for a few unique strongly cemented soils. Forest soils are specifically prone to compaction due to their loose, friable structure and high porosity. Soil compaction occurs naturally despite the focus on the impacts of management activities. Timber harvests are not the sole cause of soil compaction in a forest environment. As Howard W. Lull said, "Whenever you put a foot down on forest or range land, you are – to a degree – compacting the soil". It is a common issue due to humans as well as animals. For example, soil can be compacted due to freeze thaw and wetting drying cycles (Cambi et al., 2015; Hillel, 1998). Additionally, induced liquefaction caused by an earthquake can cause soil compaction as well as animal trampling. However, the most common cause of soil compaction is a result of human activities. Such activities can enact major forces with a vertical component to the ground (Cambi et al., 2015).

Despite being a common occurrence and universal process, in forest soils it is generally viewed as a concern when it is caused by timber harvests or other human activities (Lull, 1959). Civil engineers and those working in soil mechanics have developed principles that forest soil scientists utilize to determine the conditions where our natural soils are at the greatest risk of compacting (Johnson et al., 2007).

After timber harvest operations are complete soil compaction can range from ten to seventy percent of that stand. This wide range of compaction can lead to a substantial impact on the soil environment (Cambi et al., 2015). Most of these impacts are negative. They include an increase in erosion, higher bulk density, less water infiltration, reduced tree growth, puddling, and decline in soil biota populations. These impacts range from short- to long-term, depending on the degree of soil compaction.

Compaction Effects on Soil Bulk Density

Due to the forces exerted on the soil surface it results in an increase in bulk density, thus reducing porosity of the soil. The ability to implement a method to measure soil compaction would help us improve our level of understanding and assist in defining best management practices. Evaluation of bulk density is one method useful in determining the level of compaction following harvest activities. Bulk density is defined as the "mass of soil particles per unit bulk volume (including the combined volumes of particles and pores), indicative of the compactness or porosity of a soil body" (Hillel, 2008). Increasing soil compaction is directly expressed as an increase in bulk density (Ares et al., 2005).

An increase in bulk density occurs due to the rearrangement of solid particles (Greacen and Sands, 1980). The upper limit of bulk density is determined primarily by the shape and size distribution of the soil particles. For most mineral soils, low initial bulk density values often contribute to a higher likelihood of 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; 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 since the soil is already dense. Many forest soils have lower initial bulk densities than 1.4 Mg m^{-3} because of high levels of organic matter from litterfall and micro- and macrofauna incorporation into the mineral soil (Powers et al., 2005). Soils with a low bulk density and a steady input of organic matter encourages the formation of a well-developed crumb structure with high porosity which typifies mineral A horizons (Cambi et al., 2015; Corti et al., 2002). Despite the desire to maintain a low bulk density, heavy harvest equipment will lead to an increased bulk density (Han et al., 2006).

Over the past century our harvesting technology has changed but historic skid trails are still encouraged to be reused for future harvests. Soil at these sites have a high initial bulk density from past activities. Restricting traffic to designated skid trails is encouraged as an effective strategy to minimize areal soil compaction on ash-cap or fine-textured soils that have a low initial soil bulk density. Most of the soil compaction that occurs, regardless of the initial bulk density, occurs in the first few passes of machinery used for skidding or forwarding (Cambi et al., 2015; Han et al., 2009).

Compaction Effects on Soil Porosity and Water Infiltration Rates

Soil porosity is the volume percentage of the total bulk soil that is not occupied by the solid particles (Sulzman and Frey, 2002). Soil compaction increases bulk density, thereby reducing pore space. When pore space is reduced it leads to an increase in soil solids by filling previous pore spaces. Porosity is made up of micropores (< 0.08 mm) and macropores (> 0.08 mm). Heavy machine traffic in the forest, such as skidders, reduce macropores to the size of micropores. Thus, macropores are most commonly reduced with an attendant increase in micropores (Seixas and McDonald, 1997). Compaction, caused by machine traffic, can reduce porosity up to sixty percent of the harvested land (Cambi et al., 2015).

An increase in micropore space often leads to an increase in 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 can retain more water than natural soil conditions at field capacity but that does not necessarily translate to more water available for the plants. Micropore water is held tightly (high matric potential) which is difficult for plants to obtain. Ultimately, a reduction in soil porosity through compaction will significantly increase soil matric potential while simultaneously reducing water holding capacity (Cambi et al. 2015).

A reduction in water infiltration rates and hydraulic conductivity leads to an increase in waterlogging (reduces soil air porosity) and/or standing water on flat terrain and increased surface runoff and erosion on steeper slopes (Cambi et al., 2015; Grace et al., 2006; Jansson and Johannson, 1998). Evidence of stagnant water is often expressed long past post-harvest in the form of redoximorphic features or chromatic features that are indicative of anoxic conditions (Cambi et al., 2015; Herbauts et al. 1996). Redoximorphic features, such as iron and/or manganese depletions and concentrations, are indicative of chemical reduction and oxidation in a low oxygen environment (Callahan, 2015).

Compaction Effects on Soil Strength

Soil strength is defined as the mechanical resistance to failure, or more simply, its ability to resist compaction (Greacen and Sands, 1980). Measurement of soil strength is another useful assessment for evaluating the degree of soil compaction (Viscarra Rossel et al., 2011). It can also be used to estimate mechanical resistance experienced by root systems (Smith et al., 1997). Limiting factors to the routine use of soil strength are that excessive compaction limits the depth of measurement and soil water content strongly influences readings (Bennie and Burger, 1988; Spain et al., 1990). Therefore, although soil strength measurements may give a better indication of root limiting factors, bulk density is still commonly used.

Compaction Effects on Soil Gas Diffusivity

The ratio of macro to micropores is important for soil air permeability. Roots and microorganisms within the soil have restricted access to available oxygen when a soil is compacted (Bodelier et al., 1996; Cambi et al., 2015; Frey et al., 2009; Startsev and McNabb, 2000). Frey (2009) found heavy machinery, rutting to a depth of five to ten centimeters, reduced soil air permeability by 96 percent. In locations where the heavy machinery churned, compacted and partially removing the topsoil, soil air permeability declined by 88 percent. Air permeability was only reduced in areas where rutting was not evident by 51 percent (Cambi et al., 2015; Frey et al., 2009).

Machine harvesting has a complex effect on carbon dioxide production and soil diffusivity (Bekele et al., 2007; Cambi et al., 2015; Fernandez et al., 1993; Goutal et al., 2012). An uncompacted soil has a lower carbon dioxide : oxygen concentration ratio relative to compacted soils. Higher ratios in compacted soils are due to a decrease in gas diffusivity (Cambi et al., 2015; Goutal et al., 2013). Root respiration and root growth is inhibited by a high soil carbon dioxide concentration. This in turn inhibits nutrient uptake resulting in reduced growth (Cambi et al., 2015; Conlin and van den Driessche, 2000; Kozlowski, 1999).

Compaction Effects on Plant Productivity

The surface horizons of forest soils are the most fertile section of the soil profile. If these fertile horizons are compacted or removed it can lead to reduced plant growth. Severe compaction, such as found on skid trails, will negatively impact forest regeneration and root development (Cambi et al., 2015; Williamson and Neilsen, 2000). Tree growth and reproduction is reduced by soil compaction due to reductions in water infiltration and air permeability. This leads to depressed forest productivity (Agherkakli et al., 2010; Ares et al., 2005; Cambi et al., 2015; Kozlowski, 1999). New trees are restricted from accessing water due to a reduction in water infiltration. Seedling roots have difficulty penetrating reduced pore space as well. Increased difficulty for seedling growth can lead to growth deformities (Greacen and Sands, 1980). A trees root growth becomes limited when the soils penetration resistance exceeds 2.5 megapascals (one megapascal is equal to one million pascals). This level of penetration resistance is commonly reached after timber harvests (Cambi et al., 2015).

Heavily impacted skid trails can result in long-term reduction of natural regeneration and negatively impact the vegetation diversity. For example, Pinard et al. (2000) found that 18 years post-harvest skid trails had fewer small woody stems when compared to the surrounding areas (Cambi et al., 2015). Cerise et al. (2013) investigated the site productivity and soil properties 45 years after timber harvests are completed as well as the site preparation for those harvest areas in a study conducted in Western Montana. The variations in the soil bulk density at these sites did not appear to have a significant impact on the establishment of ponderosa pine seedlings and growth after the soil was disturbed. Plantation trees might have had a competitive edge over other trees due to the type of site preparation that was completed on the soil types found on the Bitterroot National Forest in Montana (Cerise et al., 2013).

When logging has induced topsoil mixing and soil displacement, there have been positive contribution to tree regeneration. For example, in areas that have a thicker than normal organic horizon that can prevent seedlings from reaching mineral soil. If seedling roots cannot reach mineral soil it limits their access to water and nutrients (Cambi et al., 2015; Löf et al., 2012; Perala and Alm, 1990; Prévost, 1997).

Compaction Effects on Soil Biota

Soil biota are strongly impacted by compaction, in a similar fashion to how vegetation is impacted. Soil compaction affects biota differently dependent on the degree of compaction as well as the type of biota present. The relative proportion of water and air volumes are affected by soil compaction thereby altering soil faunal communities, depending on the severity of compaction and displacement. Overall, the typic response is negative, showing microarthropod litters decreasing in number if impacts are persistent beyond one-year post-disturbance (Cambi et al., 2015). Although compaction can be detrimental to the soil biota, it is the soil biota that can contribute to soil recovery. Soil compaction can be reduced due to the activities of ecosystem engineers, such as earthworms. Faunal community activities can counteract detrimental effects caused by soil compaction (Cambi et al., 2015).

Soil Displacement and Erosion

Soil displacement is the movement of soil from one place to another. At times erosion is used in place of soil displacement or is a result of soil displacement. It becomes a growing concern after the soil is compact and abundant rains come across the landscape. Soil displacement can negatively affect numerous characteristics for either short- or long-term periods of time. Organic matter accumulation is an important characteristic of forest soils, compared to agricultural soils. In a forest environment organic matter accumulates because it is not tilled into the soil like it is in agricultural soils. Organic matter content and accumulation is vital for forest survival (Martin, 1988). It provides trees and understory vegetation a supply of nutrients vital for healthy growth and regeneration as a nutrient storage bank. Additionally, soil displacement removes this nutrient storage bank as well as nutrients from the site and relocates it. On steeper slopes a loss of nutrient holding capacity occurs as well as the nutrients being stripped away. Loss of soil greatly reduces the amount of nutrients that can be stored (Martin, 1988).

When human disturbance removes the roots of vegetation along with the forest floor it may lead to erosion, as the roots are no longer there to hold the soil in situ (Martin, 1988). Erosion is most often associated with timber harvest occurring on steeper slopes (Johnson et al., 2007). Erosion is defined as the detachment and removal of soil particles from the soil surface, by running water or by wind (Hillel, 2008). There are two types of erosion, geological and accelerated erosion. Geological erosion is the natural process that takes place in the absence of human influence. Accelerated erosion, on the other hand, is what takes place when human activities disturb the soil or the vegetation or both through timber harvests and excavation for roadways (Brady and Weil, 2010).

Rutting and Puddling

Rutting is a common aftereffect of soil compaction in forest soils as well as being a main cause or contributor to soil displacement. Ruts refer to the deep tracks that are created by either a single pass or multiple passes of wheeled or tracked vehicles (Froehlich and Robbins, 1986). These deep tracks are the consequence of vertical and horizontal soil displacement. The tire or track forces from the heavy machinery cause soil displacement and subsequent rut formation rather than simply soil compaction when it is beyond critical water content (Cambi et al., 2015; Hillel, 1998; Horn et al., 2007; Vossbrink and Horn, 2004; Williamson and Neilsen, 2000). They are found either in the middle or sides of skid trails associated with shearing stresses and soil compression in moist or wet soils (Cambi et al., 2015; Horn et al., 2007).

On flat terrain ruts may serve as rain collection basins when the water table reaches the surface or a reduction in water infiltration occurs. On slopes, either steep or gradual, ruts may serve as preferential routes for water runoff during and after major rain events (Cambi et al., 2015; Christopher and Visser, 2007; Startsev and McNabb, 2000). Preferential routes, such as this, can cause continuous erosion thus making the ruts deeper and deeper (Cambi et al., 2015; Schoenholtz et al., 2000). Rut formation is heavily influenced by the mass of the timber harvest machinery used. Ideally, the lightest possible machinery should be used on soils that have a low bearing capacity (Cambi et al., 2015).

Reduced water infiltration due to compaction can lead to soil puddling. Water dispersed soil particles results in differential settling rates, allowing clay particles to lie parallel upon settling. This commonly occurs in ruts following tire slippage. Disturbance that causes puddling frequently destroys surface soil structure resulting in a dense crust. This crust exhibits the same effects as a thin, compacted layer (e.g., inhibition of water infiltration; Binkley and Fisher, 2013). Reduced water infiltration from puddling can lead to soil displacement during rain events on steep slopes (Cambi et al., 2015; Rab, 1996). Additionally, puddling reduced the success of germination and increased the mortality rate of loblolly and slash pine seedlings following a harvest event in the southeast (Binkley and Fisher, 2013).

Soil and Site Characteristics Prone to Deformation

A soil is more prone to deformation depending on its physical characteristics. These include initial bulk density of an undisturbed site, particle size distribution, soil organic matter content, moisture content, and ground slope (Cambi et al., 2015; Corti et al., 2002).

A soil's texture, or particle-size distribution, will influence the degree of compaction. Particle-size distribution is important as fine-textured soil, such as a loamy or clayey soil, are predominately more susceptible to compaction compared to coarse-textured soils (Binkley and Fisher, 2013; Cambi et al., 2015; Hillel, 1998; Wästerlund, 1985). In some unique scenarios the effects of compaction may be less permanent depending on the soil texture. If a fine-textured soil contains a considerable amount of shrink-swell clays, then the long-term effect of compaction may decrease greatly. This is due to the nature of shrink-swell clays and the density reducing action that occurs with wetting and drying cycles (Binkley and Fisher, 2013).

Soil structure is another important factor in terms of soil compaction. It is the capacity of the aggregates to withstand pressure of heavy machinery without breaking down into smaller aggregate sizes. Increasing the size of the aggregate, and thus soil structure, allows a soil to withstand heavy machinery pressure without disintegrating into smaller pieces (Cambi et al., 2015; Page-Dumroese et al., 2006).

Compaction severity depends on equipment type used during site preparation and timber harvest activities. Logging machinery greatly varies in their axle/wheel/track load, size of contact area with the soil, tire pressure, and dynamic shear forces. Most of the machinery used in harvest operations range from 5,000 to 40,000 kilograms in mass (Cambi et al., 2015; Elisson, 2005; Jansson and Wästerlund, 1999). Greater mass will exert higher pressure directly onto the contact area (Cambi et al., 2015).

Soil moisture content is another important factor to consider when heavy machinery is utilized. A 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 have a higher occurrence of compaction due to water content lowering soil strength. Soil pore water acts as a lubricator of surrounding soil particles, thus as soil moisture content increases, frictional forces between soil particles declines leading to a reduction in soil bearing capacity. Reducing soil bearing capacity in turn increases the risk of soil compaction (Cambi et al., 2015). Once soils reach saturation, soil displacement dominates over compaction (Binkley and Fisher, 2013).

Degree of soil compaction can be influenced by harvest practices and slope location. Increase in the degree of compaction is induced by harvesting as slope increases. Distribution of loads are more confined on steep slopes leading to an increase in soil compaction in skid trails. Additionally, how operators maneuver on the slopes when the equipment is fully loaded impacts the degree of soil compaction (Cambi et al., 2015). Past studies have focused on how different harvest methods impact soil compaction. Some harvest methods have a lower impact on the soil than others. Jansson and Wästerlund (1999) found that when lightweight forest machinery, with a mass ranging from 5,000 kilograms to 9,000 kilograms, were used in timber harvest operations a minor increase in soil penetration resistance was observed. Study area consisted of sandy loam soils, more coarse-fraction soil, sustaining young stands of Norway spruce in Sweden (Cambi et al., 2015).

Volcanic Ash

Volcanic ash, from the eruption of Mount Mazama approximately 7,700 years ago, is an important component of many Pacific Northwest soils and are a valuable resource to the region from both an economic and ecological viewpoint (McDaniel and Wilson, 2007). Mixing and deep deposits of volcanic ash are found across many mid- to high-elevation forest soils (Geist and Cochran, 1991; Kimsey et al., 2019; McDaniel and Wilson, 2007; Meurisse et al., 1991). Most importantly, their inherent properties of volcanic ash lead to a greater susceptibility to soil compaction (Cerise et al., 2013) rutting, and mixing of topsoil and forest floor material (Allbrook et al., 1996; Cambi et al., 2015; Page-Dumroese, 1993; Parker, 2007).

Deposits are superficial and overlay the 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). Although they are fine-textured clay content is low (0-27 percent clay). This is 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 et al., 1996; Cambi et al., 2015; Cerise et al., 2013; Page-Dumroese, 1993; Parker, 2007).

Due to their fine textured nature, and the presence of volcanic glass (i.e. interlocking soil particles), volcanic ash soils often retain relatively greater levels of soil moisture, increasing their susceptibility to compaction during harvest activities. Furthermore, volcanic ash-influenced soils appear to have a similar degree of soil compaction over a broad range of soil moisture (Craigg and Howes, 2007). This increased susceptibility to compaction and the interlocking nature of volcanic glass particles lead to slow recovery rates (Froehlich et al., 1985; Johnson et al., 2007). Froehlich et al. (1985) found across harvest units in central Idaho significant compaction on and off skid trails – highlighting their vulnerability to even minimal machine passes. In particular, they found these ash-influenced soils to have a 26 percent higher bulk density at a depth of 15 centimeters within the skid trails twenty to twenty-five years post-harvest (Froehlich et al., 1985; Johnson et al., 2007). Other studies have shown similar results post-harvest with the most noticeable soil alteration being compaction (Cambi et al., 2015; Gier et al., 2018).

Soil Recovery

Human impacts to soils can be long lasting. Numerous studies have been conducted to gain a better understanding of soil recovery and lasting impacts post-harvest. Studies focusing on soil recovery risk comparing soil types that are not similar after disturbance. For example, if a study is designed to compare the bulk density of a disturbed site to an undisturbed site there could be variations in soil type and texture. On a skid trail a study might sample a subsurface soil horizon because the surface soil horizon was displaced while the undisturbed site is sampled from the surface soil horizon. Sampling bulk density from different horizons could result in false conclusions if it is not accounted for (Johnson et al., 2007).

The depth at which the impacts occur may influence amount of time required for soil to recover after disturbance. Closer to the soils surface then usually it is able to recover in less time than deeper in the profile (Cambi et al., 2015). For example, Page-Dumroese et al. (2006) found that some coarse-textured soils in the top ten centimeters of the soil profile had recovered to the original bulk density five years after harvest. In that same five years the soil had not recovered to the original bulk density in the next ten to thirty centimeters of the soil profile (Cambi et al., 2015; Page-Dumroese et al., 2006).

A study conducted on the Eden Forest Management area located on the southeastern seaboard of New South Wales, Australia investigated soil recovery after the construction of skid trails. They found that skid trails had a mean surface bulk density of 1.4 Mg m^{-3} regardless of soil types. In addition, they found there was no significant recovery toward pre-harvest soil bulk density up to five years post-harvest (Croke et al., 2001). They also found a general trend of increasing soil bulk densities with soil depth along the skid trails. As seen with surface bulk density, there was no significant reduction in subsurface bulk density up to five years post-harvest, indicating the persistence of surface/subsurface soil compaction over the five-year monitoring period (Croke et al., 2001). Bulk density is used as an index of relative compaction, yet it does not allow for an assessment of soil strength.

Like most areas of research, there is still room for advancements. Research investigating the amount of time needed for harvested forest soils to recover is lacking. Previously, the focus of soil science in terms of forestry soils has been nearly completely devoted to short-term investigations (Cambi et al., 2015; Rab 2004; Zenner et al., 2007). Research that has been conducted has helped us understand that amount of time needed for recovery is highly variable. Due to several site-related factors this variability is for both physical and biological soil properties. Factors include slope of terrain, soil thickness, texture, organic matter content, activity of soil biota, and biomass. Additionally, climate and pedoclimate will contribute or inhibit soil recovery (Cambi et al., 2015; Reisinger et al., 1992; Suvinon, 2007; Zenner et al., 2007).

Previous studies have shown soil disturbance from heavy machinery can persist for several years or decades following harvest activities (Cambi et al., 2015). Thus, sites that are significantly degraded, require active remediation of the soil. This could be intensive site remediation or focused on specific soil physical or biological characteristics depending on remediation goals. Determining priorities for site remediation is important. In cases where the priority is not to restore the above- and belowground structure and function to pre-disturbance levels then it may only require manipulation of a single chemical, physical, or biological portion of the soil system in order to improve the system's overall state. Manipulations can then be compared to the prior disturbed state as evidence of recovery (Heneghan et al., 2008).

When the goal of restoration is to improve the soil ecosystem to a specific reference condition an increasingly sophisticated understanding of the soil is necessary. To achieve a desired goal, managers must understand the physical, chemical, and biological properties of the soil. It has been long recognized the integral role of soil, in positive revegetation of degraded sites; however, explicit soil ecological knowledge is still in a relatively early stage of development. It is this knowledge that recognizes the interaction between the principal components of the soil system and the feedback between aboveground and belowground ecosystem processes. As soil ecological knowledge increases it can then be used to inform restoration practices (Heneghan et al., 2008).

Chapter 2: Assessing Soil Disturbance Recovery After Timber Harvests on the Malheur National Forest

Research Summary

Forest managers on national forests in the United States are mandated by the National Forest Management Act (NFMA) of 1976 to maintain soil productivity when planning management activities, such as timber harvests (Burger et al., 2010). While soil disturbance is generally viewed as having negative impacts on forest productivity, some disturbance may actually be beneficial to forest productivity depending on inherent soil properties (*e.g.*, texture, organic matter content, slope; Craigg and Howes, 2007). The impacts of soil disturbance caused by timber harvests is site specific. Many studies have shown that soil disturbance after timber harvesting can last decades (Cerise et al., 2013; Croke et al., 2001; Froehlich et al., 1986; Gier et al., 2018; Heninger et al., 2002; Johnson et al., 2007; Kimsey and Roché, 2012; Kimsey et al., 2019), while other studies indicate that forest soils are fairly resilient to harvest impacts (Greacen and Sands, 1980; Johnson et al., 2007; Landsberg et al., 2003; Xu et al., 2017). Previous work on forest soils has been devoted to short-term investigations regarding the effects of timber harvests (Cambi et al., 2015; Rab, 2004; Zenner et al., 2007), but little is known about how climate, soil type, harvest system and inherent soil properties may influence soil recovery rates.

Negative impacts from ground-based timber harvest operations, such as compaction and rutting, soil displacement or erosion, can reduce both soil and stand productivity with reductions attributed to reduced saturated hydraulic conductivity (Purser and Cundy, 1992); infiltration (Startsev and McNabb, 2000); sorptivity (Malmer and Grip, 1990); pore-size distribution and volume (Huang et al., 1994; Lenhard, 1986); and microbial biomass, number and activity (Croke et al., 2001; Dick et al., 1988; Smeltzer et al., 1986; Torbert and Wood, 1992). In contrast, harvest activities that increase soil density (*e.g.* decreased porosity in sandy soils) have also been shown to have a positive effect on inherent soil properties for some soil types by increasing soil water holding capacity (Gomez et al., 2002a), unsaturated water flow (Sands et al., 1979), root contact with soil (Bhadoria, 1986), or nitrogen uptake (Gomez et al., 2002b). These soil changes can lead to conditions more favorable for tree growth (Powers et al., 2005). Whether positive, negative, or neutral the relationship of site factors, forest management, soil disturbance and vegetation impacts continue to be a management concern for ensuring stand productivity. Furthermore, understanding soil recovery rates after disturbance is an important factor in the relationship of site factors and future land management or restoration needs.

One of the most common disturbances from timber harvest is soil compaction. During harvesting or site preparation, trafficking from heavy machinery exerts pressure on the soil applying a downward dynamic force. Equipment vibration can also cause compaction (Johnson et al., 2007) to depths of 30 cm (Page-Dumroese, 1993). Throughout the compaction process, solid particles are rearranged reducing soil pore space in general (Hillel, 2008), reducing the amount of large pores in particular (Greacen and Sands, 1980; Johnson et al., 2007). Consequently, ground-based harvest operations are a frequent contributor to soil compaction, where the degree and extent drive the direction (positive or negative) of the impact and can be site specific for both soil and vegetation (Brais, 2001; Cambi et al., 2015; Gomez et al., 2002a; McNabb et al., 2001; Smith, 2003). The degree of soil compaction impact is largely dependent on soil particle size distribution, soil structure (aggregate size), moisture content (Cambi et al., 2015; Corti et al., 2002) and presence of volcanic ash (Craigg and Howes, 2007). Fine particle sizes, such as those found in loamy or clayey soil, are predominately more susceptible to compaction compared to a coarse-textured sandy soil (Binkley and Fisher, 2013; Cambi et al., 2015; Hillel, 1998; Wästerlund, 1985). However, soil moisture alters these general responses drastically. An increase in soil moisture content reduces the frictional forces between soil particles leading to a reduction of the bearing capacity of the soil, thus leading it to be more susceptible to compaction (Cambi et al., 2015). Dry soils have a high degree of interlocking and particle-to-particle bonding allowing them to resist deformation due to friction (Cambi et al., 2015; Hillel, 1998). Finally, the areal extent of compaction can extend beyond the edge of a skid trail creating soil impacts at a larger scale than just the trafficked areas (Solgi et al., 2020).

Timber harvest operations can also lead to topsoil displacement. This type of displacement is the removal of the surface mineral soil, primarily the A horizon but does not include rutting caused by the machinery (Page-Dumroese et al., 2009b). This type of disturbance is not well documented, highly variable, and difficult to predict in pre-harvest planning (Tew et al., 1986). Soil displacement occurs as the result of a blade scraping the soil surface or where wheels churn the soil during equipment turns. Displacement can also occur when logs or whole trees are scraped across the soil surface. Removing the surface mineral soils exposes the subsoil which tends to more erodible and can result in nutrient displacement. Natural soils typically increase in density with depth and displacement can expose this higher density resulting in lower vegetation production, reduced root growth, and an increase in invasive species (Rab, 1999). Also, surface soils contain high amounts of organic matter which is important for maintaining soil and site productivity for the future (Napper et al., 2009). In addition to topsoil displacement, topsoil mixing is commonly seen after timber harvests. This is when the topsoil is mixed with the subsoil and results in destruction of soil structure (Whitford, 2009) and an increase in organic matter decomposition (Sanaullah et al., 2011).

Platy soil structure is another common result of heavy machinery traffic over 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 destroys the soils natural structure. A consequence of this is a reduction of total pore space . Platy soil structure can inhibit roots from penetrating these layers. Large roots may penetrate platy layers, but fine or medium roots may not (Napper et al., 2009).

Lastly, trafficking from timber harvest operations may result in ruts (deep grooves in either the forest floor, mineral soil, or both) that move water offsite (if the site is steep), reduce or inhibit aeration (Cambi et al., 2015; Frey et al., 2009), or result in soil plates that restrict root growth (Binkley and Fisher, 2013). This type of disturbance is associated with puddling where the soil surface is sealed due to equipment turning across the mineral soil surface. Both ruts and puddled soil result in decreased soil drainage, increased mean annual water tables, and alteration of soil productivity and hydrologic function (Aust et al., 1998). Furthermore, the singular or combined effects of soil mixing, displacement, puddling, and rutting cause disruptions in water flow on and into the soil surface (Ares et al., 2005; Binkley and Fisher, 2013).

Because there is a wide range of soil disturbance that can occur during harvest operations, it is important to characterize all forms so that it is clear what types of disturbance are associated with different logging systems and which impacts may influence the residual trees or new stand. Understanding the relationship between soil type, climate, stand history, and the type and severity of impacts can lead to refinement of harvest operations and site preparation methods that match site and soil with equipment and harvest timing.

In eastern Oregon, specifically the Blue Mountains, soils in this region are largely volcanic ash derived soils. Previous studies have found that compaction may persist for 20 or more years found at depths of 10 to 15-cm in volcanic ash soils (Geist et al., 1989). In contrast, studies have found that fine-textured soils with andic properties (Soil Survey Staff, 2019a) were found to be compacted 32 years after timber harvesting in forests in the Oregon Coast Range (Geist et al., 1989; Wert and Thomas, 1981). Volcanic ash derived soils have slower surface and subsurface recovery rates (Geist et al., 1989). For the Blue Mountains organic matter content is an important component of the soils due its contribution to the fertility index. For these soils, the nutrient base is primarily in the form of organic matter (Snider and Miller, 1985).

Therefore, my goal was to evaluate site, climatic, and harvest method impacts on soil disturbance. To accomplish this, I monitored soil visual and physical attributes in forest stands that were harvested at different times on the Malheur National Forest. My objectives were to (1) evaluate the areal extent of soil disturbance resulting from timber harvests that occurred over a period of 40 years on the Malheur National Forest of the United States Forest Service, (2) evaluate soil recovery to pre-harvest levels, and (3) determine which soil properties or site characteristics contribute to recovery.

Methods

Study Location

This study was conducted on the Malheur National Forest in eastern Oregon (Figure 2.1; Figure 2.2). The study area is located by Bates, Oregon, 30 miles northeast of John Day, Oregon, USA on a harvest unit approximately 31,000 ha in size. Elevation ranges between 1331 to 1585 meters, with mean annual air temperature (MAAT) of 6.1° C and mean annual precipitation (MAP) of 58.54 cm (PRISM Climate Group, 2019). The frost-free season is 55 to 70 days, depending on elevation. Slopes range from flat to 40 percent.

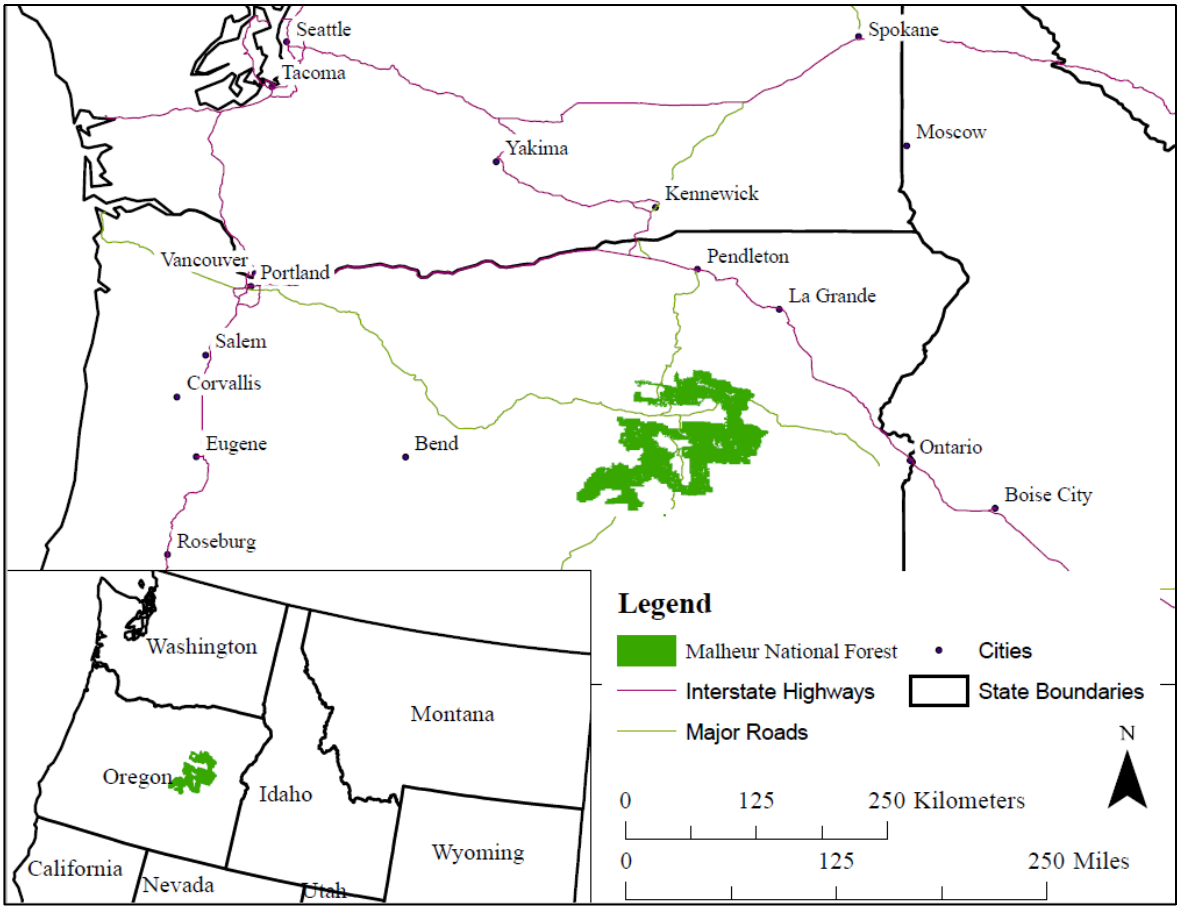

Figure 2.1: Location of the Malheur National Forest in reference to the state of Oregon and the Pacific Northwest, USA.

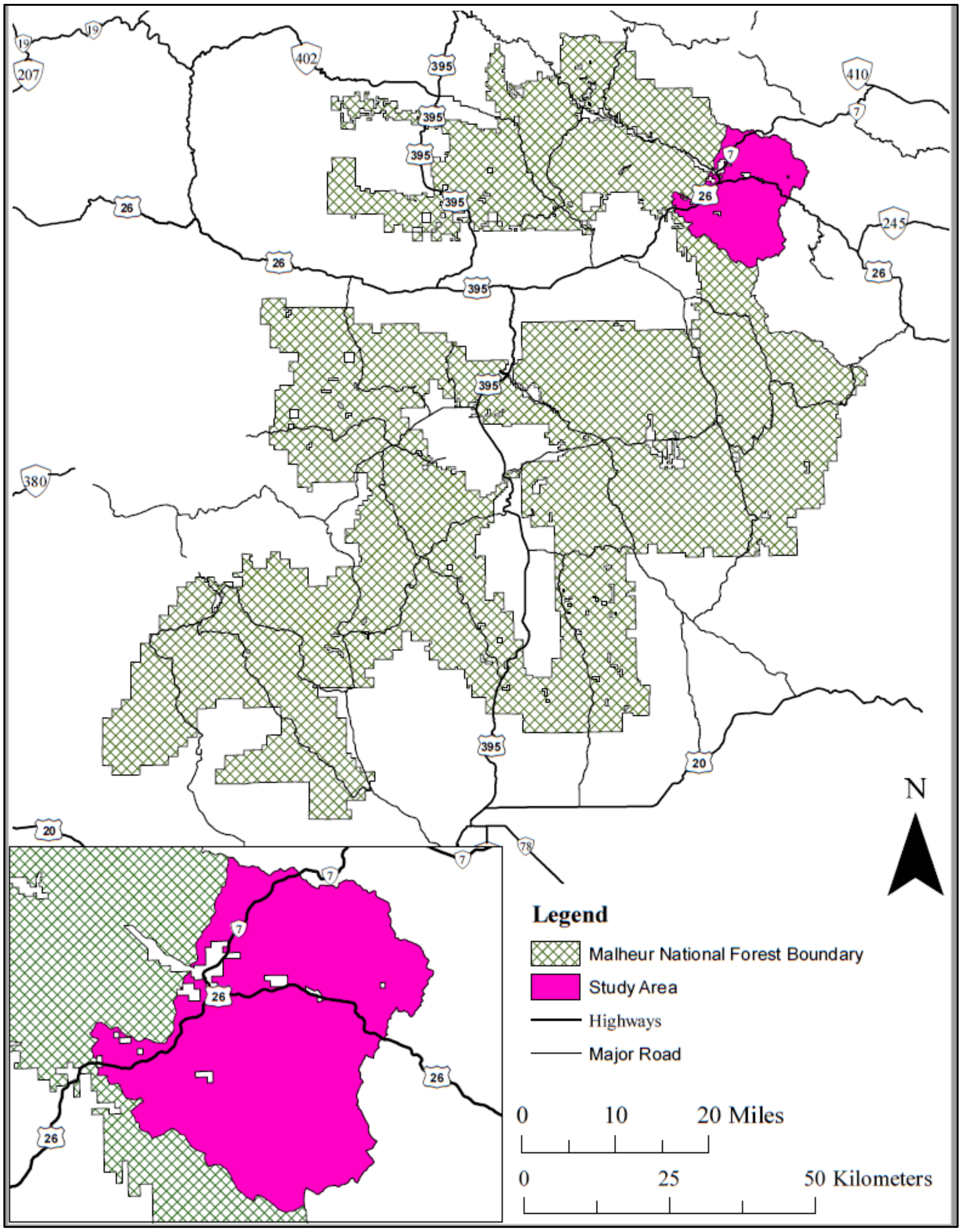

Figure 2.2: Location of study area in reference to the Malheur National Forest, Oregon.

Potential natural vegetation communities vary depending on location within the study area. The intent of potential natural vegetation was to express the mature vegetation that would establish when given a specific set of environmental limitations while excluding the influence of humans. It is defined as the final successional stage of vegetation that is identified based on existing mature stages (Chiarucci et al., 2010). In general, tree species include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), lodgepole pine (*Pinus contorta* Douglas ex Loudon), and ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson). Understory species include bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve ssp *spicata*), common snowberry (*Smphoricarpos albus* (L.) S.F. Blake), grouse whortleberry (*Vaccinium scoparium* Leiberg ex Coville), Idaho fescue (*Festuca idahoensis* Elmer), onespike danthonia (*Danthonia unispicata* (Thurb.) Munro ex Macoun), pinegrass (*Calamagrostis rubescens* Buckley), Sandberg bluegrass (*Poa secunda* J. Presl), and twinflower (*Linnaea borealis* L.)

Stand Selection

Stands of varying post-harvest ages were stratified using a sequence of steps within ESRI ArcGIS 10.5.1 software (ESRI, 2017). Soil complexes were mapped for the entire 31,000 ha utilizing data from the USFS Terrestrial Ecological Unit Inventory (TEUI) for the area (USDA Forest Service, 2019). These complexes were overlain with the Malheur National Forest historic logging layer to stratify each stand by last timber harvest year, type of cutting method used (commercial thin or shelterwood final cut) and equipment utilized (ground-based skidder or tractor logging). Stands were identified and stratified by years since harvest (5, 10, 20, and 40 years post-harvest). Finally, each stand was subsequently stratified by slope and aspect. This final grouping ensured that only one aspect was represented in a given stand which also minimized the potential for a wide range of slopes in a single stand. Slope was stratified as 0 to 15 (low), 15 to 30 (moderate), and 30 to 45 percent (high). General stand aspect was stratified as north (azimuth 316°-45°), east (azimuth 46°-135°), south (azimuth 136°-225°), west (azimuth 226°-315°) and flat (no slope or degree of incline on the ground).

Soil Disturbance Monitoring

Using the Forest Soil Disturbance Monitoring Protocol (FSDMP) soil disturbance monitoring data was collected (Page-Dumroese et al., 2009a). Within each of the 51 stands monitored 30 monitoring data points was collected utilizing a 95 percent confidence level and 10 percent (+/- 5 percent) confidence interval for capturing site influence on disturbance variability. A CI is an interval that should contain the true parameters value, if the process is properly utilized (Ott and Longnecker, 2010). Typically, with the FSDMP more than 30 points per stand would be assessed but is dependent on soil variability. Sample point numbers are dependent on the CL, CI levels. A small ($\leq$ 1 m) pit was dug and the soil profile described at each stand to ensure the soils mapped from the TEUI data were accurate. From each soil pit textures were described for each mineral horizon utilizing the feel method. Each sample was sieved in the field through a 2 mm sieve then hand textured. The texture of the first mineral horizon that was determined by hand texturing was compiled for analysis. Along with this texture clay percentage classes were established for each texture (low, moderate, or high clay content; Figure 2.3; Table 2.1). Clay classes were necessary to delineate silt soils with wide ranging clay content, but did not vary in textural class (i.e., silt loam ranges from 0 to 27.5 percent clay content).

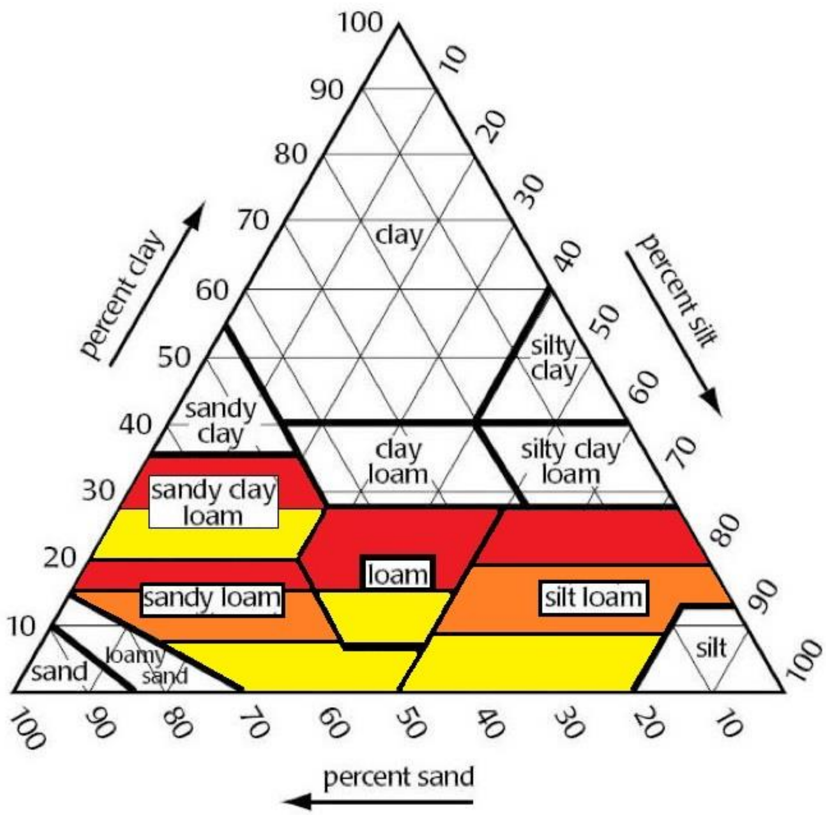

Figure 2.3: Soil textural triangle illustrating different clay percentages.

Table 2.1: Description of each textural class and range of clay percentages, as illustrated in the soil textural triangle in Figure 2.3.

Texture	Bin	Clay Percentage
Sandy Loam	Low	0 – 8%
Sandy Loam	Moderate	9 – 15%
Sandy Loam	High	16 – 20%
Silt Loam	Low	0 – 9%
Silt Loam	Moderate	10 – 19%
Silt Loam	High	20 – 28%
Loam	Low	6 – 15%
Loam	High	16 – 28%
Sandy Clay Loam	Low	20 – 27%
Sandy Clay Loam	High	28 – 36%

At each sample point, the amount of disturbance was assessed and classified into one of four severity classes. These severity classes range from 0 (undisturbed) to 3 (highly impacted; Table 1, Page-Dumroese et al., 2009a).

Table 2.2: Examples of soil visual indicators and management activities by disturbance severity class, as described in FSDMP: Volume I: Rapid Assessment (Page-Dumroese et al., 2009a).

Disturbance Type	Severity Class 0	1	2	3
Equipment Impact				
Past Operation	None.	Dispersed	Faint.	Obvious.
Wheel Tracks	None.	Faint wheel tracks evident (<5 cm deep).	Wheel tracks or depressions are > 5 cm deep.	Wheel tracks highly evident, > 10 cm deep
Penetration and resistance	Natural Condition.	Increased resistance in surface (10 cm).	Increased resistance in top 30 cm.	Increased resistance is deep, >30 cm.
Soil physical condition	Natural Condition.	Soil structure change from granular to massive or platy in surface (10 cm).	Soil structure change in surface (30 cm). Generally continuous.	Soil structure change extends beyond 30 cm and is continuous.
Displacement				
Forest Floor	None.	Forest floor present and intact.	Forest floor partially intact or missing.	Forest floor layers missing.
Mineral Soil	None.	No topsoil displacement; minimal mixing with subsoil.	Mineral topsoil partially intact; may be mixed with subsoil.	Topsoil removed, gouged, piled. Surface soil mixing with subsoil.
Erosion	None.	Slight erosion (i.e. sheet erosion).	Moderate erosion (i.e. sheet or rill erosion).	Large amount of erosion; gullies, pedestals and rills.
Burning	None.	Light impacts; forest floor charred but intact. Gray ash becomes discreet and surface lightly charred to black; structure intact.	Moderate impacts; consumed litter layer & charred or consumed humus layer. Mineral soil not visibly altered, but organic matter partially charred	Deep impacts; entire forest floor consumed; top layer of mineral soil visibly altered. Mineral soil black due to charred or deposited organic matter or is orange.

Climatic Data

Climatic data for stands was collected through the use of latitude/longitude coordinates and ClimateNA (Wang et al., 2016; The University of British Columbia, 2019). Climatic data included annual, seasonal, and monthly variables from historical data for 30-year normal for the time period of 1981 through 2010 (Wang et al., 2016). This range was utilized because it aligned with the 40-year chronosequence of harvest stands monitored that occurred from 1978 through 2013. Annual variables included those that were directly calculated, such as mean annual temperature, and derived annual variables like the number of frost-free days. Seasonal variables also included those that were directly calculated and derived seasonal variables. Lastly, monthly variables were primary monthly variables, such as mean temperatures for each month, and derived monthly variables.

Moisture deficit is the difference between potential evapotranspiration and dependable precipitation. When excess moisture is present it is indicated by a negative deficit value (Hargreaves, 1975). George Hargreaves developed the 1985 Hargreaves equation as a predictive method for reference crop evapotranspiration. It is most commonly utilized to provide reference crop evapotranspiration predictions for weekly or extended periods of time that can be utilized in irrigation planning (Hargreaves and Allen, 2003). The 1985 Hargreaves equation is as follows:

$$\mathrm{ET}_o = 0.0023\, R_a\, (\mathrm{TC} + 17.8)\, \mathrm{TR}^{0.50}$$

Where: ET_o is the reference crop evapotranspiration

0.0023 is an adjustment for the coefficient to be used for months of peak demand

R_a is extraterrestrial radiation

TC is the temperature in degrees Celsius

TR is the daily temperature range (mean maximum temperature minus mean minimum temperature

This equation requires minimum data and easy to computer (Hargreaves and Allen, 2003).

Soil Properties Data

Once stands were stratified and digitized in an ArcGIS layer further data collection for each stand was gathered through a variety of digital sources. USFS TEUI data was used to collect information on soil parent material, soil depth to restrictive layer and wind erodibility index (USDA Forest Service, 2019). Dominant soil series was identified from STATSGO (NRCS State Soil Geographic database) or SSURGO (Soil Survey Geographic) databases which was accessed through SoilWeb (Beaudette and O'Green, 2009).

Soil property data, not characterized in the field, was accessed through Web Soil Survey (Soil Survey Staff, 2019b). From the soil data available values were collected for the dominant soil series in each stand. Soil data collected from this site included clay, silt, and sand percentages as well as organic matter content. The soil textural class, bulk density in g cm^{-3}, and depth to restrictive layer (lithic bedrock) was also collected for the first 30 cm of mineral soil. Coarse fragment content as well as presence of volcanic ash was documented through the use of field observations and official soil series descriptions (Soil Survey Staff, 2019a). Coarse fragment content is for the first 30 cm of mineral soil. Volcanic ash was classified as no volcanic ash present, vitrandic, andic, or within the Andisol soil order.

Data Analysis

All analysis was completed in SAS software version 9.4 (SAS Institute Inc., 2016). All monthly, seasonal and annual 30-year normal climatic data were reduced through the use of PROC VARCLUS to avoid autocorrelation in similarly related variables, leading to overfitted models. This procedure helped decrease the redundancy of variables in the model by creating clusters of nonoverlapping variables that can be interpreted as unidimensional, a feature shared with principal component analysis (Nelson, 2012). Upon completion of the VARCLUS procedure, retained site and soil data were analyzed utilizing stepwise multiple linear regression through SAS PROC GLM utilizing stand disturbance percentage as the response variable (SAS Institute Inc., 2018). For this analysis, disturbance percentage is the sum of Class 1, 2, and 3 disturbance. Inherent variability in soil factors motivated the use of a higher alpha value (α=0.1), therefore a higher p-value, in order to assess soil or site characteristic affects in this study. ANOVA (analysis of variance) Type III sum of squares from PROC GLM were utilized.

Results

Harvest Season and Time

Prior to inclusion of soil characteristics in stepwise regression, we found that harvest operations that took place in spring, summer, or fall resulted in higher disturbance than winter harvest operations. However, once soil characteristics entered, this weak relationship was no longer significant (p-value > 0.1). There is a trend towards recovery after 10 years has passed since the last harvest operation had concluded.

Climate

Similar to harvest season, prior to inclusion of soil characteristics in the stepwise regression model, we found these two climatic variables significant. The two climatic variables that were significant was spring Hargreaves climatic moisture deficit (CMD) and autumn maximum air temperature (Tmax_at). Once soil properties were entered into the model, these relationships are no longer significant.

The spring Hargreaves climatic moisture deficit measures the difference between potential evapotranspiration and dependable precipitation. As the CMD increases the amount of soil disturbance decreases (Figure 2.4). When harvests occurred during dry spring seasons it resulted in less soil disturbance. Amount of soil disturbance is displayed on the y-axis while the CMD for the spring season is displayed on the x-axis in millimeters in Figure 2.4.

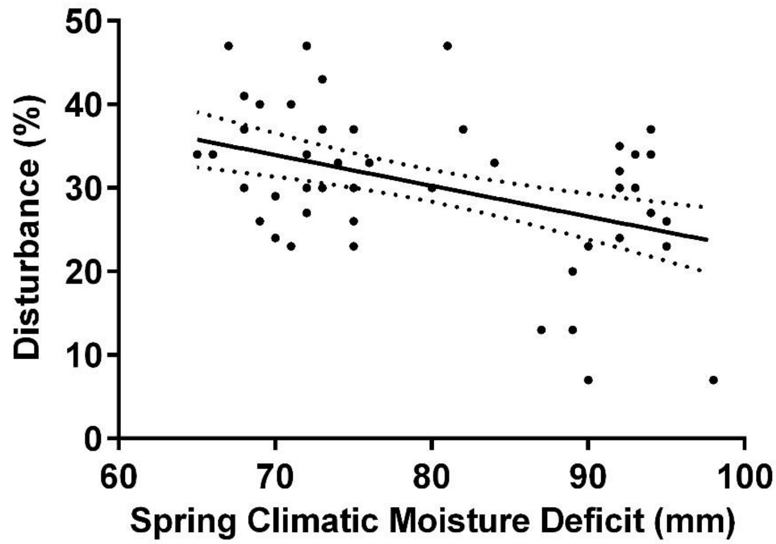

Figure 2.4: Soil disturbance (percent) relative to the spring Hargreaves climatic moisture deficit (mm) while holding all other values constant. Solid line on graph is the simple linear regression fit to the data. Dotted lines are the 90 percent confidence intervals.

The mean maximum temperature during autumn resulted in higher disturbance percentage (Figure 2.5). As the mean maximum autumn temperature decreased the amount of disturbance observed increased. Warmer mean maximum temperatures resulted in less disturbance when harvesting occurred during autumn months.

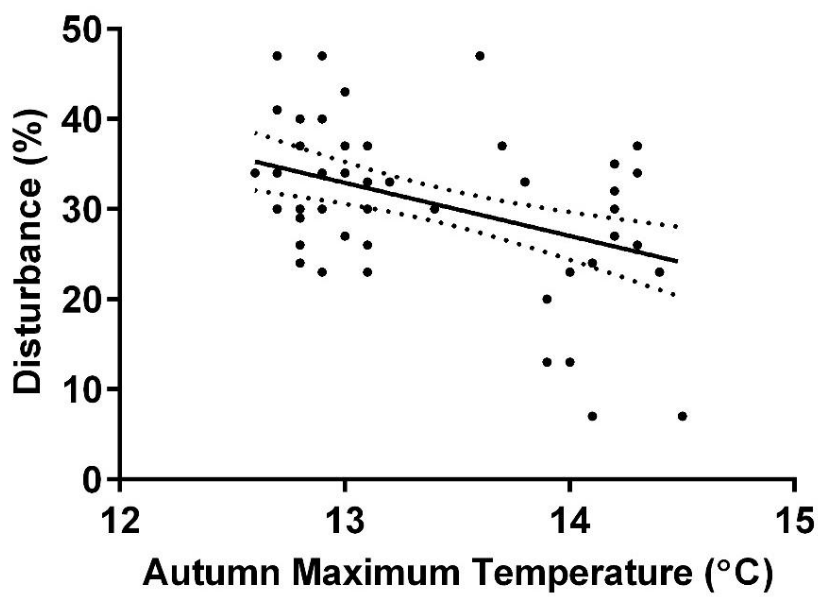

Figure 2.5: Soil disturbance (percent) relative to the Autumn maximum temperature (C°) while holding all other values constant. Solid line on graph is the simple linear regression fit to the data. Dotted lines are the 90 percent confidence intervals.

Soil

The main effects that significantly affected soil disturbance in the model (p-value < 0.10) was clay, silt content, and volcanic ash classification. Two-way interactions that significantly affected disturbance ($p < 0.10$) included clay x silt content, depth to restrictive layer x coarse fragment, and silt content x depth to restrictive layer (Table 2.3)

Table 2.3: Significant model variables and their associated probability values (alpha = 0.10).

Variable	***p*-value**
Clay Content (percent)	0.0309
Silt Content (percent)	0.0213
Ash Classification	0.0542
Clay content (percent) x Silt content (percent)	0.0317
Depth to restrictive layer (cm) x Coarse fragments (percent)	0.0370
Silt Content (percent) x Depth to restrictive layer (cm)	0.0444

Stands characterized within Andisol soil order, had a significantly higher percentage of soil disturbance ($p = 0.0017$) than soils classified as vitrandic or andic. Soils not influenced by volcanic ash had a significantly lower amount of soil disturbance ($p = 0.0522$). The presence of an Andisol on any given harvest stand increased any disturbance rating by approximately 40 percent ($p < 0.1$; Figure 2.6). Soils with an ash presence, but would not qualify as an Andisol, on average would increase a soil disturbance rating by approximately 18 percent. However, the variability in these soils was too great to say it was significantly different than those soils without an ash presence ($p > 0.1$).

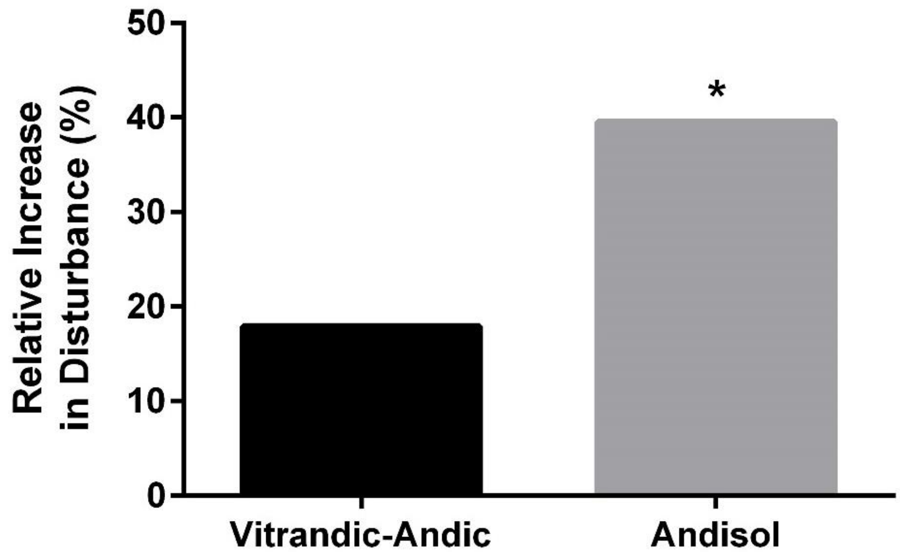

Figure 2.6: Percent change in soil disturbance relative to no ash present while holding all other values constant.

There was a strong interaction in soils with varying admixtures of silt and clay. We found that as silt content increases relative to clay content there was a significant increase in disturbance (p = 0.0317). In contrast, as clay content increases relative to silt content, disturbance impacts decrease (Figure 2.7).

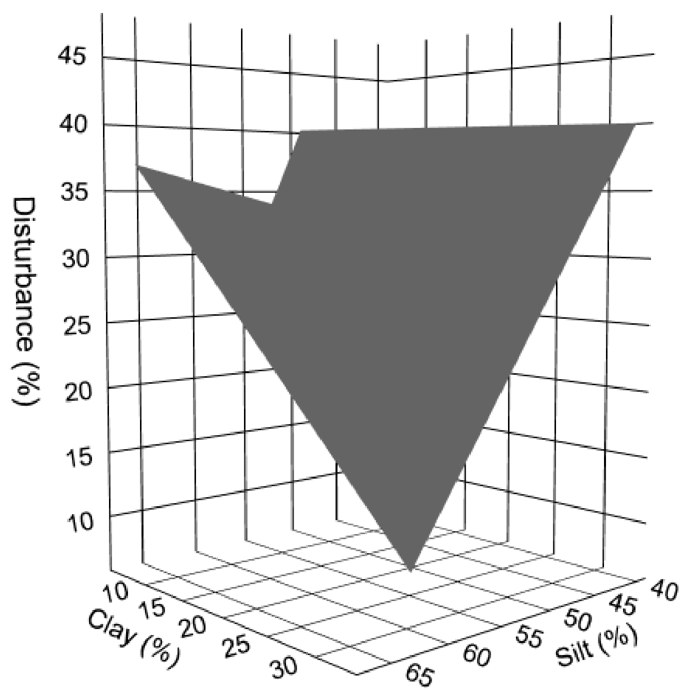

Figure 2.7: The effect of clay and silt content (percent) on soil disturbance (percent).

Furthermore, deep silty-textured soil profiles significantly increased in the potential for soil disturbance and seen in this model as the interaction between silt content (percent) and depth to restrictive layer in centimeters (p = 0.0444; Figure 2.8).

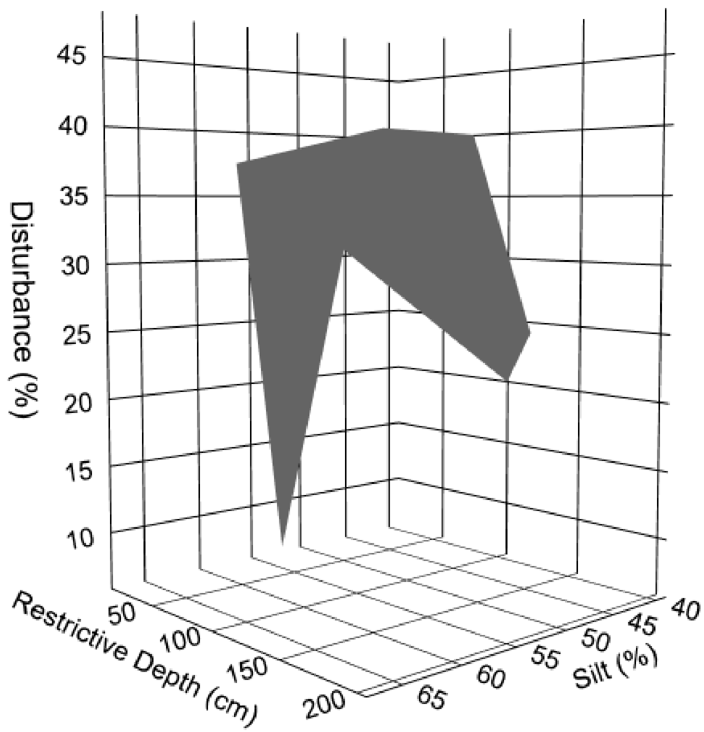

Figure 2.8: The effect of silt content (percent) and depth to restrictive layer (cm) on soil disturbance (percent).

The interaction of coarse fragment content and depth to restrictive layer significantly lowers soil disturbance (p = 0.0370). As the coarse fragment content increases in deep soils the amount of disturbance also increases (Figure 2.9). Shallow soils, soil profiles that are 30 cm in depth till it reaches the restrictive lithic layer, had a lower amount of soil disturbance with 45 to 60 percent coarse fragments than deeper soils.

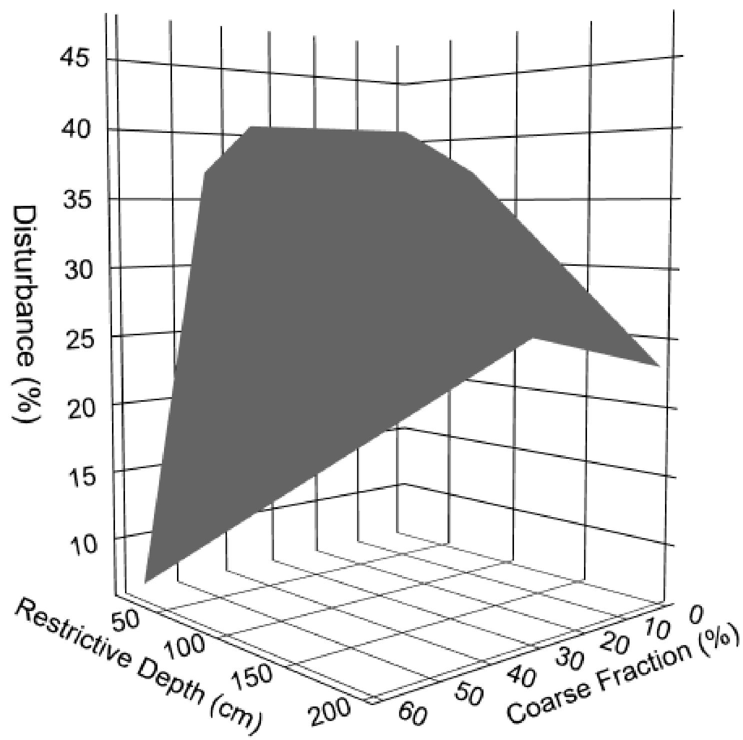

Figure 2.9: The effect of depth to restrictive layer (cm) and coarse fraction (percent) to percent soil disturbance.

Discussion

Soils are an essential component for sustaining the function and productivity of forests. Forest management activities that reduce organic matter levels, compact the mineral soil, cause puddling, rutting or erosion can decrease site productivity and disrupt hydrologic function. The use of visually determined soil disturbance monitoring can be used by foresters, soil scientists, logging supervisors, machinery operators, and other specialists to evaluate the amount and areal extent of soil disturbance to help inform best management practices and the need for restoration activities (*e.g.*, ripping skid trails; Aust et al., 1998). Soil monitoring conducted both pre- and post-harvest will also identify if (1) soil processes and hydrologic function have been disrupted, (2) soil recovery is occurring, and (3) harvest or site preparation methods should be adjusted. In general, many national forests use Class 2 or greater soil disturbance, with an areal extent of >15 percent, to indicate that a soil has been detrimentally impacted (D. Page-Dumroese, Research Soil Scientist, pers. comm. October 24, 2019) and might lead to declines in stand growth or soil function. On some soils (i.e., ash-influenced) smaller impacts (*e.g.*, Class 1 or 2 disturbances) from harvest operations can last particularly long (Froehlich et al., 1985; Page-Dumroese, 1993) and greatly impact tree growth (Cerise et al., 2013; Froehlich et al., 1986).

My findings indicate that clay and silt content, presence of deep volcanic ash deposits (Andisols) were the main effects that significantly affected soil disturbance. Soils with a high amount of clay content (>20 percent clay) are more readily compacted during timber harvesting (Robinson et al., 2011; Williamson and Neilsen, 2000), but those containing 50 to 70 percent clay and silt are susceptible to the greatest amount of compaction (Smith et al., 1997; Williamson and Neilsen, 2000). The clay content is stabilizing the silt reducing compaction and disturbance. These soils are susceptible to compaction. Soil moisture content is another important factor that influences soil compaction that works along with clay content.

Compacted soils can limit plant growth by inhibiting roots from penetrating the soil. Roots rely on large pore spaces in the soil to penetrate deeper into the soil profile as well as moving soil particles around smaller pore spaces to allow root tips to grow. In a compacted soil the pore spaces can be too small or too rigid that inhibits roots from growing through these locations (Page-Dumroese et al., 2006) Although when a soil is compacted to its growth-limiting soil bulk density it drastically reduces most pore spaces in the soil to the point they are drastically smaller than the plants growing roots. At this point root growth is stopped due to the inability to exert the amount of pressure the roots would need to overcome the mechanical resistance of the compacted soil to move soil particles (Aubertin and Kardos, 1965; Daddow and Warrington, 1983; Wiersum, 1957). A soils growth-limiting bulk density is influenced by the soils texture. This is a strong influence due to the variation of pore sizes for the average soil texture as well as the mechanical resistance of a compacted soil. Soils with a large amount of fine particles (clay and silt) results in smaller pore diameters as well as an increased penetration resistance at a lower bulk density when compared to a soil with a large amount of coarse particles (Daddow and Warrington, 1983).

Harvest operations that occur in spring (March 20-June 21) can cause substantial soil impacts because soils often have a high soil moisture content. This study found that if there is a relatively dry spring when harvesting occurs it would result in lower disturbance. This was likely due to warm, dry springs during these harvest seasons. As the soil moisture deficit increases during the spring then the amount of soil disturbance decreases, as seen from the spring Hargreaves climatic moisture deficit. Interestingly, when harvest operations were conducted during a hot, dry fall (September 23-December 21) season there was an increase in soil disturbance. Fall harvest operations lack much in the way of understory plants and therefore, there is little vegetation to buffer equipment impacts to the forest floor and mineral soil resulting in an increase in soil disturbance. This is in terms of utilizing the existing vegetation as a mat to buffer the soil from disturbance such as compaction. It is unknown if a slash mat was employed during harvest operations. Since this is a retrospective study, I could not determine if there was a snowpack or frozen soil at the time of harvest.

Reeves et al. (2011) found that landtype was an important factor for influencing the potential to be disturbed during timber harvest and in my study, harvest season, slope, and aspect were used similarly to landtype. Winter harvesting trended towards a lower amount of soil disturbance both on the Malheur (this study) and on the Kootenai National Forest (Reeves et al., 2012). Typically, winter harvesting occurs on either frozen soils or a snowpack that will reduce disturbance from occurring.

Rock content is an important factor governing a soils ability to resist compaction. The type and size of rocks (gravel, cobbles, etc.) also factor into how susceptible the mineral soil may be to equipment trafficking. Soils with a high level of coarse rock-fragments in the profile may be one reason soil disturbance is less on some soil types (Williamson and Neilsen, 2000). Corns (1988) found that coarse-textured gravely soils resisted compaction after being impacted by heavy forestry equipment used in a timber harvest (Corns, 1988; Williamson and Neilsen, 2000). Soils with a high gravel content, more than 15-20 percent by volume, acts as a supporting frame. This helps distribute stress throughout the soil across the surface. It protects the fine earth fraction considerably from compaction and increase precompression stress considerably. Soils that have levels of very high gravel content are found that there is not enough fine earth fraction in the spaces between the gravel that can become more heavily compacted (Rücknagel et al., 2013).

Rock fragments that are found below the surface of the soil are able to support the soils existing structure. This allows the rock fragments to have a negative effect on the soil's susceptibility to compaction (Poesen and Lavee, 1994). Saini and Grant (1980) found that when a dynamic load was applied to a soil with a loamy texture, the rock fragments present decreased compaction of the fine earth fraction. The smallest rock fragments were found to be the most effective at reducing the potential for compaction (Poesen and Lavee, 1994; Saini and Grant, 1980).

This study represents a chronosequence of 40 years since the last timber harvests were accomplished. While we did not see a significant recovery after 10 years, there was evidence that recovery begins at approximately year 10 following post-harvest. Variability in data and the significant presence of volcanic ash across most soils may be the primary reasons we did not see substantial recovery. Similarly, Gier et al. (2018) found that volcanic ash-cap soils did not show signs of recovery. Ash-cap soils often experience a greater degree of compaction as compared to other mineral soils and the increased bulk density can last greater than 20 years (Froehlich et al., 1985). My data is not similar to that from the Kootenai National Forest in Montana where soil recovery occurred in the first 3-5 years (Gier et al., 2018). A majority of soil on the Malheur National Forest did not show a recovery trend. Similar to my study, Gier et al. (2018) found that volcanic ash-cap soils did not show signs of recovery. In this study there was ash-cap soils and non-ash soils. Gier et al. (2018) found that the soil disturbance recovery was not constant for all soil types. Majority, 86 percent, of the non-ash soil stands sampled had a reduction in soil disturbance when compared to initial soil disturbance data that was collected between 1992 and 2006. Ash-cap soils on the Kootenai National Forest that were sampled had varying amounts of soil moisture as well as varying depths of ash in the soils that were resampled (Gier et al., 2018). Lack of recovery on volcanic ash soils poses a risk to future stand productivity, water movement and storage, understory production, and other ecosystem services (Daddow and Warrington, 1983; Purser and Cundy, 1992; Smeltzer et al., 1986).

Soil recovery after timber harvests was not constant throughout all stands monitored for this study. There is a trend towards recovery after 10 years post-harvest, but it is not statistically significant. Volcanic ash-cap soils may not recover as facilely from compaction as soils that do not contain volcanic ash. These soil types are very sensitive to disturbance.

Management Implications

Recovery from soil disturbance is not a constant process for all soil types sampled and, on soils with a volcanic ash-cap, the recovery period may last numerous decades with the potential to cause decreased stand productivity or altered hydrologic function. As noted by other authors (*e.g.,* Flatten, 2002; Johnson et al., 2007; Reeves et al., 2011; Williamson and Neilsen, 2000) winter (December 22-March 19) logging can limit the amount of soil disturbance. Areas with dry spring weather are also good candidates for early season harvest operations. Commercial thinning on deep soils with a high silt, low clay and low coarse fragment content resulted in greater soil disturbance. On this soil type limiting harvest operations to winter may reduce the amount of soil disturbance. This would be suggested for winter harvest operations as well to take advantage of frozen soil or a snowpack.

The FSDMP is an important tool for rapid assessment of both pre- and post-timber harvest soil disturbance and recovery rates. Furthermore, collecting soil monitoring data is crucial for ensuring sustainable harvest operations for the future. Documenting some level of disturbance prior to harvest operations begin is an important step that will describe the type of legacy disturbance within a stand. Utilizing this data to gain a better understanding of soil recovery and how different timber harvest operations impact different soil types is contingent upon collecting accurate data throughout all national forests. Employing a consistent soil monitoring protocol is imperative to ensuring the data collected can be used over time to further expand our understanding of how soils recover after disturbance.

Determining the cause and effect relationship of growth-limiting soil impacts, coupled with variations in climate and site properties, is difficult (Curran et al., 2007). However, soil disturbance is identifiable with visual categories and can be managed with careful harvest operations. Therefore, monitoring soil visual properties in a pre- and post-harvest environment and over time helps determine longer-term effects both on and off-site and promotes adaptive management (Curran et al., 2005). Understanding the range of soil impacts is the first step in determining soil changes. The next step will be to use vegetation growth to validate the soil disturbance categories (Page-Dumroese et al., 2012) thereby determining (1) which FSDMP categories are appropriate to determine when disturbance may be detrimental to soil processes, stand productivity, and hydrologic function and (2) best management practices that promote limited disturbance.

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