EQUIPMENT TRIAL IN A WET-MESIC RED MAPLE STAND

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Abstract:

The objective of this trial was to use soil quality measurements to determine if any combination of equipment type and slash armoring of skid trails limited the potential for soil compaction and rutting during wet conditions, potentially expanding the logging operability window in these stand types. Four different types of equipment and two slash treatments were used to harvest timber in a wet-mesic red maple stand during wet conditions. Results suggest that the 8-wheeled, tracked equipment on slash covered skid trails may be effective at reducing compaction and rutting under wet conditions for this stand type. However, further trials may be necessary to clarify results before conditions for expanding of the operability window of these stands can be definitively recommended.

Equipment Trial in a wet-mesic Red Maple Stand

FLAMBEAU RIVER STATE FOREST (FRSF)

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INTRODUCTION AND OBJECTIVES

Soil compaction is perceived as one of the leading causes of soil degradation resulting from forest operations (Brais, 2001). Soil compaction during timber harvesting alters soil structure and hydrology by increasing bulk density, breaking down aggregates, decreasing porosity, aeration and infiltration capacity and by increasing soil strength, water runoff, erosion and waterlogging (Kozlowski, 1999; Grigal, 2000; Startsev and McNabb, 2000). Severe compaction of soil has been shown to adversely impact plant growth through the alteration of physical soil properties and plant physiological dysfunctions (Wronski & Murphy 1994). Growth inhibition and/or mortality of woody plants by soil compaction have been thoroughly documented in timber harvesting areas (Sands & Bowen 1978, Cochran & Brock 1985, Reisinger et al. 1988, Stewart et al. 1988, Firth & Murphy 1989, Alameda & Villar, 2009).

When the soil is not strong enough to support the weight of a vehicle, long depressions or ruts form. Rutting generally occurs when the soil pores are filled with water, essentially causing the soil to "liquefy". The deep furrows created by ruts can damage and sever tree roots and trunks, resulting in decreased nutrient uptake, declines in tree growth, entry points for disease and insects, increased vulnerability to wind throw, and tree mortality, if the damage is severe enough. Rutting also compacts and displaces soil, reducing aeration of soil, decreasing infiltration of water and, ultimately, degrading the rooting environment for plants. Rutting can occur on both mineral and organic soils. In wet conditions, ruts may be formed by only a single pass of equipment (WDNR, 2008). Slash reinforcement may be an effective means of reducing soil compaction and rutting on skid trails, especially in wet conditions (Eliasson & Wasterlund, 2007; Han et al 2006; Han et al 2009

The red maple stand on the FRSF that was the site of these trials is mainly comprised of soil that is somewhat poorly drained, with the depth to water table of only 6 inches. The entire stand is subject to a high water table that seasonally approaches the surface. These types of stand conditions can be difficult to work in because of the water and organic material in the soils. These soils may have a lower weight-bearing capacity and may be more susceptible to rutting. Often these stands can only be harvested during frozen ground or extremely dry conditions which limit the times of the year during which forestry operations can occur.

The objective of this trial was to use soil quality measurements to determine if any combination of equipment type and slash armoring of skid trails limited the potential for soil compaction and rutting during wet conditions, potentially expanding the logging operability window in these stand types. Four different types of equipment and two slash treatments were used to harvest timber in a wet-mesic red maple stand during wet conditions. The timber sale design was established in consultation with Jim Halvorson, FRSF Superintendent, Heidi Brunkow, FRSF Forester, Mike Blomquist, SAPPI Forester, and Carmen Hardin, DNR Forest Hydrologist. The timber sale was set-up and administration was overseen by FRSF staff and SAPPI covered the costs of providing different equipment to harvest the stand.

Stand Information

The stand for the equipment trial is located on the north side of County Road W, 2 miles west of the Flambeau River State Forest (FRSF) headquarters. The stand is approximately 20 acres in size, measuring 1500 feet by 600 feet, and is a red maple stand with a black ash component that is common within the FRSF. The overstory consisted primarily of small saw-sized red maple over pole-sized swamp hardwoods, with of pockets of hard maple and ash regeneration. Musclewood and hazel were also present and very dense in some areas. The understory also contained some areas of heavy sedge. The habitat type for the stand is ArAbCo (Acer rubrum-Abies/Cornus). This type is strongly associated with silt loams, and is best suited for management of balsam fir, white spruce, aspen and red maple. The moisture regime is wet-mesic and the nutrient regime is medium. To the north and west of this stand the elevation drops and becomes dominated by black ash. To the east, the elevation rises slightly and is currently dominated by aspen.

The average basal area for the stand prior to harvesting was 125 ft^2/acre, with an average stand diameter of 10". The stand age is approximately 80 years old. For prescriptive purposes the trial area was divided into 2 stands. However, for the purpose of study design and evaluation, the two areas are considered and discussed as one stand. The smaller stand (4 ac.) included scattered mature aspen and a coppice harvest was prescribed for the objective of aspen regeneration. The larger area had scattered hard maple and ash regeneration. A single tree selection, marked to 80 ft^2/acre, was prescribed for the objective of conversion to northern hardwoods.

Soil Information

The site is dominated by silt loams. The eastern third of the site is comprised of Chequamegon silt loam. The western two-thirds is Magnor, very stony-Magnor complex. Chequamegon silt loam generally has silt loam in the top 32 inches and then transitions into a sandy loam below that. The soil is moderately well drained, with a water table depth of only 12 inches. The Mangor, very stony-Mangor complex has silt loam in the top 21 inches, and then transitions to sandy loam and fine sandy loam. The soil is somewhat poorly drained, with the depth to water table at only 6 inches. Both soils are subject to a high water table that seasonally approaches the surface.

Some of the area is mapped as wetland per the Wisconsin Wetland Inventory. The wettest part of the sale is marked as a leave area with no harvest prescribed for this trial. The stand is in proximity, though not adjacent to Long Creek, a tributary of the Flambeau River.

Equipment Information

The sale was harvested by the same processor, but designed to test four different forwarder configurations. The processor was a Timbco Model 415 Processor with 36 inch wide tracks, weighing approximately 48,000 pounds. The four different forwarder configurations used to skid the wood were:

- Franklin Model 132, single bunk (4 wheels), 26 inch wide tires (normal), weighing approximately 21,000 pounds (designated "4-Wheels, Regular Tire"), 33,000 pounds loaded (2.5 cds.)

- Timberjack Model 1010, single bunk (4 wheels), 34 inch wide tires (extra wide), weighing approximately 26,000 pounds (designated “4-Wheels, Big Tire”), 33,000 pounds loaded (2.5 cds.)
- John Deere Model 1110, double bunk (8 wheels), 26.5 inch wide tires (normal), weighing approximately 38,140 pounds (designated “8-Wheels, No Track”), 69,340 pounds loaded (6.5cds.)
- John Deere Model 1110, double bunk (8 wheels), 26.5 inch wide tires (normal) with 28 inch wide tracks on front and back, weighing approximately 38,140 pounds (designated “8-Wheels, Tracked”), 69,340 pounds loaded (6.5cds.)

Skid Trail Layout Information

Eight skid trails were designated for the harvest. Each skid trail ran east to west. All of the skid trails went the length of the harvest area, except for the 8-Wheels, Tracked skid trails which by-passed a leave area. Each type of forwarder configuration had two skid trails, one with no slash and one with slash (Figure 1).

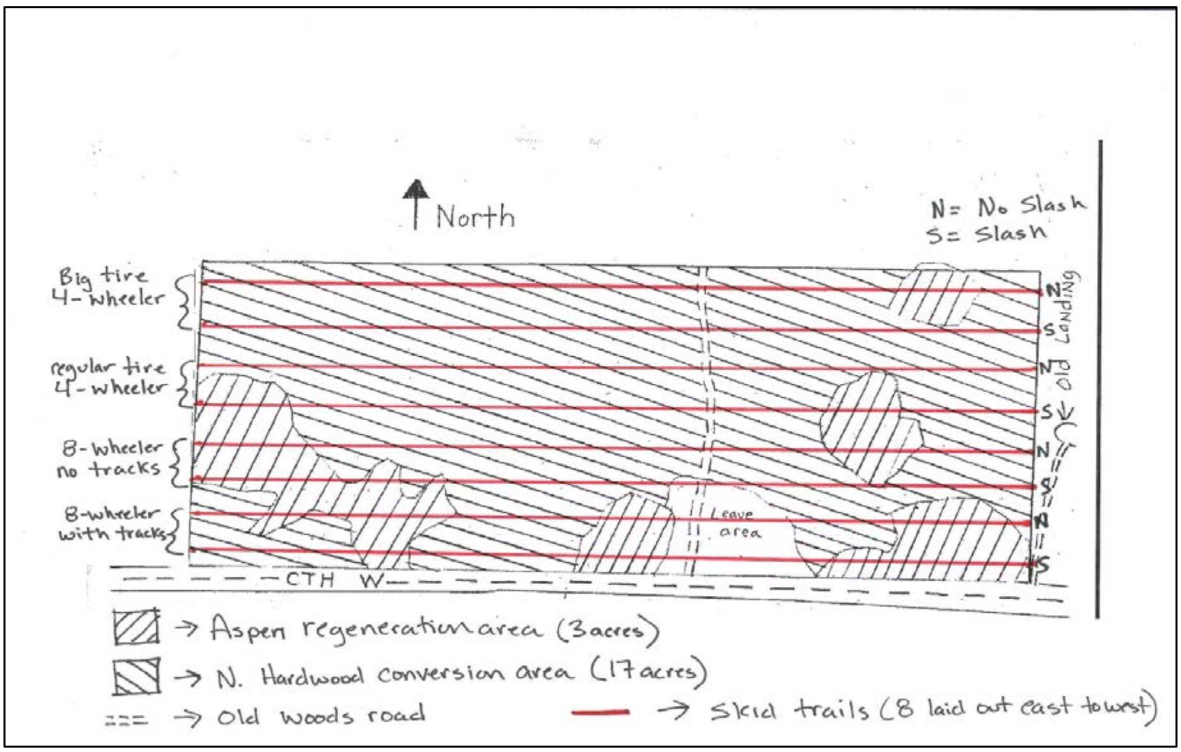

Figure 1: The study design included 8 skid trails (locations on map approximate), laid out east to west which ran the length of the harvest area. There were two skid trails for each equipment type, one with slash armoring, and one without slash. Note: The 8-wheeled tracked skid trails bypassed the leave area.

Weather Condition Information

The timber sale was harvested in September and October 2011. The rainfall dates and amounts during the trial were:

- September 18, 2011: 0.35 inches
- September 27, 2011: 0.20 inches
- September 28, 2011: 0.10 inches
- September 29, 2011: 0.40 inches
- October 12-13, 2011: 1.80 inches

According to the NOAA weather station in Park Falls, WI, the normal average rainfall (1981-2010) for September and October are 3.6 inches and 4.07 inches respectively. In 2011, the Park Falls NOAA weather Station received 1.84 inches in September, 2011 and 2.96 inches in October, 2011. Rainfall during the trial period was below average for the area, however conditions were wet due to daily rainfalls in proximity to harvest operations – more than 3 inches of rain fell during the harvest period.

METHODS OF DATA COLLECTION AND SOIL IMPACT DEFINITIONS

Pre-harvest, soil resistance and bulk density were measured in the harvest area. The pre-harvest results are for the entire stand. Post-harvest, soil resistance and bulk density were resampled within wheel tracks every 100 feet along skid trails. The skid trails were also monitored for presence and length of ruts post-harvest.

Soil Resistance, or penetration resistance, is the detection of compacted soil that can limit root development. Soil resistance was measured with a soil tensiometer (lbs./inch^2) pre-harvest and post-harvest. Eight measurements, taken at equal lengths, were recorded along each of the designated skid trails.

Bulk density is the dry mass of a given volume of intact soil in kg/l. Well-developed soil structure increases pore volume and decreases bulk density. In general, increases in bulk density can be harmful to tree growth because it is an indication of compaction, more mass per volume, which can restrict root penetration and reduce aeration. For this study, bulk density was measured by collecting a consistent known volume of soil at equal intervals along each skid trail (sampling cores provided by UW-Madison Soil Testing Lab). The soil samples were given to the UW-Madison Soil Testing Lab, which conducted the bulk density tests.

Ruts are depressions in the soil made by the passage of a vehicle or equipment. Excessive rutting compacts the forest floor, reduces the ability of soil to absorb water and can alter the natural flow patterns through a stand. In addition, ruts with retained water can serve as a population sink for forest amphibians. For this study, ruts were sampled by walking the skid trails and measuring ruts at least 6 inches deep and 5 feet long. For each trail a percent rutted was calculated based on the total length of rutting.

RESULTS

Soil Resistance

There are no known and easily defined thresholds or standards for soil resistance and impacts to growth and/or regeneration. Any developed thresholds would be dependent on soil type and moisture regime of a particular stand as well as tree species (Carmen Hardin, personal communication). Soil resistance readings of 0-100 PSI are common in uncompacted soils. Soil readings of 300+ PSI are common in heavily trafficked areas, though readings of 300+ PSI can also be found naturally in very tightly packed sandy soils.

Pre-Harvest versus Post-Harvest

Across all forwarder configurations, there was an increase in soil resistance following harvest. The forwarder with 8-wheels had a smaller increase in soil resistance than either of the forwarders with 4-wheels which had much larger increases in severely (300+ PSI) and moderately (200-300 PSI) compacted soils. The 8-wheeled forwarder with tracks had a much smaller increase in severely compacted soils than any other equipment configuration (Figure 2).

Figure 3 relates changes in soil resistance to location along each of the skid trails. It is difficult to discern any particular pattern from this data that could be related to the number of passes by the skidder. In this case, equipment entered on the east end of the site (see Figure 1), and the plots on the east received more skidder passes than the plots on the west end of the site. However, in general, we don't see the plots with higher soil resistance readings clustering on the eastern plots. Soil texture and moisture strongly influence susceptibility to compaction (Ampoorter et al, 2010; Han et al, 2006; Han et al, 2009; Powers et al, 2005). In this case differences in soil texture and moisture across the sight could be masking any soil resistance pattern that may be due to number of equipment passes.

No Slash versus Slash

For three of the four forwarder configurations, there was a smaller increase in moderate to severely compacted soils on the skid trails with slash. The only exception was the John Deere (8-wheel) forwarder with tracks, which has slightly less soil resistance on the skid trail with no slash (Figure 2). However, skid trails with slash were not uniformly covered, possibly because in general, single tree selection harvests have less slash available. The measurements were taken at equal intervals on each skid trails, but the slash distribution was patchy, and in some instances there was slash at the sample point and at others, there was no slash present. Interestingly, the processor operator noted that it was difficult to identify where skid trails had been covered with slash. It is likely that if skid trails had been consistently and uniformly armored the difference in soil compaction between skid trails with and without slash would have been even greater.

In addition, results for the 4-wheeled equipment configurations are unexpected and difficult to interpret (Figure 2). Some of the variability may be due to differences among operators and/or varying soil conditions and types throughout the site.

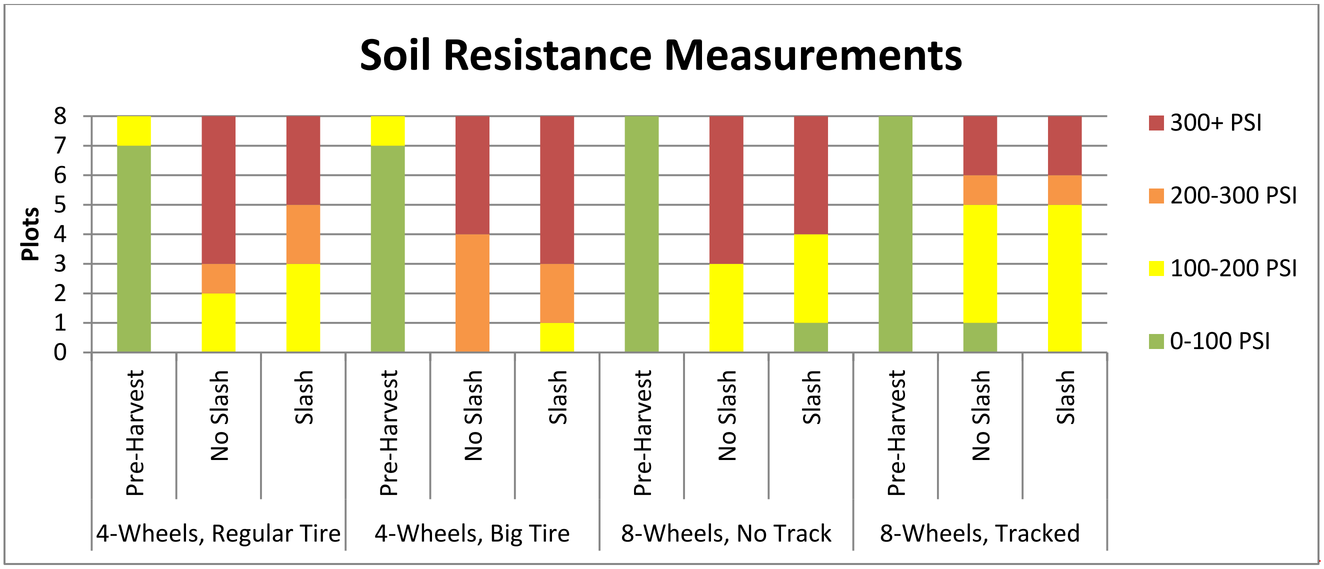

Figure 2: Describes the change in soil resistance pre-harvest and post-harvest for each equipment trial and slash treatment. Plots on vertical axis are grouped by soil resistance, not by location, in order to compare change in soil resistance across each trial (e.g. 4-Wheel, regular tire, etc.). For example for the 4-Wheels, Regular Tires trial, pre-harvest 7 out of 8 soil resistance measurements were 0-100 PSI. Post-harvest, on the no slash treatment, 2 plots had soil resistance measurements of 100-200 PSI, 1 plot was 200-300 PSI, and 5 measurements were 300+ PSI.

Soil Resistance (PSI)												
	4 Wheels, Regular Tire			4 Wheels, Big Tire			8 Wheels, No Track			8 Wheels, Tracked		
Plots (East to West)	Pre-Harvest	No Slash	Slash	Pre-Harvest	No Slash	Slash	Pre-Harvest	No Slash	Slash	Pre-Harvest	No Slash	Slash
100 ft	0-100	100-200	100-200	0-100	300+	300+	0-100	100-200	300+	0-100	100-200	100-200
200 ft	0-100	300+	100-200	0-100	300+	200-300	0-100	100-200	300+	0-100	0-100	200-300
300 ft	0-100	200-300	100-200	0-100	200-300	300+	0-100	300+	300+	0-100	100-200	100-200
400 ft	0-100	300+	200-300	0-100	300+	200-300	0-100	300+	300+	0-100	300+	300+
500 ft	100-200	300+	300+	100-200	200-300	300+	0-100	300+	100-200	0-100	200-300	300+
600 ft	0-100	300+	300+	0-100	200-300	300+	0-100	100-200	0-100	0-100	100-200	100-200
700 ft	0-100	300+	200-300	0-100	200-300	100-200	0-100	300+	100-200	0-100	100-200	100-200
800 ft	0-100	100-200	300+	0-100	300+	300+	0-100	300+	100-200	0-100	300+	100-200

Figure 3: Describes the change in soil resistance pre-harvest and post-harvest for each equipment trial and slash treatment by location along a east to west transect. For example, for the 4-Wheels, Regular Tires trial, the first plot, 100ft in, pre-harvest the soil resistance measured 0-100PSI. For the no slash and slash treatments, the 100 ft. plot measured 100-200PSI.

Bulk Density

There are no known and easily defined thresholds or standards for bulk density and impacts to growth and/or regeneration for forest soils. The critical bulk density that limits root penetration and/or impacts growth varies with tree species, soil moisture content, and soil texture (Sutton, 1991; Cassel, 1983). Higher bulk density results in lower porosity, poorer aeration, slower water filtration, and lower ion diffusion rates

(Barber, 1974). In wetter conditions, higher bulk densities that would not normally restrict root penetration in forest soils, have poor root growth because of anaerobic conditions resulting from low air-filled pore volume (Fisher & Binkley, 2000). Warncke and Barber (1971) found that in soft silt loams, ion diffusion declined to its lowest level at bulk density 1.3 g/cm^3. Zisa et al (1980) reported severe reduction (75%) in root penetration of pine species on silt loam at a bulk density of 1.40 g/cm^3. In agricultural cropland systems, Arshad et al (1996) reported root growth restriction at >1.80 g/cm^3 for sandy soils, >1.65 g/cm^3 for silty soils, and >1.47 g/cm^3 for clayey soils. Most of the post-harvest bulk density measurements in Figure 3, appear to be below the threshold values found in literature. However, because impacts will vary widely with soil conditions, tree species, and interactions between bulk density, soil moisture and oxygen availability, it is not possible to draw any definitive, widely applicable conclusions about impacts based on this data. Table 2 shows a literature review of bulk density thresholds for observed impacts.

Table 2: Various bulk density impact thresholds from primary literature.

System/Soil	Bulk Density Impact Threshold	Observed Impact	Reference
Agricultural cropland	>1.80g/cm^3, sandy soil; >1.65g/cm^3, silty soil; >1.47g/cm^3, clayey soil	Root growth restriction	Arshad et al, 1996
Agricultural cropland	1.4 to 1.6g/cm^3, wet soils; 1.75 g/cm^3, coarser textured soils	Upper limits of root penetration	Cassel, 1983
Silver maple, loam soils	1.5 g/cm^3 to 1.7 g/cm^3 depending on soil water content)	reduction in root penetration	Day et al, 2000
Douglas fir on sandy loam	1.45 g/cm3	seedling root development impeded	Minore et al, 1969
Loblolly pine on loamy soils	1.3 g/cm^3, sandy clay loam; 1.4 g/cm^3, loamy sand	Seedling heights lower. Depth of rooting and weights of roots and shoots reduced.	Tuttle et al, 1988
Loblolly pine on loamy soils	1.9 g/cm^3	Decreased seedling establishment (44%-46%)	Tuttle et al, 1988
Soft silt loams	1.3 g/cm^3 to 1.5 g/cm^3 depending on soil moisture	decline in ion diffusion	Warncke & Barber, 1972
Pine species on silt loam	1.40 g/cm^3	Severe reduction in root penetration (75%)	Zisa et al, 1980
Pine species on silt loam	1.80 g/cm^3	Reduced seedling establishment	Zisa et al, 1980

Pre-Harvest versus Post-Harvest

There is generally little meaningful difference between the pre-harvest and post-harvest bulk density samples. The 8-wheel, tracked, and the 4-wheel, big tire, forwarders showed the largest increases in bulk density measurements (Figure 3). This may be the result of timing and/or soil variation.

No Slash versus Slash

For this study, bulk density sampling data does not reveal any conclusive differences between the no slash versus slash covered skid trails (Figure 4). As previously mentioned, the lack of observable differences between slash covered skid trails and skid trails with no slash may be due of the scattered, inconsistent nature of the slash on the armored skid trails, which may be due to the single tree selection harvest where large amounts of slash may not be available.

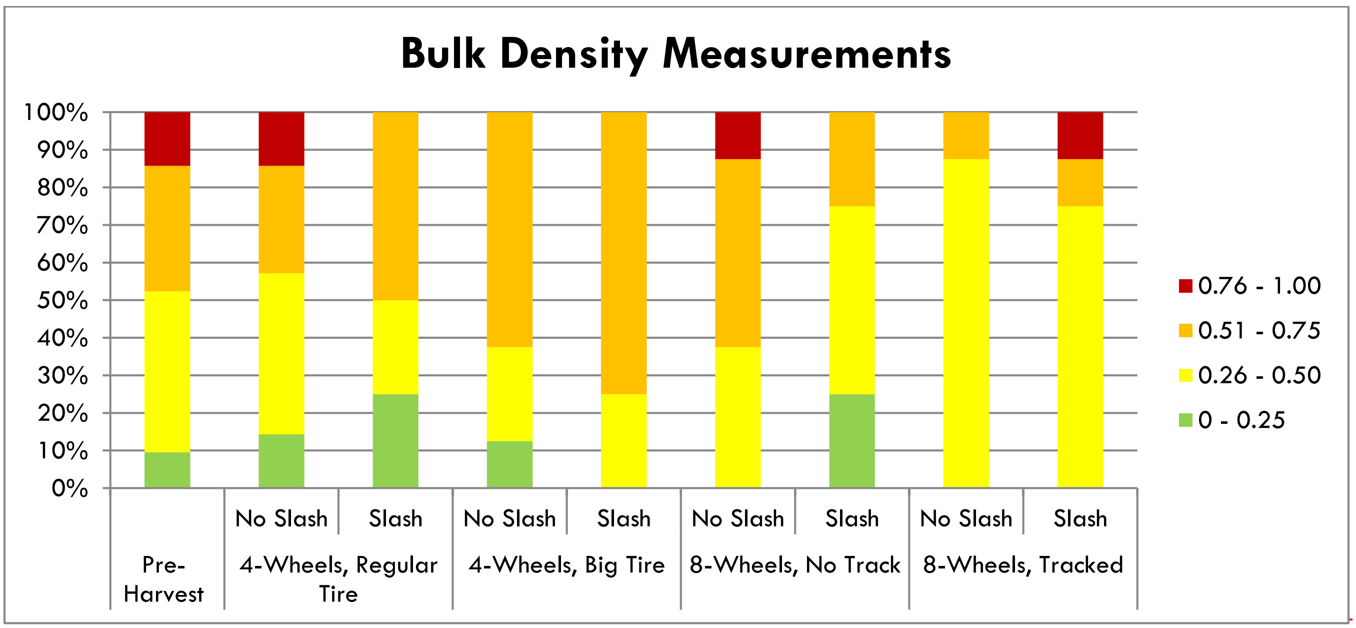

Figure 4: Describes the changes in bulk density (kg/l) for each equipment trial and slash treatment (1 kg/l = 1 g/cm^{3}). Each bar represents the percentage of each treatment that fell into each of the bulk density ranges. For example, approximately 10% of the pre-harvest bulk density measurements were 0-0.25 kg/l, approximately 40% were between 0.26 – 0.50 kg/l, approximately 30% measured 0.51 – 0.75 kg/l, and approximately 15% 0.76 – 1.00 kg/l.

Rutting

Each skid trail was walked post-harvest to determine how much, if any, rutting had occurred during the timber harvest. For each skid trails with obvious rutting, the length of each rut at least 6 inches in depth and 5 feet in length was measured and a percent rutted was calculated for each trail (Figure 5).

Pre-Harvest versus Post-Harvest

A small amount of rutting (<20% of trail) was observed on six of the eight equipment trials. No rutting was observed with the 8-wheeled tracked forwarder(Figure 5). Of the three equipment types, rutting was observed. In this instance, there did not appear to be any advantage to having equipment with 4 wheels versus 8 wheels, if the forwarder was not tracked. The primary advantage appeared to be gained once the tracks were placed on the equipment. In the three weeks the sale was operational, nearly 3 inches of rain was received.

No Slash versus Slash

It appears from the trial that the amount of rutting did decrease in all three forwarder configurations when slash was placed on the skid trials. However, slash was not evenly distributed across the slash armored skid trails. It is likely that if the slash application had been more uniform the amount of rutting would have decreased further. It is important to note that the availability of slash is dependent on the number of marked trees, so in single tree select areas it may be difficult to have enough uniformly distributed slash.

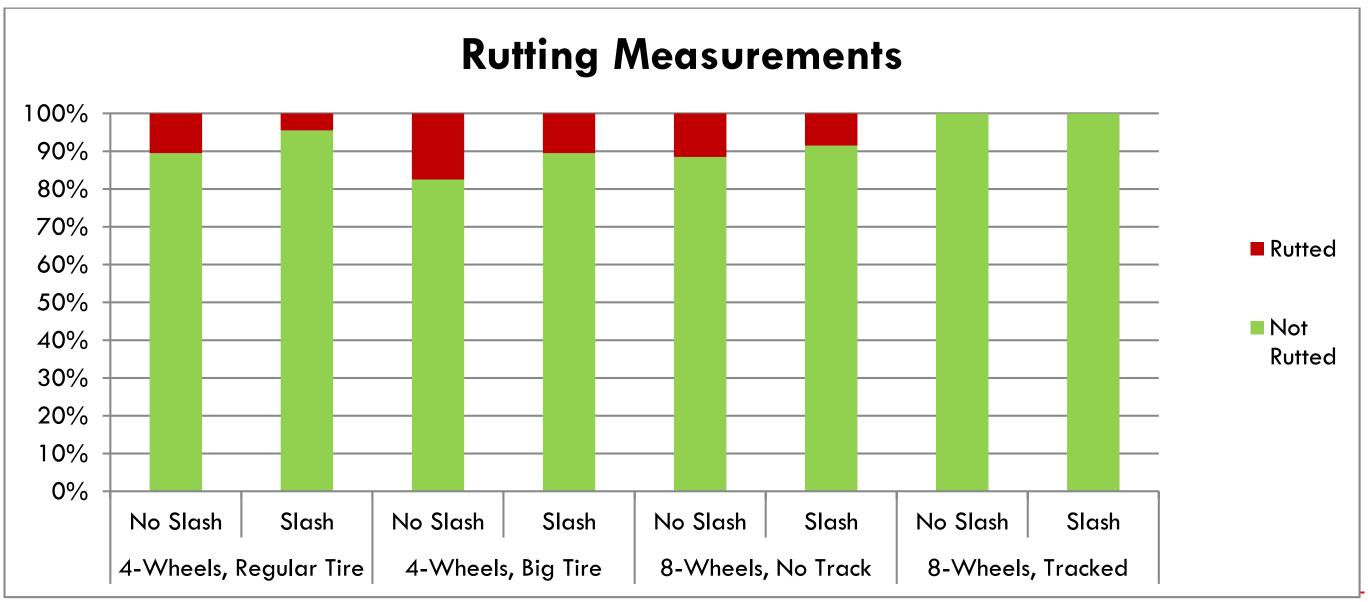

Figure 5: Describes rutting on skid trails for each equipment trial and slash treatment.

Figure 6: Example of slash deposition on the 4-wheels, regular tire skid trail

Conclusion

This equipment trial did not provide any definitive, quantifiable evidence regarding the four equipment configurations; however, some general conclusions can be drawn. From an equipment perspective, the 8-wheel, tracked forwarder combination offered the most potential to decrease soil compaction and rutting on this site. There were negligible differences between the 4-wheel~~s~~ and 8-wheel~~s~~ configurations without tracks. It appears that adding the tracks to the wheel equipment increased the protection to the soil resource.

For skid trials, the addition of slash appeared to generally decrease the potential for soil compaction and rutting. However, the slash deposition was not uniform on the skid trails, possibly due to the lack of available slash, and the protection offered by the slash may have been increased had the slash deposition been more consistent.

In wet conditions, this trial indicates that tracked equipment on slash covered skid trails will offer the greatest protection to soil resources and help minimize soil compaction and rutting. However in single tree select areas it may be difficult to have enough uniformly distributed slash. It is possible that with the use of tracked equipment and the placement of slash, that the operability window of some these sites could be expanded. However, additional trials on other soil types and replications with more uniform slash deposition would be beneficial in clarifying the results of these trials.

Acknowledgements

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REFERENCES

Alameda, D. and R. Villar. 2009. Moderate soil compaction: Implications on growth and architecture in seedlings of 17 woody plant species. *Soil and Tillage Research*, 103:325-331.

Ampoorter, E. L. Van Nevel, B. De Vos, M. Hermy, and K. Verheyen. 2010. Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. *Forest Ecology and Management* 260: 1164-1676.

Arshad M.A., Lowery B., and Grossman B. 1996. Physical Tests for Monitoring Soil Quality. In: Doran J.W., Jones A.J., editors. Methods for assessing soil quality. Madison, WI. p 123-41.

Barber, S.A. 1974. Influence of the plant root on ion movement in the soil, p. 525-564 in EW Carson, Ed. The plant root and its environment. Univ. Virginia Press, Charlottesville.

Brais, Suzanne. 2001. Persistence of Soil Compaction and Effects on Seedling Growth in Northwestern Quebec. *Soil Science Society of America Journal*. 65: 1263-1271

Carmen Hardin, Personal Communication. June 26, 2014.

Cassel, D.K. 1983. Effects of soil characteristics and tillage practices on water storage and its availability to plant roots. In Raper, C.D. Jr. & Kramer, P.J. (editors). Crop relations to Water and Temperature Stresses in Humid Temperate Climates, pp 167-186. Westview Press, Boulder, CO.

Cochran, P.H. and Terry Brock. 1985. Soil compaction and Initial Height Growth of Planted Ponderosa Pine. USDA Forest Service. *Pacific Northwest Forest and Range Experimental Station Research Note* PSW 434, Portland, OR.

Day, S.D., J.R. Seiler, and N. Persaud. 2000. A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiology, 20: 257-263

Eliasson, L. and I. Wasterlund. 2007. Effects of slash reinforcement of strip roads on rutting and soil compaction on a moist fine-grained soil. *Forest Ecology and Management*, 252:118-123.

Firth, J. and G. Murphy. 1989. Skidtrails and their Effect on the Growth and Management of Young *Pinus radiata*. *New Zealand Journal of Forest Science*. 19:22-28.

Fisher, R.F. and D. Binkley. 2000. Ecology and Management of Forest Soils. 3rd ed. New York: Johm Wiley & Sons, Inc.

Grigal, David F. 2000. Effects of extensive forest management on soil productivity. *Forest Ecology and Management*, 138: 167-185

Han, H.S., D. Page-Dumroese, S.K. Han, and J. Tirocke. 2006. Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. *International Journal of Forest Engineering*, 17(2):11-24.

Han, S.K., H.S. Han, D.S. Page-Dumroese, and L.R. Johnson. 2009. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. *Canadian Journal of Forest Research*, 39:976-989.

Kolowski, T.T. 1999. Soil Compaction and Growth of Woody Plants. *Scandinavian Journal of Forest Research*. 4: 596-619.

Minore, D., C.E. Smith & R.F. Woollard. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, Research Note PNW-112.

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

Reisinger, Thomas W., Gerry L. Simmons, and Philip E. Pope. 1988. The Impact of Timber Harvesting on Soil Properties and Seedling Growth in the South. *Southern Journal of Applied Forestry*. 12: 58-67

Sands, R., Bowen, G.D., 1978. Compaction of sandy soils in radiata pine forests: effects of compaction on root configuration and growth of radiata pine seedlings. *Aust. For. Res.* 8, 163–170.

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

Stewart, Rodney, Henry Froehlich, and Eldon Olson. 1988. Soil Compaction: An Economic Model. *Western Journal of Applied Forestry*. 3:20-22

Sutton, R.F. 1991. Soil properties and root development in forest trees: a review. Forestry Canada. Information Report O-X-413.

Tuttle, C.L. M.S. Golden, & R.S. Meldahl. 1988. Soil compaction effects on *Pinus taeda* establishment from seed to early growth. *Can. J. For. Res.* 18: 628-632.

Warncke, D.D. and S.A. Barber. 1972. Diffusion of Zn in soils: II The influence of soil bulk density and its interaction with soil moisture. Soil Sci. Soc. Am. Proc. 36: 42-46

Wisconsin Department of Natural Resources (WDNR). 2008. Maintaining Soil Quality in Woodlands. Retrieved July 9, 2014. (http://dnr.wi.gov/topic/forestmanagement/documents/pub/fr-409.pdf)

Wronski, E.B., Murphy, G., 1994. Responses of forest crops to soil compaction. In: Soane, B.D., van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Elsevier, Amsterdam, pp. 317–342.

Zisa, R.P., H.G. Halverson, and B. Stout. 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service Research Paper NE-451. Northeastern Forest Experiment Station, Broomall, PA.