Effect of Ground Based Harvesting Equipment on Soil Physical Properties

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Abstract

Logging in the Pacific Northwest is a key driver in local economies that are natural resource dependent. For many communities in the Pacific Northwest, logging is a livelihood that runs back many generations. The 2021 world population is about 7.8 billion human beings. With the population continuing to increase, the housing market is also on the rise, creating additional demands on logging and manufacturing of lumber. Foresters and loggers have responsibilities to steward the forests. This responsibility includes sustainable operations to ensure a future for the timber industry. There is also a major responsibility to sustain the contribution to the world supply of wood products. The environmental responsibilities that come with logging operations are crucial to creating a sustainable environment. One of the primary pieces of equipment used in ground-based logging operations is a rubber-tired skidder. Rubber-tired skidders are large tractors specifically designed to collect and skid timber for harvest and transport to a landing. During the process of harvesting and skidding trees, the forest floor experiences an exponential amount of weight and displacement. This weight causes soil compaction, and the displacement exposes mineral soil. Skidders establish primary skid trails which become heavily compacted causing the soil’s elasticity to diminish. This study examines the change in soil bulk density caused by rubber-tired skidders in different traffic intensities. The need to use rubber-tired skidders will be present and soil disturbance will not be completely avoidable. The recommendation is to limit the use of rubber-tired skidders to designated skid trails following Best Management Practices (BMPs).

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Dedication

I want to thank my dad, sister, and Mike for the support over the years and just overall being around for me. My kids for being the reason I wake up every day, why I work so hard, and the reason why I strive to be the best. Marissa, you have been my rock through this incredible journey that has led up to this moment. None of this would be possible if it weren't for your sacrifices as a wife and mother. I want to give you the world and will forever be thankful that I have a partner that will support me no matter what. Thank you for being my lab assistant through this research. Grandma, thanks for the help financially and always being the one person who always believed in me. I'd like to thank my mom for this path, the reason I am where I am in life, the reason I can achieve my dreams. You were the best role model that I could ask for and I am glad to be following in your footsteps.

Thank you to my grandpa, I wish we could share these moments together. I thank you for everything you did for me growing up. Thank you for being there for me when I needed it most.

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Chapter 1: Introduction

Logging in the Pacific Northwest is a key driver in local economies. For many communities in the Pacific Northwest logging is a livelihood that goes back many generations. The 2021 world population is about 7.8 billion human beings (Population Reference Bureau, 2021). With the population beginning to rise to high rates, the housing market is also on the rise and the need for logging is greater than ever to produce lumber. With logging comes responsibilities to the forests and using sustainable operations to ensure a future in the timber industry. There is a major responsibility for foresters and loggers to sustain the contribution to the world supply of wood products (Kimmins 1996).

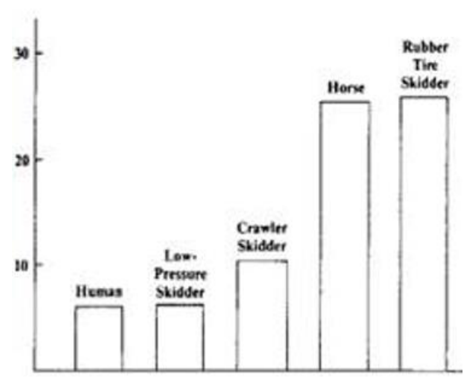
By definition, sustainable means a method of harvesting or using a resource so that the resource is not depleted or permanently impacted. Despite a growing global population, there are finite natural resources available for use. The practice of sustainable forestry to meet the increasing worldwide demand for wood products is a primary goal of the Idaho Forest Practices Act and organizations like the Sustainable Forestry Initiative (Heninger et al. 1997). One shortcoming many natural resource managers around the world may have in common is their lack of understanding of, or sensitivity to, soil as a vital component of the forest ecosystem and a key determinant of the sustainability of timber and other forest values (Kimmins 1996). The Idaho Forest Practices Act was implemented to guide foresters and members of the Idaho timber industry to a more sustainable future. In Idaho, the Idaho Department of Lands administers the FPA, a law created in 1974 to promote active forest management and ensure that the health of forest soil, water, vegetation, wildlife, and aquatic habitat is maintained during the growing and harvesting of forest trees in Idaho (Idaho Department of Lands 1974).

For a forest to remain sustainable, one of the most important factors is to prevent detrimental soil disturbance. The U.S. Forest Service manual sets the limit for detrimental soil disturbance at no more than 15% for an active area (Nash 2021). Detrimental disturbance will reduce the potential of the forest and cause loss of soil or soil fertility (Poore 1989). To ensure sustainable forest management and harvest practices, there is a responsibility to take the steps necessary to protect the long-term productivity of forestlands, including soils.

Maintenance of soil productivity is a statutory mandate of the National Forest Management Act (NFMA) of 1976 (Reeves et al. 2011). Forest soil can suffer from various threats, some of which are human induced. Mechanized timber harvesting allows for high productivity however, it may also negatively impact forest soils. In recent decades, the use of mechanized logging systems in forest management has increased exponentially (Cambi et al. 2015). Soil compaction originating from logging operations has a significant impact on the porosity of soils, alters habitat for the soil organisms, and restricts root growth (Schnurr et al. 2006).

Ground based logging causes the highest amount of disturbance to the forest floor (Reeves et al. 2011). Soil disturbance during logging operations is primarily caused by rubber-tired skidders, crawler tractors, collecting and piling slash or preparation for planting and these activities compact the soils reducing plant growth (Cullen 1911). In recent years logging vehicles and equipment are becoming more powerful and increasingly heavier causing soil compaction in forests (Cambi et al. 2015).

Figure 1.1 comparing the pounds per square inch created between different variables of harvesting timber.



Forest management practices have seen an increase in the use of heavy machinery in the forest to improve time and cost efficiency of harvesting operations (Gent and Morris 1986). Alternative options exist outside of ground-based logging such as cable logging, tethered logging and helicopter logging. These alternatives reduce the amount of soil disturbance compared to ground-based harvesting (Reeves et al. 2011). During construction operations, drum-type rollers are used routinely to compact soils for road applications. Kneading compaction is typically accomplished by using a sheepsfoot roller that gradually increases the amount of pressure until the desired compression is achieved (Crawford et al.

2021). The interaction of the tires on rubber-tired skidders used in forest harvesting operations resembles that of kneading compaction machines, but with far less pressure than the equipment designed for that purpose (Page-Dumroese et al. 2007).

Soil compaction can be affected by many factors including season, soil moisture, amount of traffic, and proper planning. During winter harvest operations soil impacts will be low if the soil is frozen or has adequate snow cover ≥15 cm (Johnson et al. 2007). The most compaction occurs on the first and second trip, additionally soil compaction is more significant on moist soil (Simpson 1981). Soil compaction reduces wood production and increases water runoff (Simpson 1981). When a logging operation occurs in a forest stand, it must account for ecosystem impacts and logging companies should be responsible for collecting and identifying soil samples to measure soil disturbance on a site (Reeves et al. 2011).

The heavy equipment driving over the soil multiple times begins to alter the structure and characteristics of the soil. Soil compaction may increase water retention and decrease pore size in coarser soils resulting in a change in the water holding capacity of soils (Cullen et al. 1911). Soil compaction mainly reduces pores larger than 5μm whereas pores .2-5 μm are typically unaffected (Van der Linden et al. 1989). Macropores are important for diffusive gas transfer and compacted soils reduce gas diffusion coefficients (Schnurr et al. 2006). Soil compaction causes an increase in bulk density because the soil aggregates collapse in larger pores creating more micropores (Startsev and McNabb 2000).

Detrimental soil compaction detected between 0-20cm is dependent on soil moisture, structure, and type of equipment (Rahman 2019). As bulk density increases, root penetration resistance increases as well (Tracy et al. 2011). Root penetration occurs in macro pores and when bulk density exceeds 1.9g/cm^3 the compacted soil will halt root growth (Rosenberg 1964). Root growth will become restricted, and roots will lack the ability to reach available resources for growth. Timber production on compacted soil in skid trails has shown minimal growth yields (Miller 2007) Trees next to the skid trails had an increase in diameter at breast height (DBH) compared to the rest of the forest over 7-11 years (Miller 2007). With a lack of competition from compacted skid trails growth yields along the skid trails increase.

Other methods of logging exist utilizing BMPs that reduces the footprint that logging may have on soil properties. Slash mats can be deliberately placed on skid trails to reduce rutting and soil compaction (Miller 2007). Reducing soil compaction will have a significant impact on forest soils in the long term and it has been demonstrated that soil compaction below 15cm can take over a century to recover (Nawaz et al. 2013). Understanding the plasticity of soils between clay soils to sandy soils also determines the amount of time it takes for soil compaction to recover to a habitable state (Cambi et al. 2015). This research examined the impact rubber-tired skidders have on a forest stand after a logging operation 11 years post-harvest. This will help better understand the long-term effects soil compaction has on regeneration and the plasticity of this type of forest soil.

Chapter 2: Methods

The stand is on a 15-hectare harvested site located approximately 12 miles west of Deary, Idaho (46.8445° N, 116.7960° W, 860 m) in the East Hatter Creek Unit of the University of Idaho Experimental Forest. The site slopes down (ranging from 5-20% slope) towards a stream at the southern edge of the unit, giving the site a south-facing aspect, with a somewhat level shelf at the northern edge. The site was logged in August 2011, with approximately 100 trees left standing to meet leave-tree obligations under the Idaho Forest Practices Act (McNassar 2013). Using photographs from satellite imagery post-harvest, skid trails were identified. Soil bulk density samples were taken from these skid trails and areas where logs were not skidded, and machinery were not driven over.

Four treatments were used to categorize the traffic intensity within the stand. The moderate machine traffic areas were identified as nine skid trails within the stand. All nine skid trails were primary skid trails and were identifiable due to the presence of deep ruts and soil displacement resulting from skidding operations. Five samples were initially taken in July 2022 from four skid trails approximately 1 meter apart within the ruts. The high machine traffic treatments were identified as the primary road around the stand. Eight samples were taken from the road, five from the southern end of the road and three from the northern end of the road. Each sample selection was approximately 1 meter apart. After analysis for sample variance, five samples were taken from five more skid trails in August 2022 in an effort to reduce variability.

Low machine traffic areas were identified as low disturbance locations. Low disturbance locations were detected by the amount of regeneration and lack of soil disturbance based off photo observations which included small clusters of Western Larch *(Larix occidentalis)* off of the main skid trails. Fifteen samples were taken from three separate areas of regeneration areas, five samples per cluster of trees. Each sample selected was within the cluster approximately 1 meter apart. No machine traffic areas were identified as undisturbed locations. Two undisturbed locations were chosen approximately five meters outside of the harvest area, one sample area on the west side of the stand and the second on the east side of the stand. The undisturbed samples were taken in areas with no sign of a previous harvest or stand/soil disturbance. Five samples from the two control sites were taken 1 meter apart. A total of 78 samples were taken from the stand: 10 no machine traffic, 15 low machine traffic, 45 moderate machine traffic and 8 high machine traffic.

Soil bulk density methods were replicated from a previous research project (Brooks 1996). Duff and debris were removed to expose the mineral soil. The bulk density cup with two 10cm metal liners was driven 20cm into the ground using the hammer slide. The hammer slide was rotated around in a circle to separate the surrounding soil from the hammer slide. The hammer slide is pulled out and the bulk density cup was removed by unthreading the hammer slide. Using the metal fitting, the stainless-steel liners were pushed out through the top. Only the bottom 10cm liner was being taken for sampling. A knife was used to create a straight edge on each side of the cylinder. The sample was then inserted into an oven safe plastic bag and labeled with the treatment and sample number. The samples were transported from the stand to the lab in a plastic tote.

Samples were placed in the University of Idaho silviculture lab in an oven at 90º C for 48 hours. The oven temperature was assessed once every twelve hours to monitor the proper oven temperature. After 48 hours the samples were removed and placed in a desiccation machine for 15 minutes. One sample was removed from the desiccation machine at a time and the door would be shut. Each sample would be weighed in grams to record the dry weight. Once all samples were collected the bulk density equation was applied. The bulk density average was calculated amongst each plot of samples. The equation for bulk density is $Y = \frac{Md}{Vt}$. The volume of the bulk density cup was 90.4098 g/cm^3. Bulk density is equal to the mass of the dry soil divided by the volume of the soil sampled.

A dry 40-gram sample was taken from the stand to identify the soil properties of the stand. The soil was placed in an Erlenmeyer flask with 100ml of distilled water. The Erlenmeyer flask was set in a mixing machine for three minutes. The Erlenmeyer flask was thoroughly rinsed and placed into a 1000ml cylinder. The cylinder was filled up to the 1000ml mark with distilled water. The cylinder was thoroughly stirred, and a hydrometer was added to the cylinder. At exactly 67 seconds the sand reading was collected. At 11 hours and 34 minutes the clay reading was recorded.

$\left(\frac{\text{67 second Hydrometer reading}}{\text{Total mass of soil}}\right) \text{x } 100 = \% \text{ Silt} + \% \text{ Clay}$ % Sand = 100 – (% Silt + % Clay)

$\left(\frac{\text{11 hr 34 min Hydrometer reading}}{\text{Total mass of soil}}\right) \text{x } 100 = \% \text{ Clay}$ % Silt = 100 – % Sand - % Clay

The third test performed on the samples was an organic matter test. Ceramic cups were individually weighed and filled with twenty grams to the hundredth decimal of dry soil from each sample. The cups were placed in a furnace set to 550º C. The cups were in the furnace for four hours; one hour to allow the oven to reach the desired temperature and an additional three hours at 550º C. The samples were removed and placed in a desiccator for thirty minutes to properly cool. Each sample was then individually weighed to identify the amount of organic matter lost. The difference in weight between the cups before the oven and after identified the amount of organic matter in each sample.

A pH test was conducted to determine the pH of the soil in the stand to better understand the stand's soil properties. The pH test was conducted in the soil systems lab with a pH probe. Five random samples were selected from the site. One sample from no traffic, low traffic and high traffic. Two samples were taken from moderate traffic. 10g of soil was taken from each sample and individually put in separate 250ml test tubes. 10ml of distilled water was added to the test tubes. The tubes were shaken for 15 seconds until thoroughly mixed. The pH probe was turned on and inserted into three separated test tubes that contained a specific pH. The probe was inserted into 3 pH, 6 pH, and 10 pH samples to verify the pH probe accuracy and consistency. After cleaning the probe, it would be inserted into one sample at a time. A pH value would be shown and annotated at which point the probe would be cleaned and inserted into the next sample until all five samples were tested.

Chapter 3: Results

Figure 3.1 shows the distributions of the soil bulk density tests using a box plot. The primary logging road was classified as high machine traffic #4, skid trails are classified as moderate machine traffic #3, areas with little disturbance are classified as low machine traffic #2 while the off-site areas have no machine traffic #1. The high machine traffic samples had the highest amount of bulk density with a median of 1.54 g/cm^3. The moderate machine traffic had a median bulk density of 1.32 g/cm^3. Low machine traffic was on the lower end for a median bulk density of 1.1g/cm^3. No machine traffic had the lowest median bulk density of 1.03g/cm^3.

Figure 3.1 Distributions of the soil bulk density tests using box plots

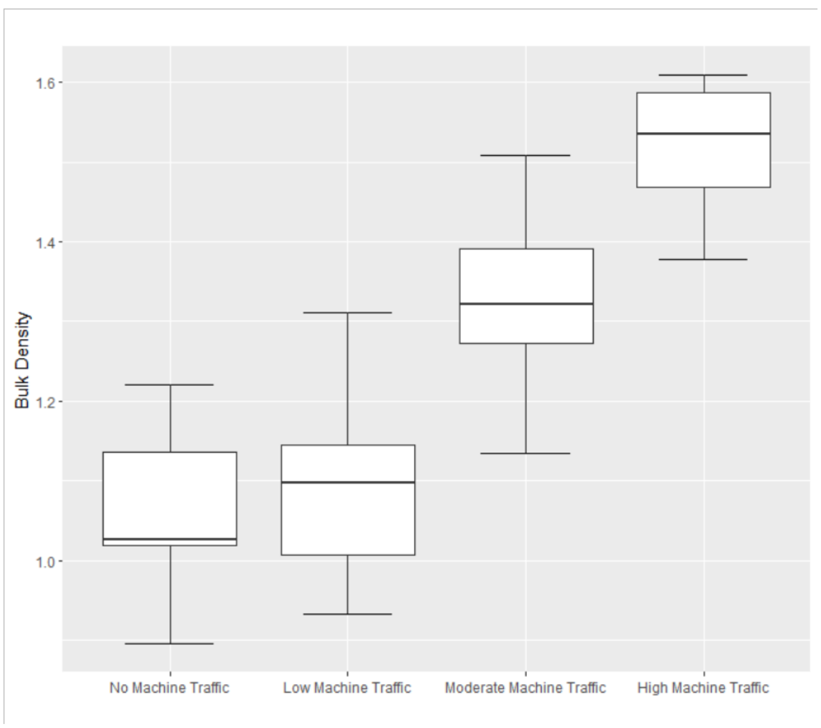


Table 3.1 Orthogonal contrasts of the machine traffic variables within the bulk density tests

	Estimate	Std. Error	t value	Pr(>|t|)
Traffic.Level 1 vs 2	-0.02937333	0.03891916	-0.7547268	4.528409e-01
Traffic.Level 2 vs 3	-0.23184803	0.02850317	-8.1341143	7.882105e-12
Traffic.Level 3 vs 4	-0.19636364	0.03664118	-5.3590971	9.347599e-07

Table 3.1 compares the differences between each category of samples in terms of soil bulk density. No and low machine traffic are not significantly different thus low and moderate machine traffic are significantly different. Moderate and high machine traffic are significantly different thus low and high machine traffic are also significantly different. The bulk density of the no and low machine traffic areas were expected to have a lower bulk density provided the lack of machine traffic.

The hydrometer results showed the stand was a silt loam with 19.6% sand, 54.5% silt and 25.9% clay. This site is classified in the Santa series of Alfisols, moderately well drained and moderately deep. They formed in deep loess with a small amount of volcanic ash in the upper horizons (NRCS, 2022) The results of the pH verified that the average pH in the stand had a mean of 4.62.

Figure 3.2 Distributions of the soil organic matter tests using box plots

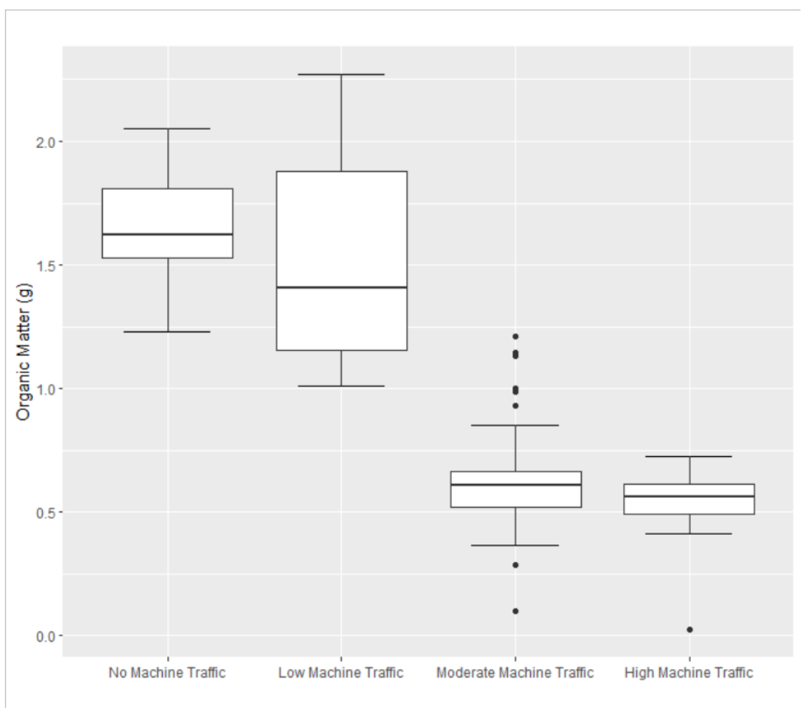


Figure 3.2 is a boxplot listed in groups and identifies the amount of organic matter in each sample. The median of organic matter samples categorized to represent each location the sample was collected from. Each sample set was categorized identical to bulk density in numerical order from no machine traffic to high machine traffic. The high machine traffic

had the least amount of organic matter with a median of 0.56g, and the moderate machine traffic had a lower amount of organic matter with a median of .61g. Low machine traffic had a median organic matter count of 1.405g. No machine traffic had a median organic matter count of 1.62g.

Table 3.2 Orthogonal contrasts of the machine traffic variables within the organic matter tests

	Estimate	Std. Error	t value	Pr(>|t|)
Traffic 1 and 2 vs 3 and 4	1.0042778	0.07623179	13.174002	4.328468e-21
Traffic 1 vs 2	0.1517667	0.11109705	1.366073	1.760534e-01
Traffic 3 vs 4	0.1296778	0.10441547	1.241940	2.181804e-01

Table 3.2 categorizes each traffic level numerically from no machine traffic to high machine traffic. Meeting expectations, no and low machine traffic are not significantly different. Moderate and high machine traffic are not significantly different. Thus, low machine traffic and moderate machine traffic are significantly different.

The organic matter count showed that no machine traffic had a median of 1 gram more organic matter compared to moderate machine traffic. The low machine traffic had a median difference of .765g more than moderate machine traffic. The correlation between bulk density and organic matter show an inverse relationship. As the median bulk density goes up throughout the site the amount of organic matter decreases. The roads with the highest bulk density throughout the site show the least amount of organic matter.

Chapter 4: Discussion

Samples were collected with the intent of identifying differences in soil bulk density between moderate machine traffic skid trails and additional levels of trafficked areas . The most abundant areas of moderate traffic were areas that were relatively closer to log decks. After 11 years the deep ruts in the moderate machine traffic areas were still visible and created useful areas to collect samples from. The high machine traffic and no machine traffic samples were taken from areas expected to have the highest bulk density and lowest bulk density. The road had been compacted after high intensities of machine traffic. Uncontrolled sites where regeneration was taking place were identified as low machine traffic areas with little soil disturbance. Off-site samples were collected where no evidence of a previous harvest and the samples were identified as no machine traffic.

No machine traffic areas had the lowest soil bulk density due to the absence of logging activity. These were areas in the stand that had no past evidence of logging operations. Due to the lack of traffic the soil exhibited no disturbance creating opportunities for regeneration. The road samples had the highest bulk density and the lowest organic matter count. The moderate traffic samples had a higher bulk density than the low machine traffic samples and also displayed a low organic matter amount. This could have been a result of compaction and soil displacement. The moderate machine traffic soil bulk density showed there will be possible root restriction on forest regeneration. This will likely lead to the regeneration of this stand being hindered.

The high traffic areas will likely not recover from compaction over long periods of time unless the road is ripped with tillage equipment. Samples were selected on the primary road to establish the amount of difference between the high traffic machine and the moderate machine samples. The moderate machine traffic samples were not hypothesized to exceed the high traffic samples, but they were hypothesized to exceed the low traffic samples in bulk density. Each traffic levels bulk density showed compelling evidence of the disturbance caused by rubber-tired skidders.

Additional samples were taken from moderate traffic areas to a soils lab where they were used in a hydrometer test to identify the soil characteristics. Using the sites coordinates on the NRCS website the soil was identified as Alfisol. This validates the silt loam texture and the presence of volcanic ash. Volcanic ash soils are silt or sandy loam (Johnson et al. 2007). Volcanic ash-influenced soils tend to be more susceptible to compaction, rutting, and mixing (Cambi et al. 2015).

Chapter 5: Conclusion

The result of this study validates rubber-tired skidders and other equipment cause soil compaction. The stand was harvested in 2011 and the samples were taken in 2022. After 11 years the compaction levels were still significantly different in the moderate and high machine traffic areas compared to the non-treated areas. The no machine traffic samples represented the bulk density baseline for the study area. The low machine traffic sites were areas that saw minimal skidder traffic.

1.9g/cm^3 is the bulk density that impedes root penetration and down to 1.3g/cm^3 stops root penetration for *Pseudotsuga menziesii* (Rosenberg 1964). High machine traffic and moderate machine traffic both exhibit bulk density lower than 1.3 g/cm^3. Although the site was treated with herbicides, over the last 11 years, there has been little progress in regeneration efforts. The only trees that remain in the stand are small portions within the low machine traffic sites and the leave trees from the past harvest. The data collected validates soil compaction does indeed play a role in the forest's regeneration.

Creating moderate machine traffic skid trails is unavoidable when performing ground-based harvesting. Certain counter measures or best management practices (BMP's) can be implemented to reduce the amount of soil compaction created by rubber-tired skidders. Placing slash in skid trails before skidding will protect the soil from rutting and compaction (Miller 2007). Harvesting in the winter while snow is on the ground, or the soil is frozen creates a buffer to prevent soil compaction (Rahman 2019). Reducing the amount of compaction on a site will keep macro pores present and have less restriction on root growth. Organic matter survives in the macropores of soil. With a higher bulk density, the overall size of the macropores are being reduced. The higher bulk density samples had the least amount of organic matter due to the macro pores available to organic matter.

Based on these observations the assumption is that this stand was harvested following Idaho's BMPs. Soil disturbance is unavoidable even when BMPs are followed, but the goal is to avoid detrimental soil disturbance. Proper planning to create skid trails throughout the stand can minimize soil disturbance. Establishing primary skid trails throughout the stand can reduce or divert runoff and prevent erosion. Understanding the soil type and the current soil moisture state will create a better understanding of the susceptibility of the soil. Avoiding wet unstable soils throughout a stand will help reduce soil compaction and erosion. In areas that are highly susceptible to soil compaction choosing alternative timber harvest techniques such as cable logging may have less impact on the forest soils.

Tracked skidders have been shown to create less soil compaction due to the surface area between the skidder and the soil (Sheridan 2003). The purpose of this study was to provide data that represented the effects that rubber tires have on soil. BMPs were created to safeguard natural resources. Understanding soil and site characteristics before harvest operations begin is the first step toward maintaining soil properties and processes (Crawford 2021). Following BMPs and using sound management decisions to reduce the amount of compaction created by a rubber-tired skidder will reduce the impact rubber-tired skidders have on soil porosity and lead to increased forest productivity.

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