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Soil response to skidder trafficking and slash application

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ABSTRACT

Ground-based timber harvesting systems are common in the United States. Harvesting machinery can negatively influence soils by increasing erosion and decreasing site productivity. Skid trails can become compacted and erosive. Slash applications to skid trails are effective for erosion control, yet few investigations have examined effects of slash on soil physical properties influenced by compaction. This research project has two objectives: (1) to compare and contrast the impacts of traffic resulting from a rubber-tired grapple skidder and a dozer using a variety of soil compaction indices, and (2) to compare effects of slash versus bare soil on skid trails trafficked by a rubber-tired grapple skidder and a dozer. The project was conducted within an upland hardwood/pine stand in the Ridge and Valley region. Skidder traffic changed both visual appearance and soil physical properties. The heavier skidder resulted in deeper visible ruts, greater increases in bulk density, and greater decreases in macro porosity when compared to the lighter dozer. This project also served as a pilot test for the AgTech sensor for forest trails. Results from sensors are briefly compared with traditional soil compaction indices. While no major relationships were found, the technology is promising for future research applications. Using slash as a means of ameliorating soil disturbance was not entirely conclusive as variation in cover had no effect on bulk density or porosity and mechanical resistance data were contradictory. Slash reduced increases in soil strength, and despite difference in sizes, the skidder and dozer resulted in similar changes in soil strength.

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Forestry; machinery; skidding; soil compaction; rubber-tired; tracked

Introduction

Mechanized systems are commonly used for timber harvesting in the southeastern United States. These systems rely on equipment to fell, transport, and process timber (Simmons 1979; Greene et al. 2013). Forest machinery is heavy and traffics a portion of harvested sites possibly causing soil compaction (McDonald et al. 1995). Hatchell et al. (1970) found the average disturbance area associated with a logging to be 12.4% in primary skid trails, 19.9% in secondary skid trails, and 1.5% in decks. Worrell et al. (2011) found 8.5% of total harvest area in deck and bladed skid trails. Machine weights are becoming significantly greater with increased axle loads (Håkansson & Reeder 1994). Increased machine weights can cause soil disturbance both on the surface and at depth (Horn et al. 2004). Traffic and compaction may adversely affect crop production and general environmental quality (Soane & Van Ouwerkerk 1995). Compacted soils can have long recovery times, ranging from 70 to 140 years (Froehlich et al. 1985; Webb et al. 1986), although soils having significant shrink-swell mineralogy or freeze-thaw climatic conditions can recover more rapidly (Greacen & Sands 1980). Soil compaction generally results in increased bulk densities and penetration resistance and decreased porosity and hydraulic conductivity (Taylor & Brar 1991).

Depending on site and soil characteristics, forest machinery can significantly alter soil properties (Horn et al. 2004). Researchers generally gather soil information, drainage properties, and current moisture content for an area of interest and then analyze changes in soil properties including bulk density, mechanical resistance, porosity, and saturated hydraulic conductivity (Greacen & Sands 1980). Research evaluations of such changes often characterize changes in soil properties before and after a harvest. Hatchell et al. (1970) showed increases in bulk density and soil strength coupled with decreases in infiltration rate leading to impaired growth and development of loblolly pine. Wet weather logging has been shown to increase bulk density, decrease pore space, and result in deep ruts disrupting root growth (Moehring & Rawls 1970; Miwa et al. 2004), although the effects of such disturbances can be ameliorated by mechanical site preparation (Passauer et al. 2013; Lang et al. 2016). Equipment passes are significant for soil compaction because skidders repeatedly traverse trails. Research indicates that regardless of soil type and condition, increases in bulk density and rut depth can be expected as number of passes increases (Koger et al. 1985), although manipulation of equipment tires and flotation can be used to reduce trafficking effects (McDonald et al. 1995).

Potential effects of soil impacts resulting from mechanized operations have led land managers to investigate operational techniques to prevent or ameliorate soil disturbance, such as the application of logging slash. Slash is commonly applied to erosion prone or low soil strength problem areas of skid trails

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and decks. Slash on skid trails may provide four major advantages. Slash can decrease soil erosion by increasing soil cover and decreasing the distance of unrestricted surface runoff (Sawyers et al. 2012; Wade et al. 2012; Vinson et al. 2017). Slash may also restrict subsequent traffic on skid trails by making the skid trails less attractive to recreationists, although evidence is anecdotal. Slash can also provide slow release of soil nutrients and provide an organic layer that may improve the site quality for natural regeneration (Eisenbies et al. 2005). Finally, slash may limit compaction caused by heavy forestry equipment. Slash application is recommended and used to control erosion (Virginia Department of Forestry [VDOF] 2011; Wade et al. 2012; Vinson et al. 2017). McDonald and Seixas (1997) examined slash as protective cover and found that the first pass of a rubber-tired forwarder across slash on sandy soils did not decrease soil compaction. However, continued traffic across slashed plots showed less impact and after 5 passes slashed treatments were impacted half that of bare soil. Eliasson and Wästerlund (2007) found that topsoil was protected from compaction due to slash reinforcement of strip roads, but results were not entirely conclusive. Heterogeneity of soils in the region ranging from peats to mineral soils combined with inconsistent slash properties and measurement techniques led to variation.

Thousands of hectares of forests are harvested annually within the Appalachian mountain region of the US; however, knowledge regarding changes in soil characteristics due to harvesting is limited (Wang et al. 2007). Previous research indicates that machine weight, ground pressure, and number of passes are significant when evaluating soil compaction (Hadas 1994). Murosky and Hassan (1991) conducted a project comparing tracked and wheeled skidders with different tire types in Mississippi to evaluate differences in machine type and found that tracked skidders resulted in less compaction and site disturbance overall. The wheeled skidder with wider high flotation tires resulted in less compaction and better flotation than narrower tires.

The literature indicates that machine weight, intensity of traffic, site characteristics, and soil properties can influence the level of disturbance caused by harvesting traffic on skid trails and that slash application to skid trails might be used to mitigate potential compaction effects. Therefore, the aim of this project was to quantify changes in soil properties associated with different levels of ground cover for both tracked and wheeled skidders and multiple machinery passes on overland skid trails in the mountains. Changes in soil properties will also allow comparisons with pilot data gathered from previously untested AgTech sensors in a forest setting.

Materials and methods

Field site

Treatments were conducted on Virginia Tech's Fishburn Forest in spring 2015. Study trails were located on 7% grades along a ridge. The upland forest consisted of chestnut (*Quercus montana*), white (*Quercus alba*), and scarlet (*Quercus coccinea*) oaks with some white pine (*Pinus strobus*) interspersed. The forest floor was not trafficked before project installation. Soils were Berks-Clymer complex having silt loam texture, moderate to well drainage, and shallow depth with many coarse fragments. Depth to sandstone bedrock was 68–124 cm (United States Department of Agriculture [USDA] 1985).

Trees, saplings, and shrubs were chainsaw felled and applied along corridors to create three travel lanes. Mechanized traffic was excluded from the study area during preparations to ensure the measurements were representative of non-trafficked conditions. Study dimensions measured 36 × 12 m and consisted of two travel lanes and a return lane adjacent to the study site (Figure 1). Travel lanes were divided into six 6 m long by 6 m wide segments. The rubber-tired skidder (skid) was assigned to one travel lane and the tracked skidder (dozer) was assigned to the other. The 6 m lane width provided adequate space for machines to traverse courses repeatedly without overlap and interference. The dozer was 2.4 m wide and the skidder was 3.4 m wide (John Deere 1985; Caterpillar 2014). Machines used a nearby existing ridge road as a return lane to exit the study area and return to the beginning point to commence another pass.

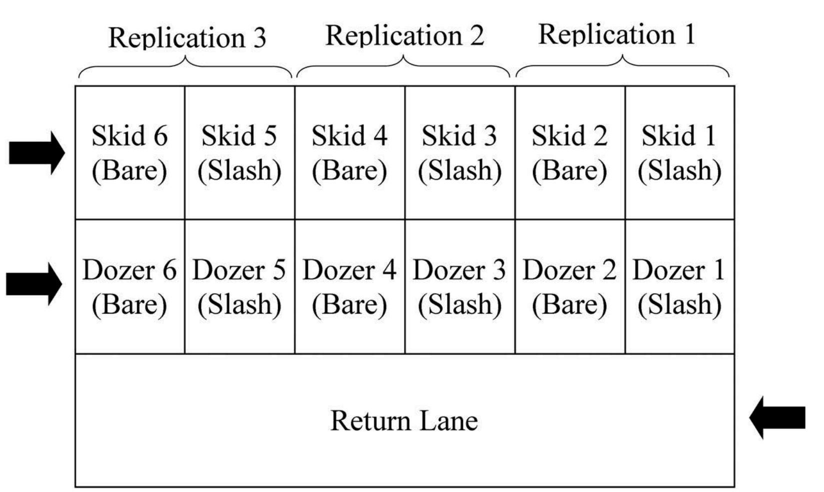

Figure 1. Study site layout; arrows represent travel direction, "Skid" or "Dozer" represent machine type, numbers represent 6 × 6 m segments, and "Bare" or "Slash" represent cover type.

Within travel lanes, three segments were assigned as bare and three segments were covered with slash. Bare treatments included existing forest floor with residual vegetation, litter, and organic material present. Slash treatments were woody debris from corridor establishment that were hand piled approximately 1 m in depth before traffic. Our applications were consistent with previous slash recommendations (McDonald & Seixas 1997; Eliasson & Wästerlund 2007; VDOF 2011). This experimental design allowed for comparison of machine, cover type, and number of machinery passes on soil properties. This design provides for three replications of each treatment.

Data collection occurred following 0, 1, 3, 6, 9, and 12 passes for each machine. Data from both machines was collected in one day to minimize variation due to weather. For each traffic sequence, soil cores were extracted, mechanical resistance values were obtained, and soil moistures were recorded (Figure 2). Soil cores were collected using standard double cylinder bulk density hammers paired with two 5 cm long × 5 cm diameter metal cylindrical rings. Two cores were extracted from each traffic lane segment to a depth of 10–12 cm after each set of passes. Cores were sealed and bagged for storage and transport. A Rimik CP20 recording cone penetrometer was used to record mechanical resistance. The penetrometer recorded in kilopascals associated with every 25 mm soil depth increment. Three mechanical resistance measurements were taken in a triangular pattern surrounding the soil core sampling location. Soil moisture was measured using a Campbell Scientific Hydro-Sense TDR meter. Two soil moisture readings were taken near the soil core location after each set of passes.

AgTech sensors were constructed following designs from Turner and Raper (2001) and deployed following an initial on-site trial. A 2.54 cm diameter bulb was connected to standard 1.52 m length of hydraulic hose with a nipple and clamp. Hydraulic hoses were connected to an Omega pressure transducer, data logger, and battery housed in a protective case, thus creating a self-contained sampling apparatus. The bulb, hose, and open end of the pressure transducer were completely filled with water. A custom-made jig and auger were used to bore laterally to the desired depth of 12.7 cm with an end location under the tracks (Figure 2). The exposed bulb and hydraulic hose were guided into this hole prior to trafficking.

Machinery

Available equipment options consisted of a large rubber-tired skidder and a small tracked dozer, which represent two operational skidding options for the region. It was impractical to pull a complete turn of logs through the course because this would disturb the slash and contaminate the bare treatments. To replicate loaded passes, a weight constructed of a metal pipe filled with concrete was suspended from the dozer's fire plow and the skidder's grapple. The aim was to simulate the lifted weight of a turn of logs. The weight was 640 kg and suspended with 27 kg of chain and binders. The ground supports the majority of the weight of a turn of logs and the machinery only supports a finite amount of each turn (Perumpral et al. 1977).

The dozer was a 1986 John Deere 450E with a rear fire plow and standard metal tracks. Dozer tracks measured 208.8 cm long and 45.7 cm wide. Both tracks have a contact area of 19,084 cm^2. The standard dozer has an operational weight of 6963 kg and a ground pressure of 35.7 kPa (John Deere 1985). For the actual measurements in the study, the fire plow, weight, and bindings were added. The 450E weighed 7938 kg including the fire plow. This combined with the suspended weight resulted in a total weight of 8606 kg and a ground pressure of 44.2 kPa (Figure 3).

The wheeled skidder was a 2014 Caterpillar 525D with dual arch grapple, winch, and front blade. Skidder tires were Firestone Forestry Special size 30.5 L–32 (20). Firestone specifications (Bridgestone Americas Tire Operations LLC 2015) indicated each tire had a flat plate area of 2439 cm^2. Total ground contact area supporting the machine was 9756 cm^2. The 525D skidder weighed 20,525 kg (Caterpillar 2014). The addition of the suspended weight increased total weight to 21,192 kg with a ground pressure of 213.0 kPa, or 4.8 times that of the dozer (Figure 4).

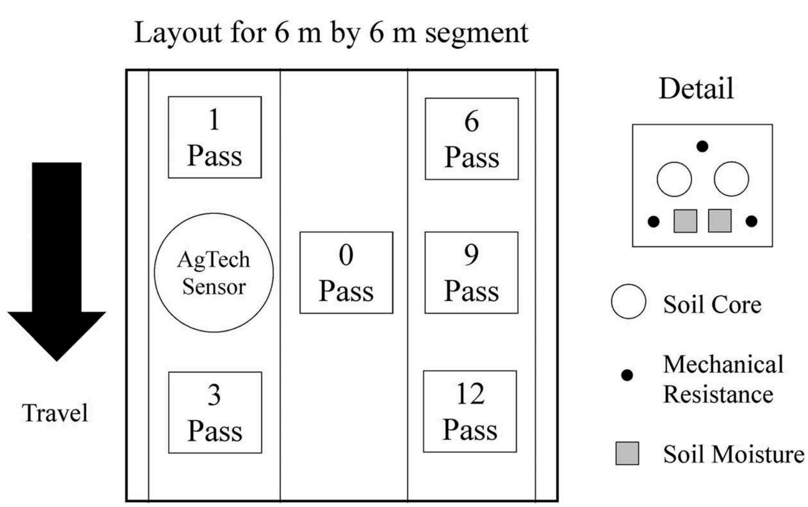

Figure 2. Sampling layout; 0 pass samples were taken between tracks and samples for passes 1, 3, 6, 9, and 12 were taken from within trafficked areas.

Figure 3. John Deere 450 dozer.

Figure 4. CAT 525D skidder.

Laboratory and data analysis

Soil cores were analyzed for saturated hydraulic conductivity, macro and micro porosity, and bulk density. Two soil cores were extracted for each set of experimental measurements. The two cores were used to calculate representative averages of soil properties for each set of passes. Mechanical resistance data were downloaded from the Rimik CP20 recording penetrometer and soil moisture data were recorded by hand in the field. Data were input into JMP software for analysis (JMP Pro 12.0.1 2015).

Saturated hydraulic conductivity was determined using the constant head technique (Stolte 1997). Soil cores were completely saturated by immersing them in water for a minimum of 24 hours. Cores were removed from immersion and placed in an apparatus that maintained a constant head of water. The quantity of water that passed through a soil core and the associated time were recorded. Soil contained numerous coarse fragments which can cause pipe flow. Samples that exhibited pipe flow (150 cm hr^{-1}) were not included in analysis (Coduto 1999). The Berks-Clymer complex had a maximum permeability of 15.24 cm/hr (USDA 1985).

Soil cores that failed to produce the minimum flow of water for measurement were assumed to be impermeable and a flow rate of 0.0001 cm/hr was assigned. The Berks–Clymer complex has a minimum permeability 1.52 cm/hr, but contains pockets of clays that are impermeable (USDA 1985). According to Coduto (1999), the minimum magnitude of flow through silt materials is 10^{-8} cm/s, and 0.0001 cm/hr corresponds to 2.7×10^{-8} cm/s.

Microporosity and macroporosity were determined using a tension table and drying oven. A tension of 50 cm of water in equilibrium with the water in the soil core results in macropores being empty leaving water in micropores only. Soil cores were immersed in water for 24 hours to achieve full saturation. Cores were placed on the tension table for 24 hours to come to equilibrium with the 50 cm applied tension. Equilibrium weights of cores were recorded and cores were baked in a drying oven at 105°C for a minimum of 24 hours to determine oven dried weights. Equilibrium weight was compared to oven dried weight to determine the percentage of micropores. Macropores were assumed to be the difference between total porosity and the percentage of micropores. Total porosity was calculated based on corrected bulk density and an assumption of 2.65 g/cm^3 density of coarse fragments.

Bulk density was determined for each core based on cylinder volume and oven dried weight which were both determined from previous porosity analysis. Bulk density values were corrected to account for coarse fragments as recommended by the Soil Survey Field and Laboratory Methods Manual (2014). Soil cores were oven dried, ground, sieved, and rinsed. Remaining fragments were oven dried and weighed. This method accounted for the weight and volume occupied by the coarse fragments.

Mechanical resistance data were recorded with a Rimik CP20 recording cone penetrometer. The device recorded penetration resistance in kilopascals for every 25 mm of soil depth penetration. Three samples were obtained for each set of experimental data collection. The three samples were averaged to form one representative set of mechanical resistance data for each part of the experiment. Following a process similar to that of Bolding et al. (2009), mechanical resistance values were regrouped into depth classes: 25–100 mm and 125–200 mm. The first depth class was compared to the soil core data as it results from the same part of the soil profile; this depth class corresponds to a depth reaching 100 mm below soil surface and soil cores were taken to a depth approximately 100 mm below the soil surface. Two volumetric soil moisture measurements were taken with each set of collected data. These values were averaged to provide a single representative value.

AgTech sensor readings were analyzed following the completion of the set of 12 passes for each machine. Text files containing raw pressure data were generated and downloaded using OM-CP Data Logger Software (OM-CP Data Logger Software 4.1.5.1 2013). Data loggers were started prior to experiment start and stopped after experiment completion with pass times being noted throughout the experiment to aid in analysis. Text file output was plotted with time as the independent variable and pressure as the dependent variable. Plots were graphically analyzed to locate flat plateaus between distinct traffic peaks. Plateaus were averaged between each set of passes and compared to initial conditions to provide stress residuals. This residual is representative of the soil's ability to rebound to a new equilibrium state following trafficking. Pressure transducer data was output in μA, so a bulb pressure transducer combination was subjected to a compression test to yield a relationship for converting a μA reading to a force in N to make units meaningful.

Machine weights were substantially different, therefore machines were analyzed separately similar to Solgi et al. (2016). Machine-cover treatments were analyzed within the construct of a Randomized Complete Block Design (RCBD) following Little and Hills (1978). The RCBD had four machine-cover-treatment combinations and three blocks. The passes were evaluated as a superimposed split block. Software was set to an alpha level of 0.05. JMP software was used to compute Student's *t*- and Tukey HSD tests. The experimental design allowed separate analysis of each type of machinery for changes in soil properties. Soil properties were compared to the initial existing condition yielding the magnitude and direction of change of a given property. This method of analysis accounted for initial variation of plots allowing comparison.

Results

The rubber-tired skidder and dozer had an impact on the visual appearance of the soils and cover of the experimental site. The skidder created deep ruts with obvious soil displacement (Figure 5) whereas the dozer did not (Figure 6). Slash treatments were compressed and limbs and branches were broken forming a mat. Results are presented separately for the skidder and the dozer because of the major difference in magnitude of weight.

Figure 5. Skidder visual disturbance.

Figure 6. Dozer visual disturbance.

A study objective was to determine if slash on an overland skid trail alters traffic effects. Average changes in soil properties were compared to initial conditions for the entire 12 passes. The treatment areas experienced two to three times greater losses in saturated hydraulic conductivity under slash treatments than bare. Cover type did not have an impact on changes in bulk density; however, the bulk densities after 12 passes were greater than those of the initial conditions. The skidder resulted in an increase of 0.2 g/cm^3 while the dozer resulted in an increase of 0.05 g/cm^3. Both machines decreased the total porosity of the soils, but the skidder resulted in three times the loss. Cover type did not result in major differences in total porosity, macro porosity, or micro porosity. For the dozer, bare treatments resulted in a slight increase of 1.7% in micropores over the 1.0% increase sustained for slash cover. For both machines, bare treatments experienced a slightly greater loss of macropores. For the skidder, bare treatments experienced an increase of 5.8% in water content while slash treatments only saw an increase of 2.3%. The dozer resulted in a loss of 1.1% in water content for bare treatments while slashed treatments water content increased by 0.4%. Soil stress residuals increased with traffic. Cover appeared to play a role in lessening the impact of the skidder over the 12 passes. Bare treatments experienced three times more impact than slashed treatments for the skidder. Cover did not appear to have played a major role for the dozer as the changes in soil stress residual were nearly the same (Table 1).

Within a given cover type for each machine, the number of passes of machinery were compared to changes in soil properties. There were major changes after 1 pass for the skidder and appreciable change for the dozer between 3 and 6 passes.

Table 1. Average results for comparison of treatment for soil properties over the entire 12 passes; reported values are changes from initial conditions.

Treatment	Change in saturated hydraulic conductivity (cm/hr)	Change in bulk density (g/cm^3)	Change in porosity (%)	Change in micro porosity (%)	Change in macro porosity (%)	Change in volumetric water content (%)	Change in bulb reading (*N*)
Skidder bare	-6.50^{a}	0.18^{a}	-6.90^{a}	2.00^{a}	-8.90^{a}	5.80^{a}	27.30^{a}
Skidder slash	-11.10^{a}	0.16^{a}	-6.20^{a}	2.00^{a}	-8.20^{a}	2.30^{b}	9.30^{b}
Dozer bare	-4.40^{a}	0.05^{a}	-1.70^{a}	1.70^{a}	-3.40^{a}	-1.10^{a}	16.20^{a}
Dozer slash	-13.10^{a}	0.05^{a}	-1.80^{a}	1.00^{a}	-2.80^{a}	0.40^{a}	17.40^{a}

*Within treatment, numeric values followed by different letters are significantly different; $p < 0.05$.

The skidder experienced a major loss in hydraulic conductivity after the first pass for both bare and slashed treatments. There was a loss of 19.7 cm/hr for bare treatments and a loss of 14.6 cm/hr for slashed treatments. After 3 passes, both cover types experienced a rebound in hydraulic conductivity. Bare treatments experienced an increase of 8.9 cm/hr above initial conditions whereas slash treatments recovered to 6.2 cm/hr below initial conditions. From 6 to 12 passes under both cover types, the skidder reflected a loss in hydraulic conductivity comparable to that after the first pass. Slashed treatments saw greater loss of saturated hydraulic conductivity than bare treatments. Changes in saturated hydraulic conductivity were closely related to macro porosity. When macro porosity declined significantly, saturated hydraulic conductivity did as well. For bare treatments 11.2% of macropores were lost after 1 pass with rebound to a loss of 7.9% after 3 passes. After 3 passes, the loss of macropores remained constant around 11.0%. For slashed treatments macropores were reduced by an average of 9.8% for passes 3 through 12. Bulk density increased by 0.2 g/cm^3 after the first pass for both cover types and remained relatively consistent for the remainder of passes from 6 to 12. No major trends emerged for change in micro porosity and volumetric water content. For both cover types, values increased with traffic and then remained relatively constant. Soil stress residuals for the skidder showed appreciable change after a single pass with bare treatments experiencing higher magnitudes of change than slashed overall. Bare treatments reached a peak at 3 passes followed by near constant response through 12 passes. Slashed treatments experienced the greatest change after 1 pass with near constant values for the remainder of trafficking.

Cover played a greater role for the dozer. Bare treatments experienced major changes after 1 pass, but did not experience appreciable change under slashed conditions until 3–6 passes. In terms of saturated hydraulic conductivity, the dozer lost 4.1 cm/hr after 1 pass for bare conditions, rebounded to a gain of 0.3 cm/hr after 3 passes, and reflected losses of about 8.0 cm/hr from 6 to 12 passes. For slashed conditions, no major loss was found after 1 pass, but a loss of 12.5 cm/hr occurred after 3 passes. Slash experienced significant losses after 6 and 12 passes of 25.3 and 26.6 cm/hr, respectively. Macro porosity was related to saturated hydraulic conductivity. Under bare conditions, the dozer lost 2.3% of macropores after one pass. The loss gradually increased to between 6.0 and 7.0% loss after 12 passes. Slashed treatments experienced a slight increase in macropores of 1.7% after 1 pass followed by losses from 3 to 12 passes. The slashed treatment lost 8.6% of macropores after 12 passes. Bulk density was increased by 0.06 g/cm^3 after 3 passes for bare treatments and reached a consistent value of 0.1 g/cm^3 for passes 9 and 12. Bulk density did not increase to 0.06 g/cm^3 until 6 passes for slashed treatments. Micro porosity increased with traffic on average for bare and slashed treatments, but no major patterns were apparent. Volumetric water content did not exhibit any apparent pattern as values reflected both an increase and decrease in volumetric water content. For both cover types, a clear pattern emerged for changes in soil stress residuals for the dozer. Although slashed treatments saw a greater change after 1 pass, both bare and slashed treatments saw small changes from passes 1 to 3 with marked change of three times the magnitude of impact occurring at 6 passes. Magnitudes of change are generally the same regardless of cover type (Table 2).

Table 2. Results for soil properties based on treatment and number of passes; values reported are changes from initial conditions.

		Change in saturated hydraulic conductivity	Change in bulk density	Change in porosity	Change in micro porosity	Change in macro porosity	Change in volumetric water content	Change in bulb reading
Treatment	Passes	cm/hr	g/cm^3	%	%	%	%	*N*
Skidder bare	0	0.00^{a}	0.00^{c}	0.00^{a}	0.00^{b}	0.00^{a}	0.00^{f}	0.00^{d}
	1	−19.68^{a}	0.18^{ab}	−6.94^{bc}	4.29^{a}	−11.24^{b}	6.17^{abcd}	27.44^{abc}
	3	8.91^{a}	0.17^{ab}	−6.35^{bc}	1.58^{ab}	−7.94^{b}	7.33^{ab}	40.54^{a}
	6	−19.6^{a}	0.22^{ab}	−8.53^{bc}	2.94^{ab}	−11.47^{b}	6.50^{abc}	31.74^{a}
	9	−5.46^{a}	0.27^{ab}	−10.29^{c}	1.23^{ab}	−11.52^{b}	9.00^{a}	36.20^{a}
	12	−2.83^{a}	0.24^{ab}	−9.14^{bc}	1.85^{ab}	−10.99^{b}	5.83^{abcd}	28.04^{ab}
Skidder slash	0	0.00^{a}	0.00^{c}	0.00^{a}	0.00^{b}	0.00^{a}	0.00^{f}	0.00^{d}
	1	−14.58^{a}	0.18^{ab}	−6.83^{bc}	2.93^{ab}	−9.76^{b}	1.67^{ef}	12.85^{bcd}
	3	−6.15^{a}	0.18^{ab}	−6.75^{bc}	2.62^{ab}	−9.37^{b}	1.17^{f}	10.36^{d}
	6	−16.29^{a}	0.28^{a}	−10.63^{c}	1.02^{b}	−11.65^{b}	2.67^{def}	8.17^{d}
	9	−13.16^{a}	0.21^{ab}	−7.83^{bc}	2.86^{ab}	−10.69^{b}	3.33^{cdef}	11.70^{d}
	12	−16.43^{a}	0.13^{bc}	−4.88^{ab}	2.64^{ab}	−7.52^{b}	5.00^{bcde}	12.64^{cd}
Dozer bare	0	0.00^{a}	0.00^{b}	0.00^{a}	0.00^{bc}	0.00^{ab}	0.00^{ab}	0.00^{b}
	1	−4.10^{a}	−0.02^{b}	0.62^{a}	2.91^{a}	−2.29^{abc}	0.17^{ab}	3.54^{b}
	3	0.26^{a}	0.06^{ab}	−2.13^{ab}	1.27^{abc}	−3.40^{abc}	−2.00^{b}	8.91^{b}
	6	−7.41^{a}	0.02^{ab}	−0.80^{ab}	1.56^{abc}	−2.36^{abc}	−1.50^{b}	25.04^{a}
	9	−9.11^{a}	0.11^{ab}	−4.22^{ab}	2.69^{a}	−6.91^{c}	−1.50^{b}	25.57^{a}
	12	−6.22^{a}	0.10^{ab}	−3.79^{ab}	1.63^{abc}	−5.42^{bc}	−1.67^{b}	33.92^{a}
Dozer slash	0	0.00^{a}	0.00^{b}	0.00^{a}	0.00^{bc}	0.00^{ab}	0.00^{ab}	0.00^{b}
	1	0.39^{a}	−0.03^{b}	1.35^{a}	−0.32^{c}	1.67^{a}	1.50^{ab}	8.80^{b}
	3	−12.49^{a}	0.04^{ab}	−1.46^{ab}	1.27^{abc}	−2.73^{abc}	−1.17^{b}	11.99^{b}
	6	−25.28^{a}	0.06^{ab}	−2.21^{ab}	2.74^{a}	−4.94^{abc}	0.17^{ab}	27.63^{a}
	9	−14.60^{a}	0.06^{ab}	−2.37^{ab}	−0.14^{bc}	−2.23^{abc}	−0.67^{ab}	24.40^{a}
	12	−26.64^{a}	0.16^{a}	−6.16^{b}	2.44^{ab}	−8.60^{c}	2.67^{a}	31.45^{a}

*Within treatment, numeric values followed by different letters are significantly different; $p < 0.05$.

Mechanical resistance data was analyzed for the effect of cover over 12 passes of the experiment. Mechanical resistance values are presented from the two uppermost depth classes; 25–100 mm (depth class 1) and 125–200 mm (depth class 2). These depth classes correspond to the same depth as extracted soil cores. As with other soil characteristics, reported numbers show change from initial conditions.

For the skidder in depth classes 1 and 2, cover had major influences. Bare treatments in depth class 1 experienced an increase of 385.0 kPa while slashed treatments experienced only an 85.0 kPa increase over 12 passes. The same held true for depth class 2. Mechanical resistance for the bare treatment increased by 607.2 kPa while slash treatments only increased by 382.0 kPa, thus indicating that sites were experiencing some traffic effects at depth. The dozer followed similar trends, but the magnitudes of increases were slightly lower. For bare treatments in depth class 1 the mechanical resistance increased by 378.7 kPa while slashed treatments increased by 73.7 kPa. For the bare dozer treatments in depth class 2, there was an increase of 490.0 kPa and there was an increase of 84.5 in slash treatments (Table 3).

Mechanical resistance data from depth classes 1 and 2 was analyzed based on treatment and number of passes. Traffic resulted in increased mechanical resistance values. The skidder and dozer showed major fluctuations in mechanical resistance for slash treatments (Table 4).

For depth class 1 and 2 bare treatments, the skidder caused significant increases in mechanical resistance for the first three passes. For passes 6 through 12, mechanical resistance dropped and maintained a consistent value. Depth class 1 reached a maximum of 710.9 kPa after 3 passes and leveled out around 350.0 kPa. Depth class 2 reached a maximum of 1102.6 kPa and leveled out around 600.0 kPa. For depth class 1 with slash the skidder caused a decrease after the first and sixth pass, but overall change was an increase of 230.0 kPa after 12 passes. A maximum of 822.5 kPa was reached with slash cover for depth class 2 after 3 passes. With further trafficking, values dropped to 274.0 kPa increasing to 402.0 kPa by 12 passes.

The dozer did not exhibit any clear pattern for bare treatments regardless of depth. Values of mechanical resistance both increased and decreased throughout the study. The magnitude of change at the second depth class was larger than the first. At depth class 1 for slash treatment with the dozer, mechanical resistance values decreased for the first 3 passes and then increased to 356.3 kPa at 6 passes. Values decreased after 9 passes, but showed an increase of 448.6 kPa after 12. Depth class 2 for the dozer with slash experienced decreases in resistance over 200.0 kPa after passes 1 and 9. All other passes increased with a maximum of 507.7 kPa after 12 passes.

Table 3. Average results for comparison treatment for mechanical resistance over 12 passes; reported values are changes from initial conditions.

Treatment	Change in mechanical resistance, 25–100 mm (kPa)	Change in mechanical resistance, 125–200 mm (kPa)
Skidder bare	384.97[a]	607.19[a]
Skidder slash	84.99[b]	382.01[a]
Dozer bare	378.70[a]	490.00[a]
Dozer slash	73.75[b]	84.47[b]

*Within treatment, numeric values followed by different letters are significantly different; $p < 0.05$.

Table 4. Results for mechanical resistance based on machine, number of passes, and cover type; values reported are changes from initial conditions.

Treatment	Passes	Change in mechanical resistance, 25–100 mm (kPa)	Change in mechanical resistance, 125–200 mm (kPa)
Skidder bare	0	0.00[def]	0.00[c]
	1	582.41[f]	754.83[ab]
	3	710.94[cde]	1102.61[a]
	6	391.86[ef]	504.03[abc]
	9	290.91[bcd]	686.46[abc]
	12	333.72[cde]	595.22[abc]
Skidder slash	0	0.00[def]	0.00[c]
	1	−118.03[ab]	431.25[abc]
	3	236.75[a]	822.50[ab]
	6	−101.28[abc]	274.86[bc]
	9	263.33[bcd]	361.47[bc]
	12	229.16[bcd]	402.00[bc]
Dozer bare	0	0.00[bcd]	0.00[cd]
	1	335.20[abc]	525.94[abc]
	3	513.92[a]	480.78[abc]
	6	394.81[ab]	692.45[ab]
	9	672.89[a]	779.75[a]
	12	355.39[abc]	461.09[abc]
Dozer slash	0	0.00[bcd]	0.00[cd]
	1	−182.97[d]	−209.64[d]
	3	−33.00[cd]	134.41[bcd]
	6	356.33[abc]	314.33[abcd]
	9	−146.42[d]	−239.95[d]
	12	448.55[a]	507.67[abc]

*Within treatment, numeric values followed by different letters are significantly different; $p < 0.05$.

Data collected with the AgTech sensors provided no clear relationship between soil stress residuals and normally accepted soil compaction indices. However, clear trends were apparent in soil stress residuals data as indicated by changes in bulb readings (Table 1). For heavier vehicles, like the skidder, soil stress residual data suggests that slash played a role in distributing the weight leading to less impact. The magnitude of change for the skidder was less for slashed treatments than for bare with a significantly lower bulb reading of 9.3 N with slash versus 27.3 N without the benefit of slash cover. In terms of soil stress residuals, cover type does not appear to be significant for lighter tracked vehicles like the dozer (Table 2).

Discussion

Trafficking associated with overland skidding changed all soil properties that were analyzed. Some results were as expected, but others were contradictory. This variation may be the result of variability of traditional measures of soil disturbance. Traditional measures pertain to specific samples and can vary based on soil type, moisture content, and operator consistency. For both types of machinery, visible ruts were present following the study. The heavy grapple skidder created deep ruts with obvious soil movement and displacement. The lighter dozer created shallow uniform ruts. Jansson and Johansson (1998) reported the same types of rutting associated with wheeled versus tracked machinery. Wang et al. (2007) noted that under wet conditions, or in cases where soil moisture is increased, heavy machinery may displace rather than compact soil. This phenomenon was noted by Sheridan (2003) in which traffic increased soil water content leading to soil displacement rather than continued compaction.

Changes in soil properties occurred within the first loaded pass for both machines regardless of cover type except for the dozer with slash treatment (effects occurred after 3–6 passes in this case). For overland skid trails experiencing traffic levels of 12 passes, wheeled skidders increased bulk density by 0.2 g/cm^3 and tracked skidders increased bulk density by 0.05 g/cm^3 in the mountains on silt loam soils. Results are similar to those found by Wang et al. (2005) and (2007). These researchers found major increases in bulk density following a single loaded pass on mountain soils with a slight decrease in bulk density after 4 passes reaching a near constant value with only gradual increases for the remaining passes. Findings are similar to the skidder data from this experiment as there was major change after 1 pass followed by generally constant and slightly increasing bulk density with further traffic.

Mechanical resistance of soils was increased after 1 pass for both the skidder and dozer bare treatments. The opposite was true for both slashed treatments as these experienced a loss in mechanical resistance following a single pass. Sheridan (2003) found increases in mechanical resistance following 2 passes for tracked machines and 10 passes for rubber-tired machines. Sheridan (2003) also reported significant losses of saturated hydraulic conductivity following traffic by heavy machinery. This is in agreement with this study as hydraulic conductivity was reduced following traffic.

Jansson and Johansson (1998) reported that both tracked and wheeled machines increase bulk density and decrease macro porosity. This finding supports the relationship found between saturated hydraulic conductivity and macropore space found in this experiment.

When soil properties are analyzed over the entire 12 passes, interesting and unexpected relationships between bare and slash cover were apparent. Slashed treatments experienced a loss in saturated hydraulic conductivity 2–3 times that experienced by bare treatments. It is uncertain why this occurred, but other researchers have explored potential causes. Wood et al. (2003) investigated slash road failures where soil properties could be negatively influenced. If portions of slash in this experiment failed, broke, or transmitted concentrated rather than dispersed loads, a greater decrease in hydraulic conductivity could be expected. Eliasson and Wästerlund (2007) clarify that slash is an operational by-product used as a road covering. This material may contain larger diameter pieces as well as small diameter branches. On a small spatial scale for sampling, samples may be influenced by large materials which may not bend under weight of traffic and concentrate loads rather than distribute them. This would put more pressure on a given volume of soil. Cover did not impact changes in bulk density or total porosity. The experiment did show the rubber-tired skidder resulted in 3 times less pore space and 3.4 times the amount of compaction than the dozer if bulk density is used as a measure. This is likely a result of weight differences. Cover did not result in any difference in the increase in micropore space for the rubber-tired skidder. The tracked vehicle saw double the increase in micropores on bare treatments than slash. Loss in saturated hydraulic conductivity was directly tied to loss of macropore space. Bare treatments saw a greater loss of macropore space than slashed. Traffic compressed larger pore spaces in the soil matrix thus removing larger conduits for moving water through the profile. Also, a heavier vehicle caused more compression and thus greater loss of pore space than the lighter vehicle. Cover played a major role in changes in mechanical resistance. Bare treatments exhibited much higher soil strength than slashed treatments. This contradicts hydraulic conductivity findings, but indicates that slash may actually serve to spread machine loads across a greater area thus reducing the soil impact. This agrees with the findings of Wood et al. (2003) and Eliasson and Wästerlund (2007). Both experiments showed that when slash was correctly placed and of the appropriate size distribution to bear the load of a machine rather than concentrate it, soils were less impacted. By correct size distribution and placement refers to slightly flexible branches placed perpendicular to traffic rather than large stiff tops that do not bend.

Further research is needed to understand the role of slash as a means of soil protection. Projects need to take place across different physiographic regions to give managers an idea of how soils are behaving on different soil types and terrain. Future projects also need to address slash placement, composition, and size as this is beyond the scope of this experiment. Slash is an encouraged method for protecting exposed soils from erosion (VDOF 2011). Although slash provides cover and has been shown to be an effective protection against soil erosion in the region (Sawyers et al. 2012; Vinson et al. 2017), this study showed that slash does not alleviate the effects of traffic on the underlying soil profile. Results that showed slash as inadequate soil protection from this study may be influenced by project design and installation, soil characteristics, sampling technique, and heterogeneity of soils on a small scale. Slash is an operational by-product and materials onsite were used. Results may have been different if composition of pine versus hardwood slash changed. Wood et al. (2003) found that common failures associated with slashed roads were caused by large diameter slash and slash placement. Large logs can be forced into the soil surface. These results were common after heavy traffic or during turning. Slash roads should be constructed of evenly distributed small diameter material. Eliasson and Wästerlund (2007) had similar findings to our experiment. Although slash was expected to reduce rutting and prevent compaction, they found no significant relationship between slash cover and reduced changes in soils. They suspected that excess traffic leads to breakage, thinning, and ultimate failure of slash roads. McDonald and Seixas (1997) found that slash cover on sandy soils resulted in no difference in soil compaction, but after 5 passes compaction of slashed plots was half that of bare plots. Wood et al. (2003) found that slash reduced negative changes in the topsoil consistent with our findings of less change in mechanical resistance within the upper depth classes.

Even though direct comparison of machines has little value because of weight differences, it was revealing that many soil properties were changed almost as much by the small dozer as the heavier rubber-tired skidder. Researchers including

Sheridan (2003) have found this. They did not find major differences between rubber-tired and tracked vehicles. Despite the major differences in ground pressure, tracked vehicles are subject to higher amounts of vibration. The larger contact area with vibration actually works to tamp the soil or cover leading to changes in soil properties.

This study served as an informative pilot project for the deployment of AgTech sensors in a forest setting. Further research is needed to explore the possibilities of AgTech sensors for data collection. These sensors would be ideally suited for research projects where excessive destructive sampling would be cost prohibitive or impractical. These sensors should be subjected to an initial test for a given soil to determine their ideal effective depth and then can be installed to collect data for an entire project at a given location.

In conclusion, this study indicated the heavier skidder resulted in more visible ruts, caused greater increase in bulk density, and caused greater decrease in macro porosity than the smaller dozer. This shows that increase in machine size may increase the amount of disturbance done to a given site. This experiment showed that providing slash cover instead of leaving the existing forest floor for overland skidding had limited effect on changes in bulk density and porosity. Mechanical resistance data were contradictory to the bulk density and porosity findings. Slash did reduce the increase in mechanical resistance when compared to bare treatments likely as a result of weight distribution on a lane-wide scale. Mechanical resistance data also contradicted the machine size finding as the impacts from the heavy skidder and light dozer were similar in magnitude in the surface depth class.

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