SOIL HYDRAULIC AND PHYSICAL PROPERTIES AS AFFECTED BY

LOGGING MANAGEMENT

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SOIL HYDRAULIC AND PHYSICAL PROPERTIES AS AFFECTED BY LOGGING MANAGEMENT

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ABSTRACT

Former studies have shown that once compacted, forest soils often recover slowly (many decades) to pre-disturbed levels for soil properties such as bulk density or penetrometer resistance. Runoff and soil erosion from forest lands increases due to effects from this soil compaction. Increased carbon sequestration is expected from forest land; however, increased runoff and erosion will negatively affect carbon sequestration in the soil. As climate change occurs, more intense rain may fall which will create challenges with runoff and erosion from compacted sites. This study was conducted to evaluate the effects of selected harvesting techniques on soil physical and hydraulic properties.

The effects of logging roads, log landing areas, and logged areas on water retention, saturated hydraulic conductivity (K_{Sat}), and bulk density were investigated on harvested sites within the Mark Twain National Forest in Callaway County, Missouri, USA on a moderately well-drained Keswick soil (fine, smectitic, mesic Aquertic Chromic Hapludalfs). Soil cores (7.6 cm by 7.6 cm) were removed in four 10-cm depth increments in June and were evaluated for saturated hydraulic conductivity, soil water retention, pore-size distributions, and bulk density. Saturated hydraulic conductivity was measured for each core sample using a constant head permeameter, or the falling head method for samples with low values. For the water retention measurements, soil cores were saturated and water retention measurements were recorded for 0.0, -0.4, -1.0, -2.5, -5.0, -10.0 and -

20.0 kPa readings. Soil aggregate samples were used for the -33 and -100 kPa water retention readings and samples passed through a 2.0 mm sieve was used for the -1,500 kPa water retention reading. The soil bulk density was also determined for the soil core samples. Pore size distributions were estimated using the water retention data from each sample.

Bulk density was significantly higher (P<0.01) for the logging road and log landing areas compared to the logged areas. This was attributed to the higher levels of soil compaction in the more trafficked areas of the site. Significant interactions (P<0.01) between treatments and soil depth occurred; logged areas increased with soil depth while the logging road and log landing areas remained fairly constant with depth. No statistical differences in bulk density were observed at the deepest sampling depth (30 to 40 cm). Saturated hydraulic conductivity was also significantly lower (P<0.01) for the logging road and log landing areas compared to the logged areas. These values were also affected by soil compaction. Values for K_{Sat} in the surface soil were 33 times greater for the logged areas compared to the logging road and log landing areas. No statistical differences in K_{Sat} values among treatments occurred at the deepest sampling depth (30 to 40 cm).

For the 0 and -0.4 kPa soil water pressures, water retention was 11% higher and 7% higher for the logged areas versus logging road and log landing areas averaged across all soil depths, respectively. Soil water retention was significantly affected (P<0.01) by soil depth for all pressures; soil water retention increased with increasing soil depth due to increases in clay content. In addition, significant interactions with soil water retention occurred among treatments and soil depth; retention decreased more with depth for logged areas compared to log landing and logging road treatments. For the macropores (>1000

micrometer diameter) and coarse mesopores (60 to 1000 micrometer diameter) combined, values were 95% higher for the logged areas compared to logging road and log landing areas within the 0 to 10 cm depth. Pores decreased with soil depth for coarse mesopores and fine mesopores (10 to 60 micrometer diameter), but increased with depth for the micropores (< 10 micrometer diameter),   The water retention and porosity values were affected by increasing soil bulk density due to differences in soil compaction.

Soil hydraulic properties which included soil hydraulic conductivity, water retention and pore size distributions were significantly affected by forest harvesting treatments. From this study, the methods used in logged areas appear to have caused less change in soil physical and hydraulic properties; however, significant changes occurred with these properties for logging roads and the log landing area. Efforts to reduce compaction should be concentrated in areas of logging roads and log landing areas.

CHAPTER 1

INTRODUCTION

Globally, each year over 11 million ha of tropical forests are destroyed. Another 6 million ha are degraded to desert-like conditions because of economic imbalances and poor land ethic (Powers et al., 1990). A multi-nation report on global trends strongly recommended that we reassess our land use policies to meet the challenges of sustainable development (Brundtland, 1987). As the population of the world continues to grow, the demand for forest products will similarly continue to increase. Soil is a fundamental resource that controls the quantity and quality of such renewable forest resources as timber, wildlife habitat, forage, and water yield; and because soil is a non-renewable resource directly affected by forest management practices it needs to be conserved (Tiarks et al., 1997). Commercial thinning of overstocked stands can reduce fuel for forest fires and provide wood products. Tree harvest necessitates a decision about the most appropriate combination of equipment to fell, to process, and to yard logs or whole trees to roadside for transport. Equipment choice is often based on extraction costs, damage to residual trees, and the extent and severity of soil disturbance (Landsberg, 2003).

Increased forest management and concern over changes in soil productivity are among the topics debated by forest managers and the public (Page-Dumroese, 2006). A key element in this debate is the use of mechanized equipment to extract timber products and the subsequent soil compaction and recovery times (Greacen and Sands, 1980; Froehlich and McNabb, 1984; Jansson and Johansson, 1998; Landsberg et al., 2003; Miller et al., 2004). A potential consequence of severe soil compaction is the significant loss of site productivity (Powers, 1991; Morris and Miller, 1994). Ultimately, the degree of

compaction caused by harvesting or site preparation affects soil properties (e.g., texture, organic matter, and water content) at the time of disturbance (Block and VanRees, 2002).

Various studies have shown that once compacted, forest soils often recover slowly (many decades) to undisturbed levels of bulk density or soil strength (Sands et al., 1979; Froehlich et al., 1985; Tiarks and Haywood, 1996). Recovery rates are dependent on many factors, but chief among them are number of repeated harvest cycles, soil moisture conditions during harvest, soil texture, and rock-fragment content (Miller et al., 1996; Williamson and Neilsen, 2000; Liechty et al., 2002). The extent of compaction, initial bulk density, depth of impact, and subsequent soil recovery are all factors that determine the consequences of timber harvesting or site preparation on productivity (Page-Dumroese, 2006). In addition, duration and variability of compaction can be significant from site to site or at depth in the soil profile (Beckett and Webster, 1971; Blythe and Macleod, 1978; Courtin et al., 1983). For instance, variability within soil textural groups, forest stands, or on skid trails can be as great as or greater than the variability between them (Courtin et al., 1983). This study proposes to evaluate the effects of selected harvesting techniques on soil physical and hydraulic properties.

Challenges with compaction occur from traffic and heavy loads when soils have insufficient strength to support these loads (Siegel-Issem et al., 2005). When soils fail, which is an increase in density due to the excess load, the bulk density of the soil increases which gives the soil sufficient strength to support the load (Hillel, 1998). Ultimately, the degree of compaction caused by harvesting or site preparation is affected by soil properties (e.g., texture, organic matter, and water content) at the time of disturbance (Block and VanRees, 2002). Moisture content is one of the most important factors influencing the

compactiblity of soils (Soane, 1990). Higher soil water content reduces soil strength allowing greater increases in density during wet conditions (Jansson and Johansson, 1998). Wet conditions cause the soil to exhibit less strength.

Soil hydraulic properties are very sensitive to compaction (Blanco-Canqui et al., 2004). Jannson and Johansson (1998) found that saturated hydraulic conductivity decreased at the 10 cm depth by two orders of magnitude due to wheel traffic. In forested settings, compaction not only decreases production but enhances runoff and erosion and negatively affects water quality (Elliot et al., 1998). Thus, management is critical to maintain good hydraulic properties to minimize runoff, erosion, and water quality.

The mass of the equipment used during harvest activities plays a significant role in determining the depth to which soil physical parameters are altered. The depth to which compaction occurs is also dependent upon the soil water content (Hillel, 1998). A practical recommendation is to minimize traffic in order to affect the soil as little as possible (Jansson and Johansson, 1998).

Maintaining optimal soil hydraulic properties in forest managed sites is critical for environmental conservation. Although the effects of timber harvest on bulk density have been studied considerably, not many studies have been conducted on harvest activities' effects on hydraulic properties in soils.

Objectives

This study is to evaluate forest harvesting treatments on soil physical and hydraulic properties. The treatments include historic logged areas, recent logged areas, logging roads, and log landings. The specific objectives of the experiment are:

-Evaluate the effects of harvesting treatments on soil bulk density and saturated hydraulic conductivity.

-Assess harvesting treatment effects on soil water retention and pore size distributions.

Hypotheses

Specific null hypotheses include:

-Soil bulk density is not influenced by forest harvesting treatments.

-Saturated hydraulic conductivity is not affected by harvesting treatments.

-Water retention at selected soil water pressures is not influenced harvesting treatments.

Pore size distributions (macroporosity, mesoporosity, and microporosity) are not affected by harvesting treatments.

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CHAPTER 2

LITERATURE REVIEW

Forest Production and Management

Forest productivity is a general term referring to growth and maintenance of all or any part of the assemblage of plants and animals that exist in forests at scales that range from microplots to entire ecosystems. In contrast, *site productivity* more narrowly refers to the growth or capacity of a site to grow trees at the scale of individual forest stands (Morris and Miller, 1994). Forest productivity can be also defined as the yield of commercially valuable timber products per unit of land over time. In a basic sense, the forest management process is the input of practices to achieve a certain kind, amount, and rate of product and service output (Burger, 2009). However, this definition is more sensitive to market conditions than site conditions; a more suitable description includes the future productivity of the forest. Often times the economic benefit of protecting the soil resources is not evident (Powers et al., 1990). Traditional economic analyses weight the worth of soil protection in terms of expected future revenues from timber harvests, and ignore the fact that site quality may decline and that yields may fall. For example, the standard Faustmann method for computing soil expectation values and economically optimal rotations commonly assumes that soil productivity holds constant or increases, but never declines (Routledge, 1987). One method to gain timely insight into long-term sustainability is to measure soil physical properties prior to and following harvest activities. Resultant values can be indicators of detrimental impacts to future forest productivity (Butnor et al., 2006). With an

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understanding of the effect of harvesting activities on soil properties, prolonging the soil's long-term productivity may be realized (Tiarks et al., 1997).

Thinning timber stands allows forests to produce more commercially valuable product per unit of land in a shorter period of time (Powers et al., 1990). Regenerated forests left to their own means take a much longer period to reach capacity, and even then, many non-native and invasive species may dominate if left unchecked (Westbrooks, 1998). Through research, an optimal balance between maximum production capacity and minimum disturbance to the long-term productivity of the forest is desired (Powers et al., 1990).

Research has shown that timber production capacity declines on non-wetland sites are related principally to site organic matter losses and soil porosity reductions (Powers et al., 1990). Soil compaction, churning, rutting, mixing, displacement, and removal are types of disturbance that can reduce tree root growth through their influence on soil physical properties (Miller et al., 2004). Compacted soils will eventually return to their natural state, but the length of time required depends on the depth of compaction, presence and depth of freezing and thawing cycles, and presence of expanding clays (Tiarks et al., 1997). Direct correlations of compaction impacts on forest plant growth are frequently unclear because compaction is often associated with other detrimental disturbances, such as soil displacement, mixing, and rutting (Page-Dumroese et al., 2006). In addition, plant growth on compacted areas (skid trails, landings, etc.) has sometimes been found to be greater than on non-impacted soil because of reduced weed competition (Miller et al., 1989; Miller and Anderson, 2002). During a 12-year economic valuation study, Kiran and Kaur (2011) showed that forest soil restoration activities by the Forest Department resulted in economic

benefits post-restoration compared to economic losses pre-restoration. Establishment of soil quality monitoring variables that are practical to use, give meaningful information over a wide range of sites, and provide a benchmark for evaluating soil change, is essential. In order to make accurate projections of future site productivity losses or gains following various soil disturbances, adequate baseline assessments must be made of important site-specific properties such as bulk density, forest floor depth, soil cover, etc. (Page-Dumroese et al., 2000). During these projections, taking soil degradation into account will have a major impact on the identification of lands on which timber production is determined not to be economical (Routledge, 1987).

Harvest Techniques

An uneven-aged timber management approach was applied in the study location. As stands of shade-intolerant trees such as oak species grow older, openings in the canopy due to natural or man-made disturbances increase the availability of light and other resources (Larsen et al., 1999). These gaps in the stand allow established seedlings, especially those which have developed large root systems over several years, to experience rapid shoot growth (Johnson, 1979; Dey et al., 1996).

Forest harvesting methods have a significant effect on the land resource. The amount of total soil disturbance varies considerably between different yarding techniques. Megahan (1980) determined that aerial and skyline cable techniques are far less damaging than other yarding techniques. Sidle (1980) presented data showing that tractors cause the greatest amount of soil disturbance (35 percent of land area) and soil compaction (26 percent of land area). Miller and Sirois (1986) compared the land area disturbed by cable,

skyline, and groundskidding systems; they found groundskidding operations to affect 31 percent of the total land area, whereas cable yarding only affected 16 percent of the total land area. Similarly, Patric (1980) found skidders to serve the smallest area per mile of road (20 acres), with skyline yarding serving the largest area per mile of road (80 acres).

The proportion of area that is disturbed by constructed roads varies widely due to differences in topography, road specifications, and logging equipment (Megahan, 1988). As a result, summaries or central tendencies of reported data only provide a very general indication of the area that may be disturbed by harvest activities. Such summaries include those by Froehlich (1977) of 1.5 to 24% of the harvest area disturbed by roads, with an average "approaching 8%"; those by Megahan (1988) of 1 to 30% of the area disturbed by roads and an added 1 to 10% of the disturbance occurring in log landings, with an average total of about 10% for tractor and ground cable harvest (Megahan, 1988). Road construction and use during timber harvest activities is probably the single greatest contributor to surface erosion in the eastern US (Patric, 1976), the southern US (Vowell, 1985), and in the western US (Megahan, 1988), where it also leads to accelerated mass flow (Grigal, 2000).

Effects of Forest Harvesting on Soil Physical and Hydraulic Properties

Methods for harvesting forests may cause significant impacts to soils. The soil is highly sensitive to ground harvesting techniques. Soil compaction affects soil density and porosity as well as soil water retention and hydraulic conductivity (Mudgal et al., 2010). Jansson and Johansson (1998) found that the depth to which soil physical parameters were influenced by traffic was about the same for tracked and wheeled vehicles. Their finding

is in agreement with their hypothesis that the mass of the machine rather than the type of ground contact determines the depth to which soil physical parameters are altered. Additionally, there is a strong relationship between the degree of compaction and the physical properties of the soil. Compaction effects have been found to be strongly dependent on soil texture and soil water regime (Gomez et al., 2002).

Higher water content reduces soil strength which allows the soil to be more compacted with a similar load (Gomez et al., 2002). Sands are usually more resistive to soil compaction while silt loam materials are more sensitive to increased loads (Powers et al., 2005). These results indicate that forest harvest management will be more detrimental to soils at higher water content.

Bulk Density and Soil Strength Findings on several North American Long-Term Soil Productivity (LTSP) installations indicated that soil compaction was short-lived and did not impact tree growth after 5 to 10 years (Eaton et al., 2005; Sanchez et al., 2006; Powers et al., 2005). However, soil texture and pre-harvest bulk densities had a large effect on productivity results and density recovery rates. As compared to coarse-textured soils, fine-textured soils often have lower initial bulk density levels, but the largest increase after a logging treatment, with a majority of compaction occurring after a single equipment pass (Williamson and Neilsen, 2000; Page-Dumroese et al., 2006). Sites with initially high bulk density values, probably due to old abandoned fields after decades of agriculture, could not be compacted much further. Clayey and loamy soils exhibited the greatest timber growth reductions following compaction treatments versus sandy soils where productivity was actually enhanced following compaction (Powers et al., 2005). It is believed that

compaction increased soil moisture availability in these course-textured soils (Gomez et al., 2002).

In a study on the effects of different levels of soil compaction in North Carolina, three levels of compaction were applied to harvested loblolly pine (*Pinus taeda L.*) plots. The compaction treatments were no compaction (C_0), moderate compaction (C_1), and severe compaction (C_2) with bulk density values of 1.33, 1.46, and 1.45 Mg m^{-3}, respectively. In this study, the researchers found that increasing levels of soil compaction resulted in a trend towards decreasing mean stand volumes (Sanchez et al., 2006). Their observation was consistent with research indicating that compaction reduces root growth and ultimately stand productivity (Morris and Miller, 1994; Fleming et al., 1998; Williamson and Neilsen, 2000). Siegel-Issem et al. (2005) used a seven by seven factorial greenhouse experiment to assess root growth as a function of bulk density and volumetric water content. The experiment demonstrated, in general, trees grown on soils with lower densities have better ability to grow well across a broader range of soil moisture conditions. Effects on soil properties following treatment also change with depth; Blanco-Canqui et al. (2004) found that bulk density increased from 1.47 to 1.52 Mg m^{-3} and organic matter decreased from 15.5 to 14.0 g kg^{-1} with depth ($P<0.01$). For claypan soils with argillic horizons, the magnitude of desiccation cracking and water depletion, which directly influence bulk density, are affected by soil texture and mineralogy (Baer and Anderson, 1997); with water depletion and desiccation cracking, bulk density increases.

Before the North American LTSP study, most field research of compaction of forest soils had been generally retrospective, and centered on growth comparisons between trees on log landings and skid trails, and on less-disturbed land nearby (Powers et al. 1990). A

study by Hatchell et al. (1970) showed that naturally regenerated pine seedlings in compacted skid trails were less than half as tall as those away from skid trails in the Lower Coastal Plain of South Carolina and Virginia. In Washington, Froehlich et al. (1986) reported that volumes of 9 to 18-year-old ponderosa pine growing in compacted skid trails 23 years after yarding activities averaged about 20 percent less than for those in less-dense soils nearby. Additionally, a study in California by Helms et al. (1986) reported that 16-year-old pine growing in skid trails and log landings where bulk densities averaged 1.19 g cm^{-3} were 13 percent shorter and had 22 percent less volume (Helms and Hipkin, 1986) than adjacent trees growing in soil densities averaging 0.83 g cm^{-3}. Overall yield was reduced by 10 percent (Helms and Hipkin, 1986).

A comparison of tracked versus wheeled machines by Jansson and Johansson (1998) found that both machines increased bulk density to a depth of 40-50 cm compared with the control treatment. Cullen et al. (1991) reported no increase in bulk density below 30 cm in soils trafficked by rubber-tired skidders or crawler tractors while Jakobsen and Greacen (1985) found that the change in soil physical properties reached at least 70 cm (26 ton harvesting unit). In a study involving winter and summer trafficked sites, Block et al. (2002) found that bulk density increased significantly at 10- and 20-cm soil depths for both winter and two of the three summer harvested sites. Soil bulk density and mechanical resistance were increased from forest grazing which reduced soil porosity and water infiltration (Krzic et al., 2006).

The environment under which soils have formed plays a major role in determining the bulk density of the undisturbed soil. Compaction has been shown to be strongly related to the original bulk density, forest type, and soil parent material (Williamson and Neilsen,

2000). In a study by Tiarks and Haywood (1996), tree heights were shortest on disked plots probably due to higher soil strength which limited root growth.

Soil Water Retention For a given region, soil type, and tree species, forest productivity is a function of volumetric water content as it varies with climate across the growing season (Siegel-Issem et al., 2005). In Missouri, it has been determined that soil water content is much greater in no-till versus tilled treatments for the upper soil depths at soil water pressures less than –20 kPa; the van Genuchten relationship was used to fit these water retention curves. For the deeper depths (30 to 40 cm), water content was higher in a tilled soil than in the no-tilled soil for all pressures; however, this was likely attributed to the claypan being at a shallower depth for the tilled site because erosion has occurred to a greater extent with continuous cultivation (Mudgal et al., 2010).

None of the sites in the North American Long-Term Soil Productivity Study had an appreciable component of shrink-swell clays (Page-Dumroese et al., 2006). In a study investigating changes in soil hydraulic properties in a regenerating rain forest, Deuchars et al. (1999) found that infiltration rate increased with increasing forest age and the water release characteristic reverted gradually from one with greater water retention at all matric potentials in the pasture plot towards that found in the primary forest.

Wide-tired skidders operating on poorly structured medium-textured boreal forest soils did not significantly affect the shape of water retention curve and pore size distributions when the soils were drier than field capacity. At greater soil water contents, the effects were limited to the air-filled pores, which suggests that damage to soil structure is lessened and integrity of the aggregates is maintained despite the compaction (Startsev

and McNabb, 2001). A comparison of a range of equipment masses during harvest activities by Vossbrink and Horn (2004) determined that the mass of the different vehicle types was not the only reason for the increase in soil stresses and precompression stresses. Even the lighter mass equipment was able to cause high stresses, thus a complete picture of the harvesting procedure requires the inclusion of the load, soil strength, water content and hydraulic properties, and furthermore this assessment must also consider the land relief.

Saturated Hydraulic Conductivity   Soil hydraulic properties are dynamic and are affected by many factors. These factors include soil structure (Fuentes et al., 2004), biological plants and organisms that grow and decay (Beven and Germann, 1982; Meek et al., 1992), shrink-swell cracks in clay soils (Baer and Anderson, 1997), and agricultural activities such as tillage and traffic compaction (Udawatta et al., 2008; Fuentes et al., 2004). In a study determining saturated hydraulic conductivity (K_{Sat}) in a tilled versus native undisturbed field, Mudgal et al. (2010) determined that K_{Sat} was almost 57 times higher at the undisturbed site (316 mm h^{-1}) than at the tilled site (5.55 mm h^{-1}). This difference was likely caused by the differences in porosity and bulk density. Variations in soil hydraulic properties could be explained by the differences in land cover and management (compaction, tillage) but also by the loss of topsoil and the thinning of the layer above the claypan (Mudgal et al., 2010).

    Williamson and Neilsen (2000) found that K_{Sat} showed a pattern of reduction with increasing compaction but there was no overall relationship with bulk density. In a study by Reynolds and Zebchuk (1996), results suggest that the magnitude, range, and pattern of

variability of K_{fs} (field saturated hydraulic conductivity) measurements were controlled primarily by the well-developed and stable soil structure at the field site, rather than by texture, organic C, or surface topography. On most soils following harvest activities, the greatest reduction in hydraulic conductivity occurs in the 0- to 10-cm soil layer. Greater damage to wet soils is associated with deformation and displacement, rather than with in situ compaction. Soils with higher moisture content visually deteriorate following fewer machine passes (Froelich, 1972; Murphy, 1982) (Williamson and Neilsen, 2000). In one study, researchers found that field effective hydraulic conductivity, K, values of the top 90 cm of the profile for mature plantation forest were 60 to 95 m/day, which were 20 to 30 times the values given in the soil survey for the Deloss series. Harvest activities did not appear to affect those K values, but site preparation for regeneration, including bedding, reduced the K to values typically assumed for the Deloss series, 3.6 m/d for the top 45 cm and 1.6 m/d for deeper layers (Skaggs et al., 2006).

Infiltration Casermeiro et al. (2003) showed that plant cover was the main factor reducing surface runoff and movement of sediments. In another study, Trojan and Linden (1998) found that residues on the surface significantly increased steady infiltration rates and the time required to reach steady-state values. Kumar et al. (2012) demonstrated that agroforestry buffer areas have higher infiltration rates which imply lower runoff compared to pasture areas. The fraction of precipitation available for stream flow, increased rates of snowmelt, and modified runoff pathways to the stream channel are increased with forest harvesting (Moore and Wondzell, 2005).

Pore Size Distribution Where soil compaction occurs, total porosity decreases and soil strength and volumetric water content increase, resulting in increased water runoff and soil erosion, less rooting volume, and poor aeration (Greacen and Sands, 1980; Elliot et al., 1998; Williamson and Neilsen, 2000; Powers et al., 1990). In an extensive literature review, Sanchez et al. (2006) found that soil porosity was one of two site properties most likely to impact long-term productivity. Mudgal et al. (2010) found that conservation practices causing compaction to the soil resulted in a significant decrease in the occurrence of coarse and fine mesopores in the upper 30 cm soil depth. Brais (2001) found stem volume to increase in coarse textured soils and linked this increase to harvest traffic compaction causing a more favorable pore-size distribution, which improved the balance between aeration porosity and available water holding capacity. Page-Dumroese et al. (2006) found that change in pore-size distributions on two of the LTSP study sites may indicate that while bulk density has decreased five years after compaction activities, macroporosity may not have recovered. Additionally, Page-Dumroese et al. (2006) concluded that loss of macropores on fine-textured soil may prove to be more deleterious to plant growth than a percent change in bulk density. An experiment by Seigel-Issem et al. (2005) showed that compaction increased bulk density for four soils representing contrasting forest soils and resulted in a reduction in total porosity in all four soils.

Powers et al. (1990) believed that root growth decreases with decreasing root water potential and/or increasing soil strength, and plant stress increases as soil macroporosity decreases to a critical minimum. The conclusion was made that growth decline is likely after substantive compaction, and that it is related to loss in total soil porosity (Powers et al., 1990). Sands et al. (1979) hypothesized that compaction-caused reductions in total

porosity may result in little change in moisture retention, and therefore plant growth proceeds relatively unaffected until root growth is inhibited; however, Gomez et al. (2002) found that changes in pore-size distribution are highly dependent on soil texture and soil water regime, and did not preclude the use of soil porosity as a monitoring tool for managers. Further, the concept of non-limiting water range (NLWR) combines the effects of several soil properties and describes the range in which water availability is non-limiting to plants. This concept states that as porosity decreases, the NLWR becomes narrower, with mechanical resistance becoming limiting at the dry end and poor aeration becoming limiting at the wet end (Letey, 1985). Seigel-Issem et al. (2005) found a decrease in root length density in three of four soils for trees grown outside this optimal range following compaction.

Macropores affect infiltration of water and solutes in soil (Trojan and Linden, 1998). Messing et al. (1997) found that dry bulk densities were generally smaller and the macroporosities larger under tree crops compared with ley/cereal crops. Saturated hydraulic conductivities also tended to be larger under the tree crops. Slopes of the linear regression lines between saturated hydraulic conductivity and each of the parameters, dry bulk density, porosity and macroporosity were steeper in the soil under agricultural crops than under tree crops. Observed differences in physical properties were considered to be an effect of land use, which had brought about changes in aggregate stability, pore size distribution, and pore continuity (Messing et al., 1997).

During the LTSP study, Powers et al. (2005) observed that soil bulk density was increased by compaction treatments, but increases were greater for soils of low to moderate initial densities and soils with initial bulk densities greater than 1.4 Mg m^{-3} showed little

increase. Diminished increase can be attributed to finer pore sizes at higher bulk densities and the difficulty of compressing water-filled soil pores. Density recovery was also found to be very slow (Powers et al., 2005). The researchers found that growth tended to be reduced by compaction treatments on the clayey soils and increased on the sandy soils. These effects were attributed to losses of aeration porosity on clays and improvements in available water holding capacity on sands (Powers et al., 2005). Kim et al. (2010) found that differences between uniformly compacted and non-compacted plots for macropore parameters were most pronounced in the upper 10 cm and that differences between treatments were not significant below 20 cm.

Management for Improving Harvested Areas A need exists for optimization of harvest management; demand for non-timber forest products and services such as water supply and quality, biodiversity and habitat, recreation opportunities, carbon sequestration, and biomass for energy and transportation fuels will continue to increase on all forest lands. This added demand for energy biomass and carbon sequestration create conflicting objectives (Burger, 2009). Several techniques exist to improve harvested areas. Recontouring techniques on forest roads can result in lower bulk densities, less surface runoff and sediment production, and greater seedling growth than both traditional and subsoiling road retirement methods, however, the cost of recontouring is greater than subsoiling or traditional retirement. Preliminary analysis indicates that subsoiling may represent the most economically viable retirement method (Kolka and Smidt, 2004). Additionally, compaction of some coarse-textured soils can actually improve moisture relations for tree growth while loamy soils are more susceptible to compaction; clayey soils

are more susceptible to rutting and churning (Miller et al., 2004). Additionally, many best management practices can be applied during harvest activities such as use of pre-designated routes which will be compacted during harvesting to minimize the extent of the affected areas and avoidance of forest roads when they are wet, soft, and easily damaged (Enyart, 2009).

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CHAPTER 3

SOIL HYDRAULIC PROPERTIES AFFECTED BY LOGGING ACTIVITIES IN

A CENTRAL HARDWOOD FOREST

ABSTRACT

Former studies have shown that once compacted, forest soils often recover slowly (many decades) to pre-disturbed levels for soil properties such as bulk density or penetrometer resistance. This study was conducted to evaluate the effects of selected harvesting techniques on soil physical and hydraulic properties. The effects of logging roads, log landing areas, and logged areas on soil water retention, saturated hydraulic conductivity (K_{Sat}), pore-size distributions, and bulk density were investigated on harvested sites within the Mark Twain National Forest in Callaway County, Missouri on a moderately well-drained Keswick soil (fine, smectitic, mesic Aquertic Chromic Hapludalfs). Soil cores (7.6 cm by 7.6 cm) were removed in four 10-cm depth increments in June 2011. Bulk density was significantly greater ($P<0.01$) and K_{Sat} was significantly lower ($P<0.01$) under the logging road and log landing areas compared to the logged areas. No statistical differences in bulk density and K_{Sat} values occurred among treatments at the deepest sampling depth (30 to 40 cm). For the 0 and -0.4 kPa soil water pressures, water retention was 11% greater and 7% greater for the logged areas versus logging road and log landing areas averaged across all soil depths, respectively. For the macropores (>1000 micrometer diameter) and coarse mesopores (60 to 1000 micrometer diameter) combined, values were 95% greater for the logged areas compared to logging road and log landing areas within the 0 to 10 cm depth. From this study, the methods used in logged areas appear to have

caused small changes to soil physical and hydraulic properties; however, significant changes occurred with these properties for logging roads and the log landing.

INTRODUCTION

Various studies have shown that once compacted by harvest activities, forest soils often recover slowly to pre-disturbed levels of bulk density (Sands et al., 1979; Froehlich et al., 1985; Tiarks and Haywood, 1996). Recovery rates are dependent on many factors, but chief among them are number of repeated harvest cycles, soil moisture conditions during harvest, soil texture, and rock-fragment content (Miller et al., 1996; Williamson and Neilsen, 2000; Liechty et al., 2002). The extent of compaction, initial bulk density, depth of impact, and subsequent soil recovery are all factors that determine the consequences of timber harvesting or site preparation on productivity (Page-Dumroese et al., 2006). In addition, duration and variability of compaction can be significant from site to site or at depth in the soil profile (Beckett and Webster, 1971; Blyth and MacLeod, 1978; Courtin et al., 1983). For instance, variability within soil textural groups, forest stands, or along skid trails can be as great as or greater than the variability between them (Courtin et al., 1983).

Compaction is caused by traffic when soils have insufficient strength to support the load (Siegel-Issem et al., 2005). When soils fail, which is an increase in density due to the excess load, the bulk density of the soil increases which gives the soil enough strength to support the load (Hillel, 1998). Ultimately, the degree of compaction caused by harvesting or site preparation is affected by soil properties (e.g., texture, organic matter, and water content) at the time of disturbance (Block and VanRees, 2002). Soil water content is one of the most important factors influencing the compactiblity of soils (Soane, 1990). Higher

soil water content reduces the soil strength allowing greater increases in density during wet conditions (Jansson and Johansson, 1998). Wet conditions cause the soil to exhibit less strength.

Soil hydraulic properties are very sensitive to compaction (Blanco-Canqui, 2004). Jannson and Johansson (1998) found that saturated hydraulic conductivity decreased at the 10 cm depth by two orders of magnitude due to wheel traffic. In forested settings, compaction not only decreases production but increases runoff and erosion and negatively affects water quality (Powers et al., 1990). Thus, management is critical to maintain good hydraulic properties to minimize runoff, erosion, and water quality.

The mass of the equipment used during harvest activities plays a significant role in determining the depth to which soil physical parameters are altered. The depth to which compaction occurs is also dependent upon the soil water content (Braunack and Williams, 1993)(Jansson and Johansson, 1998). A practical recommendation is to minimize traffic in order to affect the soil as little as possible (Jansson and Johansson, 1998).

Maintaining optimal soil hydraulic properties in forest managed sites is critical for environmental conservation. Although the effects of timber harvest on bulk density have been studied considerably, not many studies have been conducted on harvest activity effects on hydraulic properties on soils. The purpose of this study was to assess the effects of different levels of timber harvesting traffic on soil bulk density, saturated hydraulic conductivity, soil water retention, and pore size distributions.

MATERIALS AND METHODS

Experimental Site History

The area selected for this study was located on the Cedar Creek unit of the Mark Twain National Forest near Fulton, Missouri. This site was historically settled by Europeans approximately 200 years before present. The site was initially managed under private ownership until the 1940s. Most European settlers in the 1800s through the early 1900s used the land for timber harvesting. After clearing, these lands were subsequently used as grazing land for cattle and other livestock. Some small areas were probably managed for hay as well as corn *(Zea maze)* and wheat grain *(Triticum aestivum)* crops. Some vegetable production occurred near homesteads (US Forest Service, 2004).

The forests originally consisted of an oak-hickory mix including some other less dominant species. Recent surveys indicate the land contains about 45% oak-hickory, 12% cedar and other hardwoods, about 6% bottomland hardwoods, and 1% locusts (Kingsley and Law, 1991). The oaks include white (*Quercus alba*), red oak group (pin oak *(Q. palustris)*, northern red oak *(Q. rubra)*, and black oak (*Q. velutina*)). The other 38% of the land is open (usually pasture with fescue and some warm season grasses) and brush.

Most of the land of the Cedar Creek unit was acquired by the U.S. federal government during the 1940's under Title II of the Bankhead Jones Act of 1937 (US Forest Service, 2004). Under the Act, the USDA-Soil Conservation Service, now the Natural Resource Conservation Service (NRCS), undertook a restoration program to improve the land. Most of the land was degraded due to overgrazing, cropping on unsuitable soils, and clearing of timber (US Forest Service, 2004). Conservation

management included fencing of water resources and pastures to control grazing. Pastures were also managed with rotational grazing (US Forest Service, 2004).

Experimental Site Information

For the experimental site, the average temperature in winter is -0.4 degrees C and the average daily minimum temperature is -5.5 degrees C (30 year average). In summer, the average temperature is 23.7 degrees C and the average daily maximum temperature is 29.6 degrees. The total annual precipitation is 114.4 cm. The average seasonal snowfall is about 49.8 cm (USDA, 1992; Guinan, 2013). The soils in the harvested areas were mapped as Keswick loam (Fine, smectitic, mesic Aquertic Chromic Hapludalfs). These soils are formed in a thin layer of pedisediments with an underlying weathered glacial till.

Soil profiles were studied from samples taken from a representative location within one of the Logged Area-recent treatments in May of 2013. Analyses were conducted for the soil horizons and data on soil physical and chemical properties for the site are shown in Table 3.1. Clay content, silt content, CEC, organic matter, and water pH (pH_w) are shown for the upper soil horizons in the table. In this study area, the claypan occurred at about the 18 cm depth on the average.

The study was conducted in portions of four harvested areas that are delineated by vegetative type into timber stands within the Cedar Creek unit. The treatments for this experimental study were defined as follows: historical logged area (Logged Area-H), recent logged area (Logged Area-R), logging road (Logging Road), and log landing area (Log Landing). Oak and hickory were the dominant species in these stands. The oak and hickory was harvested in October and November of 2007. For wildlife enhancement

purposes, the Forest Service determined a need to provide 40-50 percent of the sawtimber component of woodland habitat exhibiting a condition of 20-30 percent forbs, grass, and shrub ground cover (US Forest Service, 2004). Size of trees selected for harvest were 30 cm DBH or larger.

Table 3.1. Soil physical and chemical properties for the study location (Keswick silt loam) (5 to 9 % slope) presented by profile horizon with standard deviations indicated in parentheses.

Soil Horizon	Soil Depth	Sand	Silt	Clay	Organic Matter	pH_w
	cm	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	
A	0 – 10	19.6 (3.32)[t]	808.7 (2.9)	171.8 (0.5)	28.8 (5.0)	5.21 (0.26)
AE	10 – 18	18.1 (0.67)	833.2 (27.0)	148.6 (26.4)	9.55 (0.42)	4.83 (0.10)
BE$_1$	18 – 28	15.4 (0.72)	760.4 (28.0)	224.1 (27.3)	12.83 (3.99)	4.71 (0.05)
BE$_2$	28 – 40	13.0 (0.01)	708.3 (0.19)	278.7 (0.18)	3.08 (4.33)	4.58 (0.04)
2Bt	40 – 60	14.2 (1.70)	542.8 (28.0)	443.0 (26.4)	2.90 (2.50)	4.60 (0.05)

[t]Number in parenthesis is the standard deviation of the mean of 2 observations.

Four replicate harvested areas were selected and used to investigate the effects of logging management on soil physical properties. The Logged Area-R treatment was harvested in October and November 2007 using uneven-aged harvest methods. The historically logged area was harvested 70 years before present with clear cutting. There were four treatments with four replicates of each treatment. Within the Logged Area-R treatment, the harvesting equipment used to retrieve the logs from the logged area through the logging road to the log landing was a rubber-tired skidder. Axel loads of the

skidder were 6.8 metric tons with 71 cm wide tires. Soil water content conditions were relatively moist (slightly below field capacity) during harvest activities. The logs at the landing were stacked approximately 2.0 m high about six logs deep.

Sampling Procedures

Undisturbed soil cores, 7.6 cm in diameter and 7.6 cm in length, were taken to determine soil water retention, porosity, saturated conductivity (K_{Sat}), and bulk density. The cores were taken from the areas June 9-14, 2011. Samples were taken from each treatment of each replication. Sample cores were taken in the center areas of the Log Landing and Logging Road treatments. Cores were taken in proximity of a harvested tree in the Logged Area-R treatment and in selected random locations in the Logged Area-H treatment. Samples were taken from four depths: 0 to 10 cm, 10 to 20 cm, 20 to 30 cm, and 30 to 40 cm. These depths corresponded in part to soil horizons: the first two depths were in the A or AE horizon and the third and fourth depths were in the 2Bt horizon. The samples were then secured in plastic bags, transported to the University of Missouri Anheuser-Busch Natural Resources Building, and stored in cold rooms at 4.0°C until laboratory measurements were conducted.

Laboratory Analysis

For the saturated hydraulic conductivity measurement, the samples were removed from the cold room and the plastic bags were removed from each of the samples. A disc was used to cover the top of the sample and flip it over without losing the core's contents. The disc which was taped on the base of the core was then removed and cheese cloth was

attached to the base of the sample with a rubber band. The sample was then flipped back over, an additional sample core ring of the same dimensions was connected to the top of the sample with a bicycle inner tube, and the sample was placed in a tub. Water was then incrementally added to the tub over the course of 72 hours to allow the samples to saturate. Bentonite slurry was applied around the edge of the surface of the soil sample to fill any openings along the core walls. Once fully-saturated, a constant head permeameter unit was used to maintain a constant hydraulichead on the samples and saturated hydraulic conductivity measurements were taken using the constant head method. The falling head method was used for samples with constant head measurements that yielded less than 5.0 mL after 30 minutes.

For the water retention measurements the samples were re-saturated and transferred to a water retention unit with ceramic plates attached to a pressure regulator. Soil cores were exposed to selected pressures set at designated levels and water retention measurements were recorded for the -0.4, -1.0, -2.5, -5.0, -10.0 and -20.0 kPa readings. Following the lower pressure measurements, the samples were removed from the apparatus and air dried in an oven at 35°C until a constant weight was reached. Additionally, a sub-sample from each core was taken from the air-dried cores and oven dried at 105°C to determine oven-dry water content which was used to measure bulk density (Dane and Topp, 2002).

For the lower soil water pressures, pressure chambers connected to pressure regulators were used. Sub-samples of the air dried cores were used for measurements: aggregates were used for the -33 and -100 kPa water retention readings and samples passed through a 2.0 mm sieve was used for the -1,500 kPa water retention reading.

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Pore size distributions were calculated using water retention data. Four classes of pore sizes were determined: macropores (>1,000 micrometers), coarse mesopores (60-1,000 micrometers), fine mesopores (10-60 micrometers), and micropores (<10 micrometers).

Statistical Analysis

A randomized complete block design was selected for the study site. Analysis of variance was conducted with SAS Version 9.3 using the GLM procedure (SAS Institute, 1989). Contrasts between treatments were also determined when ANOVA was run. Contrasts included 'Compacted vs. Non-Compacted' (Log Landing and Logging Road vs. Logged Area-R and Logged Area-H), 'Logged Area-R vs. Logged Area-H', and 'Logging Road vs. Log Landing'. Least significant differences between treatments were estimated at the P<0.05 level from SAS using the appropriate error term

RESULTS AND DISCUSSION

Soil Water Retention

Analysis of variance results for soil water retention as a function of soil water pressure reveal that there were no significant differences (P>0.05) among treatment means for any of the soil water pressures (Table 3.2). The 'compacted vs. non-compacted' contrast was significant (P<0.05) at 0.0 and -0.4 kPa. The 'logging road vs. log landing' contrast was not significant for any pressure. The water contents at 0.0 and -0.4 kPa were significantly greater for the logged area treatments compared to the logging road and log landing treatments. The greater values for the logged area treatments were probably due

to more compaction in the logging road and log landing treatments. Larger pores are influenced by compaction; thus more larger pores were present in less compacted treatments.

There were significant differences (P<0.01) due to soil depth at all soil water pressures (Table 3.2). Generally, there were greater water contents in the surface 10 cm compared to the second 10 cm depth for soil water pressures > -20 kPa. There was an increase in water content from the second to the fourth soil depths. This was due to the higher clay content of subsoil horizons (Table 3.1). There were significant interactions (P<0.05) between treatment and soil depth at all of the soil water pressures (0.0 to -1500.0 kPa). These results were probably due to more rutting and erosion in the logging road and log landing treatments and subsequently shallower depth to clay horizon, resulting in greater soil water contents as compared to the historic and recent logged area treatments.

Significant differences among treatments for specific soil depths are shown in Fig. 3.1. For the first soil depth, significantly higher (P<0.01) soil water content was present for the two logged area treatments compared to the logging road and log landing treatments for the 0.0 and -0.4 kPa pressures (Fig. 3.1A). These results were probably due to vegetation regrowth in the logged areas and less initial compaction with subsequent higher porosity compared to the logging road and log landing treatments and are similar to findings by Deuchars et al. (2011). Water content was greater for the logged area-recent treatment compared to the logging road and log landing treatments for the surface two depths at the 0.0 and -0.4 kPa pressures (Fig. 3.1A-B); however, there were no significant differences between treatments for the third depth for these pressures (Fig. 3.1C). The logging road treatment had greater water content than the logged area treatments for the

fourth depth at this pressure (Fig. 3.1D). The logging road treatment had significantly greater water contents compared to the logged area treatments at all of the pressures at the fourth depth. This was probably due to more soil compaction in the logging road treatment and a subsequently faster and shallower depth to the claypan horizon, which resulted in higher soil water contents at these pressures.

In summary, there were greater soil water contents for the logged area treatments compared to the logging road and log landing treatments for the first depth at higher soil water pressures. However, there was higher water content in the logging road treatment for all of the soil water pressures for the fourth depth. Seobi et al. (2005) and Mudgal et al. (2010) found similar increases in water content at deeper depths for a claypan soil in northeast Missouri.

Table 3.2. Water retention as a function of soil water pressure (0.0 to -1500 kPa) as affected by buffer treatments and soil depth.

	Soil water pressure (kPa)									
	0.0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-33.0	-100	-1500
	--- m^3 m^{-3} --									
Treatment mean										
Logging Road (LR)	0.446	0.451	0.429	0.405	0.388	0.373	0.355	0.275	0.210	0.141
Log Landing (LL)	0.470	0.454	0.430	0.406	0.389	0.373	0.353	0.271	0.211	0.139
Logged Area-R (LAr)	0.520	0.494	0.453	0.409	0.375	0.350	0.321	0.268	0.174	0.105
Logged Area-H (LAh)	0.494	0.474	0.449	0.422	0.397	0.378	0.356	0.281	0.193	0.115
Depth mean										
0-10 cm	0.530	0.506	0.465	0.429	0.396	0.367	0.339	0.263	0.185	0.114
10-20 cm	0.464	0.450	0.421	0.389	0.363	0.342	0.318	0.263	0.157	0.088
20-30 cm	0.470	0.451	0.430	0.402	0.382	0.368	0.349	0.297	0.210	0.135
30-40 cm	0.485	0.467	0.444	0.423	0.407	0.396	0.378	0.300	0.234	0.165
Analysis of variance P > F										
Treatment	0.073	0.173	0.443	0.661	0.508	0.249	0.108	0.901	0.274	0.331
Compacted vs. NC[†]	0.020	0.048	0.123	0.364	0.818	0.393	0.161	0.931	0.089	0.087
LAr vs. LAh	0.209	0.344	0.826	0.417	0.153	0.073	0.040	0.496	0.360	0.651
LR vs. LL	0.846	0.872	0.950	0.938	0.926	0.998	0.912	0.817	0.962	0.941
Depth	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Treatment by Depth	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.014	<0.010	<0.010	<0.010

[†]Compacted included LR and LL treatments; NC referred to non-compacted which included LAr and LAh treatments.
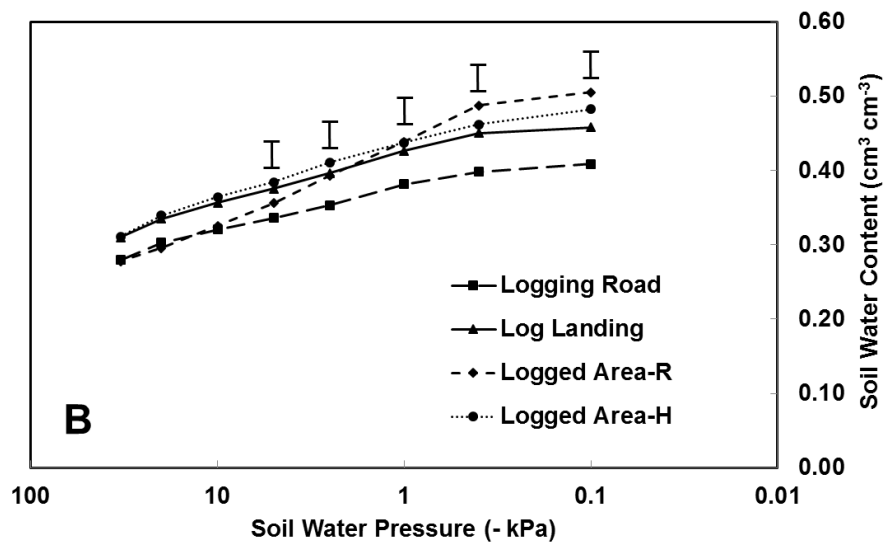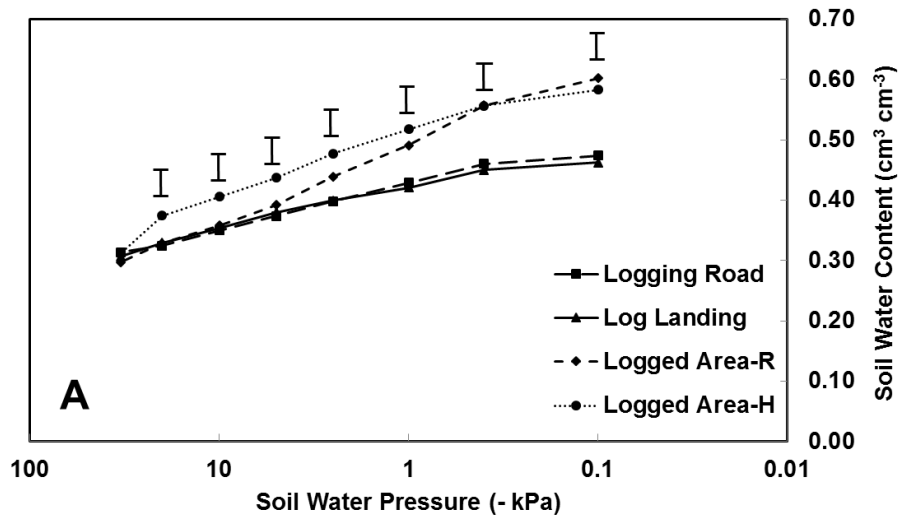
Figure 3.1. Effects of logging treatments on soil water retention at depths of A) 0 to 10 cm, B) 10 to 20 cm, C) 20 to 30 cm, and D) 30 to 40 cm. Bars indicate LSD (0.05) values and are presented at pressures when significant differences occurred among treatments.
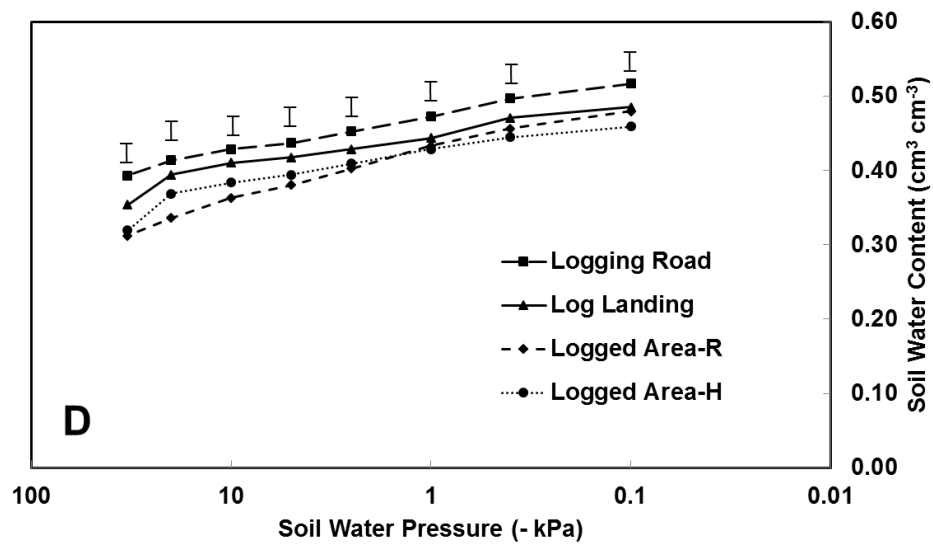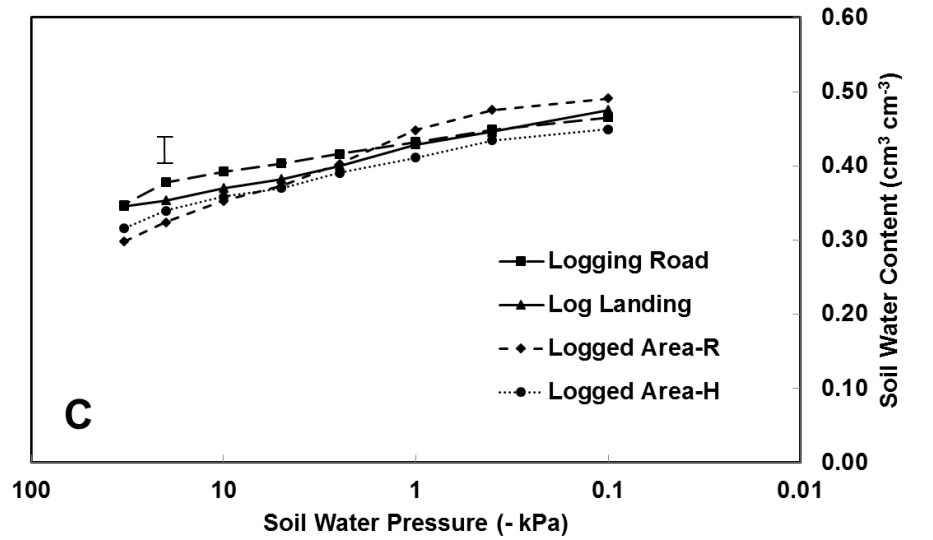
Figure 3.1 (cont.). Effects of logging treatments on soil water retention at depths of A) 0 to 10 cm, B) 10 to 20 cm, C) 20 to 30 cm, and D) 30 to 40 cm. Bars indicate LSD (0.05) values and are presented at pressures when significant differences occurred among treatments.

Pore-Size Distributions

Logging treatments and soil depth had statistically significant (P<0.01) effects on coarse mesoporosity (Table 3.3). Soil depth also had a significant effect on total porosity, fine mesoporosity, and microporosity as well as coarse mesoporosity. The 'compacted vs. non-compacted' contrast indicated that the logged area treatments had more total porosity, macroporosity, and coarse mesoporosity compared to the logging road and log landing treatments. The 'logged area-recent vs. logged area-historic' contrast indicated that the logged area-recent treatment had more coarse mesopores than the logged area-historic treatment. This was probably due to the greater amount of root development from vegetative regrowth, less initial compaction, and subsequent effect on pores in the logged area treatments. There were no significant differences in macroporosity, fine mesoporosity, and microporosity among the treatments.

Soil depth had a significant effect on all pore size classes except macropores (Table 3.3). For all pore size classes, there was a decrease in porosity from the surface depth to the second depth. This was probably due to an increase in bulk density for the second depth. There was an increase in porosity with depth from the third to the fourth depths for fine mesoporosity and microporosity. Microporosity increased as a function of depth from the second to the fourth depth probably due to the increase in clay content with depth for this soil (Table 3.1). There were significant interactions between treatment and depth for all pore size classes except macroporosity (Table 3.3).

Table 3.3. Total pores, macropores, coarse mesopores, fine mesopores, and micropores as affected by logging treatments and soil depth.

Treatment	Total Pores	Macropores (>1000 μm)	Coarse Mesopores (60 - 1000 μm)	Fine Mesopores (10 - 60 μm)	Micropores (<10 μm)
			-------------------- $m^3\ m^{-3}$ --------------------		
			0 – 10 cm depth		
Logging Road (LR)	0.474[b]	0.014[b]	0.086[c]	0.151[ab]	0.223[b]
Log Landing (LL)	0.462[b]	0.012[b]	0.070[c]	0.162[a]	0.218[b]
Logged Area-R (LAr)	0.602[a]	0.045[a]	0.165[a]	0.095[c]	0.297[a]
Logged Area-H (LAh)	0.583[a]	0.026[b]	0.119[b]	0.124[c]	0.313[a]
			10 – 20 cm depth		
Logging Road (LR)	0.409[c]	0.010[a]	0.062[b]	0.116[a]	0.221[a]
Log Landing (LL)	0.458[bc]	0.008[a]	0.075[b]	0.131[a]	0.245[a]
Logged Area-R (LAr)	0.505[a]	0.018[a]	0.132[a]	0.124[a]	0.232[a]
Logged Area-H (LAh)	0.483[ab]	0.020[a]	0.078[b]	0.139[a]	0.246[a]
			20 – 30 cm depth		
Logging Road (LR)	0.465[a]	0.017[a]	0.045[b]	0.087[a]	0.316[a]
Log Landing (LL)	0.475[a]	0.029[a]	0.064[b]	0.068[a]	0.314[a]
Logged Area-R (LAr)	0.491[a]	0.016[a]	0.103[a]	0.102[a]	0.271[a]
Logged Area-H (LAh)	0.449[a]	0.015[a]	0.064[b]	0.083[a]	0.287[a]
			30 – 40 cm depth		
Logging Road (LR)	0.517[a]	0.020[a]	0.060[a]	0.095[a]	0.342[a]
Log Landing (LL)	0.485[a]	0.014[a]	0.053[a]	0.110[a]	0.307[ab]
Logged Area-R (LAr)	0.480[a]	0.024[a]	0.076[a]	0.109[a]	0.272[b]
Logged Area-H (LAh)	0.459[a]	0.014[a]	0.050[a]	0.117[a]	0.278[b]
Treatment mean					
Logging Road (LR)	0.466	0.015	0.063	0.112	0.275
Log Landing (LL)	0.470	0.016	0.065	0.118	0.271
Logged Area-R (LAr)	0.520	0.026	0.119	0.107	0.268
Logged Area-H (LAh)	0.494	0.019	0.078	0.116	0.281
Depth mean					
0-10 cm	0.530	0.024	0.110	0.133	0.263
10-20 cm	0.464	0.014	0.087	0.127	0.236
20-30 cm	0.470	0.019	0.069	0.085	0.297
30-40 cm	0.485	0.018	0.060	0.108	0.300
Analysis of variance P > F					
Treatment	0.073	0.090	<0.010	0.818	0.901
Compacted vs. NC[†]	0.020	0.036	<0.010	0.686	0.931
LAr vs. LAh	0.209	0.128	<0.010	0.491	0.496
LR vs. LL	0.846	0.884	0.855	0.638	0.817
Depth	<0.010	0.180	<0.010	<0.010	<0.010
Treatment by Depth	<0.010	0.084	<0.010	<0.010	<0.010

[†]Compacted included LR and LL treatments; NC referred to non-compacted which included LAr and LAh treatments.
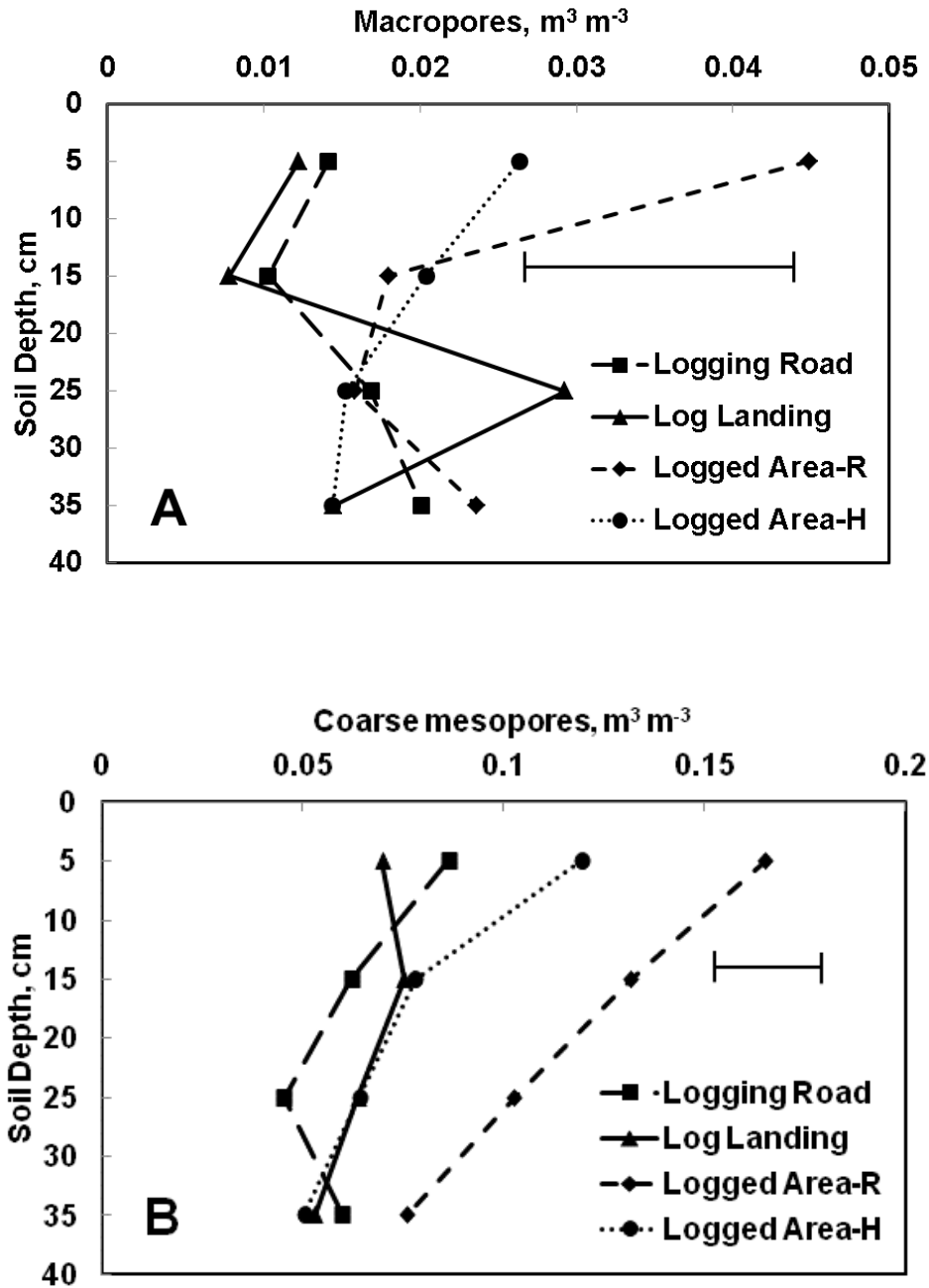
Figure 3.2. Effects of logging treatments and soil depth on pore-size classes of A) macropores (>1000 µm diam.), B) coarse mesopores (60-1000 µm diam.), C) fine mesopores (10 to 60 µm diam.), and D) micropores (<10 µm diam.). Bars indicate LSD (0.05) values and are presented for pore-size classes with significant differences among treatments.
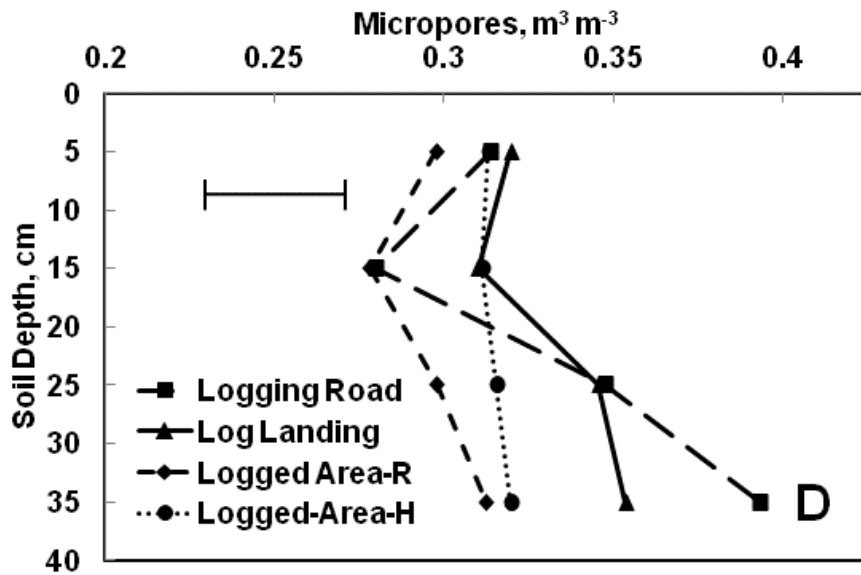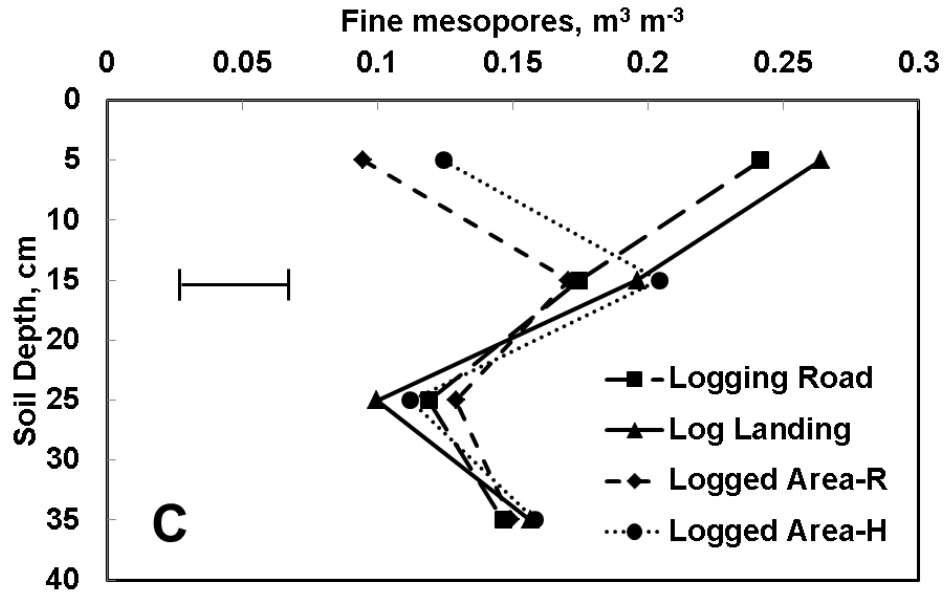
Figure 3.2 (cont.). Effects of logging treatments and soil depth on pore-size classes of A) macropores (>1000 μm diam.), B) coarse mesopores (60-1000 μm diam.), C) fine mesopores (10 to 60 μm diam.), and D) micropores (<10 μm diam.). Bars indicate LSD (0.05) values and are presented for pore-size classes with significant differences among treatments.

Porosity means for logging treatment and soil depth combinations for the study are presented in Table 3.3. There were significant differences among treatments for total porosity for the upper two depths (Table 3.3). Total porosity is decreasing between the first and second depths then increasing for the third and fourth depths (Table 3.3). Total porosity for the logged area treatments was significantly ($P<0.01$) greater than for the logging road and log landing treatments for the first depth. There was greater total porosity in the logged area recent treatments compared to the logging road and log landing treatment for second soil depth. Differences among treatments for coarse mesoporosity also existed (Fig. 3.2B). Coarse mesoporosity was greater in the logged area treatments compared to the logging road and log landing treatments for the first soil depth. The logged area-recent treatment had greater coarse mesoporosity compared to the logging road and log landing treatments for all soil depths except the 30-40 cm depth (Fig. 3.2B). Fine mesoporosity was greater in the logging road and log landing treatments compared to the logged area treatments for the 0-10 cm depth (Fig. 3.2C). Microporosity was greater in the logging road treatment compared to the logged area treatments for the 30-40 cm soil depth (Fig. 3.2D).

Jansson and Johansson (1998) studying silt loam soils found that harvesting traffic caused pores >60 μm to decrease whereas the smaller pores increased following harvest activities. Micropores may be unaffected and soil porosity changes may be confined to the larger pores in the profile during logging activities (Startsev and McNabb, 2001). Additionally, vegetative growth following logging activities may have a significant effect on porosity at the upper soil depths. Significant differences in coarse mesoporosity were

found for the first three depths studied between the logged areas and logging road and log landing treatments in the current study.

Bulk Density

The analysis of variance for soil bulk density is presented in Table 3.4. Significant differences (P<0.05) occurred among logging treatments and soil depths, and for treatment by depth interactions. There were significantly lower bulk density values for the logged area treatments compared to the logging road and log landing treatments as shown in the 'compacted vs. non-compacted' contrast. Bulk density increased in the second and third depths relative to the first depth. The lowest bulk density was found in the first depth as expected due to vegetative regrowth and freeze-thaw cycles.

Bulk density means for logging treatment and soil depth combinations are presented in Table 3.4. Bulk density was significantly lower (P<0.01) for the logged area treatments compared to the logging road and log landing treatments for the first and second depths (Fig. 3.3A). Bulk density values in the logged area- recent treatment were found to be similar to values measured by Mudgal et al. (2010) in a managed prairie claypan soil in central Missouri which has not been subjected to much equipment traffic. There were no significant differences among treatments for the lower two soil depths.

Page-Dumroese et al. (2006) found soil bulk density increases were noticeable to a depth of 30 cm. This agrees with our results where at the deeper depths there were no significant differences across treatments but at the upper depths there were large differences. The top 10 cm had significantly lower bulk density values due to the logged area treatments.

Saturated Hydraulic Conductivity

The analysis of variance of saturated hydraulic conductivity (K_{Sat}) in soil core samples is presented in Table 3.4. There were significant differences in K_{Sat} among treatments, soil depths, and treatment by depth interactions.

K_{Sat} was significantly higher ($P<0.01$) for the logged area treatments compared to the logging road and log landing treatments as indicated by 'compacted vs. non-compacted' contrast (Table 3.4). The K_{Sat} for the logged area treatments was more than thirty-three times higher compared to the logging road and log landing treatments for the first depth. K_{Sat} decreased from the first depth to the second due to an increase in bulk density. A study by Williamson and Neilsen (2000) also showed a pattern of decreasing K_{Sat} with increasing compaction, although there was no overall relationship with bulk density. The lowest K_{Sat} values were measured in the fourth depth due to the higher concentration of smectitic clay in this horizon.

Table 3.4. Means of K_{Sat} and arithmetic means of bulk density as affected by buffer treatments and soil depth.

Treatment	K_{Sat}	Bulk density
	------------------- mm h^{-1} -----------------	------ g cm^{-3} ------
0 – 10 cm depth		
Logging Road (LR)	.274^c	1.388^a
Log Landing (LL)	.919^c	1.426^a
Logged Area-R (LAr)	28.8^a	0.987^b
Logged Area-R (LAh)	10.7^b	1.010^b
10 – 20 cm depth		
Logging Road (LR)	.330^a	1.578^a
Log Landing (LL)	1.00^a	1.430^b
Logged Area-R (LAr)	3.21^a	1.211^c
Logged Area-R (LAh)	2.46^a	1.322^c
20 – 30 cm depth		
Logging Road (LR)	0.098^a	1.416^a
Log Landing (LL)	0.428^a	1.389^a
Logged Area-R (LAr)	3.82^a	1.279^b
Logged Area-R (LAh)	0.861^a	1.426^a
30 – 40 cm depth		
Logging Road (LR)	0.134^a	1.290^a
Log Landing (LL)	0.0642^a	1.368^a
Logged Area-R (LAr)	1.92^a	1.355^a
Logged Area-R (LAh)	0.829^a	1.396^a
Treatment mean		
Logging Road (LR)	0.209	1.418
Log Landing (LL)	0.604	1.403
Logged Area-R (LAr)	9.442	1.208
Logged Area-R (LAh)	3.710	1.289
Depth mean		
0-10 cm	10.174	1.203
10-20 cm	1.752	1.385
20-30 cm	1.301	1.378
30-40 cm	0.737	1.352
Analysis of variance P > F		
Treatment	<0.01	0.011
Compacted vs. NC†	<0.01	<0.01
LAr vs. LAh	0.020	0.170
LR vs. LL	0.851	0.792
Depth	<0.01	<0.01
Treatment by Depth	<0.01	<0.01

†Compacted included LR and LL treatments; NC referred to non-compacted which included LAr and LAh treatments.
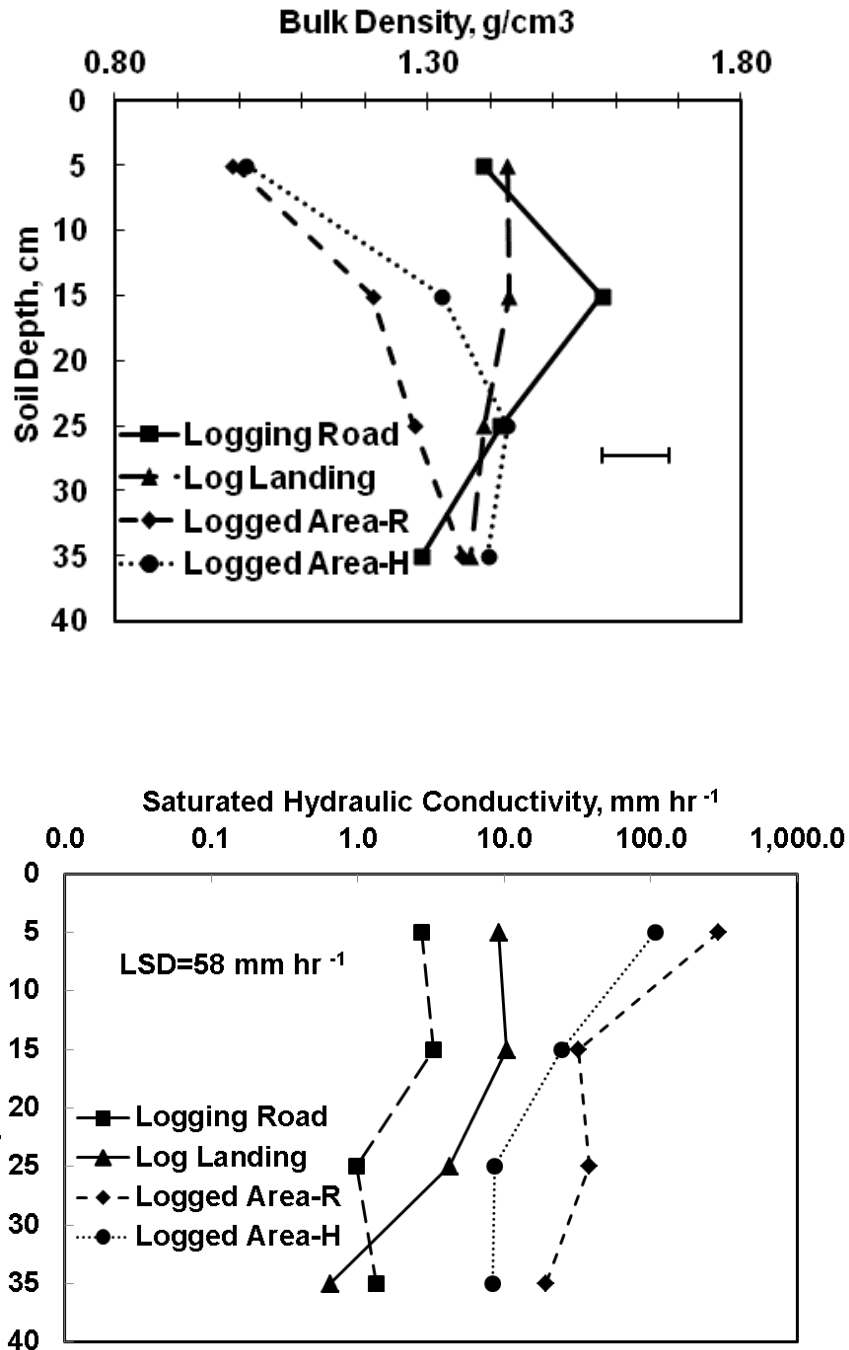
Figure 3.3. Effects of logging treatments and soil depth on A) bulk density and B) saturated

hydraulic conductivity (K_{Sat}). The bar indicates the LSD (0.05) value for bulk density (A)

and the LSD (0.05) value for K_{Sat} is listed on the graph (B) due to the log scale.

SUMMARY

This study was conducted to evaluate the effects of different levels of timber harvest treatments on soil hydraulic properties. Soil water retention, pore-size distribution, bulk density, and saturated hydraulic conductivity were compared for four treatments at four soil depths. The four treatments were logging load, log landing, logged area-recent, and logged area-historic.

The logging road and log landing treatments had significantly lower water content than the logged area treatments at 0 and -0.4 kPa soil water pressure. These differences were attributed to less reduction in porosity for the logged area treatments. The logged area-recent (0.520, 0.145) and the logged area-historic (0.494, 0.097) treatments had significantly greater total porosity, and combined macroporosity and coarse mesoporosity (pores >1000 μm diam. and 60-1000 μm diam.) than the logging road (0.466, 0.078) and log landing (0.470, 0.081) treatments. Logged area treatments (1.25 g cm^{-3}) also had significantly lower bulk density values compared to logging road and log landing areas (1.41 g cm^{-3}). Significant differences among treatments existed for the two first sampling depths but not the lower two depths. K_{Sat} values for the logged area treatments were significantly higher than those of the other two treatments for the first sampling depth. Values for K_{Sat} in the surface soil were 33 times greater for the logged areas compared to the logging road and log landing areas.

Soil hydraulic properties which included soil hydraulic conductivity, water retention and pore size distributions were significantly affected by forest harvesting treatments. From this study, the methods used in logged areas appear to have caused less change in soil physical and hydraulic properties; however, significant changes occurred

with these properties for logging roads and the log landing area. Efforts to reduce compaction should be concentrated in areas of logging roads and log landing areas.

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CHAPTER 4

CONCLUSIONS

A study was conducted to evaluate different levels of selected timber harvest treatments on soil hydraulic properties. Maintaining good values of soil hydraulic properties is critical for forest management to improve tree production and water conservation in forested watersheds. The properties for this study included soil water retention, pore-size distribution, bulk density, and saturated hydraulic conductivity. Logging road, log landing, logged area-recent, and logged area-historic were the four treatments.

The conclusions from this study include the following:

1. The logging road and log landing treatments had significantly lower water content than the logged area treatments at 0 and -0.4 kPa soil water pressure. These differences were attributed to less reduction in porosity for the logged area treatments.

2. The logged area-recent (0.520, 0.145) and the logged area-historic (0.494, 0.097) treatments had significantly greater total porosity, and combined macroporosity and coarse mesoporosity (pores >1000 μm diam. and 60-1000 μm diam.) than the logging road (0.466, 0.078) and log landing (0.470, 0.081) treatments.

3. Logged area treatments (1.25 g cm^{-3}) also had significantly lower bulk density values compared to logging road and log landing areas (1.41 g cm^{-3}). Significant differences among treatments existed for the two first sampling depths but not the lower two depths.

4. Saturated hydraulic conductivity (K_{Sat}) values for the logged area treatments were significantly higher than those of the other two treatments for the first sampling depth. Values for K_{Sat} in the surface soil were 33 times greater for the logged areas compared to the logging road and log landing areas.

Soil hydraulic properties which included soil hydraulic conductivity, water retention and pore size distributions were significantly affected by forest harvesting treatments. From this study, the methods used in logged areas appear to have caused less change in soil physical and hydraulic properties; however, significant changes occurred with these properties for logging roads and the log landing area. Efforts to reduce compaction should be concentrated in areas of logging roads and log landing areas.

APPENDICES

APPENDIX A

Table A. Soil physical and chemical properties of a representative location within one of the Logged Area-recent treatments within the study area (5 to 9 % slope) presented by profile horizon for the observations.

Soil Horizon	Observation	Soil Depth	Clay	Silt	Organic Matter	pH$_w$
		cm	%	%	g kg^{-1}	
A	1	0-10	17.14	80.67	32.3	5.39
	2	0-10	17.21	81.07	25.2	5.02
AE	1	10-20	13.00	85.24	9.2	4.76
	2	10-20	16.73	81.41	9.8	4.90
BE$_1$	1	20-30	24.34	74.06	15.7	4.67
	2	20-30	20.48	78.03	10.0	4.74
BE$_2$	1	30-40	20.45	78.25	6.1	4.55
	2	30-40	27.86	70.84	0.0	4.60

APPENDIX B

Table B.1. Volumetric water content at 0.0, -0.4, -1.0, -2.5, and -5.0 kPa soil water

pressures for Logged Area-Recent (LA-R), Logged Area-Historic (LA-H), Logging

Road (LR), and Log Landing (LL) treatments; (Tmt = Treatment, SS = sub-sample).

Tmt	Depth	Replicate	SS	Soil Water Pressure (kPa)
				0.0	-0.4	-1.0	-2.5	-5.0
	cm			cm^3 cm^{-3}
LA-R	0 – 10	1	1	0.666	0.634	0.557	0.491	0.421
			2	0.671	0.563	0.463	0.408	0.368
		2	1	0.622	0.567	0.486	0.434	0.391
			2	0.614	0.602	0.556	0.495	0.421
		3	1	0.560	0.484	0.423	0.395	0.380
			2	0.542	0.524	0.475	0.440	0.412
		4	1	0.561	0.556	0.495	0.441	0.380
			2	0.582	0.529	0.474	0.408	0.365
LA-R	10– 20	1	1	0.530	0.515	0.474	0.415	0.371
			2	0.524	0.510	0.478	0.421	0.377
		2	1	0.511	0.462	0.425	0.382	0.352
			2	0.536	0.528	0.460	0.411	0.378
		3	1	0.497	0.483	0.417	0.391	0.362
			2	0.537	0.523	0.457	0.422	0.391
		4	1	0.457	0.443	0.408	0.368	0.318
			2	0.451	0.436	0.390	0.338	0.298
LA-R	20-30	1	1	0.484	0.480	0.449	0.410	0.371
			2	0.565	0.557	0.499	0.437	0.388
		2	1	0.535	0.515	0.494	0.422	0.379
			2	0.516	0.506	0.489	0.431	0.388
		3	1	0.478	0.461	0.449	0.420	0.397
			2	0.434	0.434	0.422	0.406	0.402
		4	1	0.447	0.432	0.389	0.348	0.325
			2	0.469	0.417	0.397	0.345	0.331
LA-R	30-40	1	1	0.503	0.452	0.442	0.396	0.370
			2	0.552	0.526	0.483	0.428	0.397
		2	1	0.481	0.467	0.460	0.407	0.371
			2	0.485	0.470	0.444	0.408	0.376
		3	1	0.463	0.427	0.419	0.404	0.379
			2	0.436	0.418	0.409	0.398	0.383
		4	1	0.490	0.490	0.448	0.441	0.438
			2	0.430	0.400	0.359	0.337	0.328

Table B.1 (continued).

Tmt	Depth	Replicate	SS	Soil Water Pressure (kPa)				
				0.0	-0.4	-1.0	-2.5	-5.0
	cm			--------------------cm^3 cm^{-3}----------------------				
LA-H	0 – 10	1	1	0.582	0.566	0.520	0.475	0.425
			2	0.574	0.556	0.514	0.460	0.411
		2	1	0.569	0.501	0.467	0.441	0.412
			2	0.560	0.559	0.533	0.499	0.461
		3	1	0.603	0.583	0.552	0.524	0.488
			2	0.584	0.559	0.530	0.501	0.463
		4	1	0.588	0.559	0.498	0.452	0.412
			2	0.605	0.568	0.524	0.468	0.425
LA-H	10– 20	1	1	0.467	0.452	0.429	0.400	0.377
			2	0.491	0.476	0.436	0.413	0.382
		2	1	0.453	0.449	0.432	0.409	0.377
			2	0.488	0.472	0.447	0.425	0.396
		3	1	0.442	0.426	0.412	0.392	0.375
			2	0.500	0.440	0.405	0.379	0.359
		4	1	0.496	0.476	0.459	0.430	0.408
			2	0.524	0.506	0.481	0.440	0.399
LA-H	20-30	1	1	0.429	0.408	0.385	0.368	0.345
			2	0.424	0.406	0.392	0.374	0.348
		2	1	0.486	0.439	0.396	0.373	0.350
			2	0.478	0.478	0.458	0.435	0.414
		3	1	0.457	0.448	0.425	0.402	0.389
			2	0.439	0.428	0.405	0.390	0.382
		4	1	0.444	0.437	0.414	0.391	0.371
			2	0.438	0.429	0.415	0.392	0.363
LA-H	30-40	1	1	0.440	0.423	0.407	0.375	0.349
			2	0.418	0.418	0.403	0.373	0.354
		2	1	0.513	0.504	0.490	0.477	0.467
			2	0.486	0.467	0.451	0.434	0.411
		3	1	0.433	0.433	0.424	0.410	0.401
			2	0.453	0.441	0.418	0.416	0.415
		4	1	0.479	0.436	0.419	0.394	0.378
			2	0.453	0.438	0.420	0.397	0.381

Table B.1 (continued).

Tmt	Depth	Replicate	SS	Soil Water Pressure (kPa)				
				0.0	-0.4	-1.0	-2.5	-5.0
cm				$cm^3 \, cm^{-3}$				
LR	0 – 10	1	1	0.429	0.428	0.408	0.385	0.365
			2	0.458	0.432	0.397	0.371	0.345
		2	1	0.482	0.482	0.439	0.413	0.393
			2	0.526	0.502	0.471	0.446	0.425
		3	1	0.463	0.451	0.431	0.402	0.384
			2	0.509	0.485	0.467	0.427	0.400
		4	1	0.470	0.462	0.406	0.354	0.321
			2	0.456	0.438	0.412	0.386	0.357
LR	10– 20	1	1	0.394	0.379	0.370	0.344	0.331
			2	0.353	0.344	0.329	0.305	0.289
		2	1	0.413	0.404	0.392	0.369	0.355
			2	0.408	0.408	0.385	0.365	0.354
		3	1	0.456	0.449	0.429	0.394	0.377
			2	0.479	0.479	0.462	0.435	0.413
		4	1	0.374	0.359	0.337	0.303	0.282
			2	0.392	0.365	0.349	0.312	0.289
LR	20-30	1	1	0.442	0.408	0.387	0.367	0.344
			2	0.448	0.419	0.401	0.380	0.362
		2	1	0.475	0.471	0.456	0.435	0.417
			2	0.453	0.452	0.441	0.423	0.412
		3	1	0.487	0.479	0.456	0.443	0.435
			2	0.504	0.497	0.483	0.469	0.459
		4	1	0.473	0.441	0.423	0.409	0.403
			2	0.441	0.421	0.409	0.401	0.395
LR	30-40	1	1	0.548	0.512	0.489	0.463	0.450
			2	0.546	0.533	0.510	0.476	0.464
		2	1	0.510	0.470	0.450	0.421	0.395
			2	0.513	0.486	0.471	0.445	0.402
		3	1	0.503	0.492	0.463	0.451	0.437
			2	0.516	0.516	0.496	0.487	0.481
		4	1	0.484	0.451	0.424	0.414	0.411
			2	0.516	0.516	0.476	0.464	0.455

Table B.1 (continued).

Tmt	Depth	Replicate	SS	Soil Water Pressure (kPa)
				0.0	-0.4	-1.0	-2.5	-5.0
	cm			----------cm^3 cm^{-3}----------
LL	0 – 10	1	1	0.405	0.402	0.373	0.365	0.350
			2	0.469	0.418	0.385	0.365	0.344
		2	1	0.432	0.418	0.398	0.378	0.375
			2	0.439	0.437	0.413	0.391	0.372
		3	1	0.450	0.450	0.429	0.406	0.383
			2	0.466	0.466	0.434	0.417	0.394
		4	1	0.518	0.505	0.479	0.448	0.419
			2	0.517	0.501	0.455	0.427	0.401
LL	10– 20	1	1	0.414	0.409	0.387	0.360	0.341
			2	0.426	0.426	0.405	0.387	0.372
		2	1	0.485	0.485	0.462	0.436	0.420
			2	0.469	0.457	0.448	0.417	0.394
		3	1	0.433	0.427	0.418	0.395	0.378
			2	0.519	0.496	0.461	0.414	0.391
		4	1	0.430	0.424	0.398	0.363	0.334
			2	0.491	0.482	0.433	0.401	0.374
LL	20-30	1	1	0.427	0.411	0.403	0.377	0.351
			2	0.417	0.383	0.368	0.348	0.329
		2	1	0.474	0.454	0.439	0.411	0.399
			2	0.494	0.481	0.467	0.435	0.409
		3	1	0.509	0.462	0.437	0.399	0.385
			2	0.498	0.409	0.394	0.354	0.340
		4	1	0.501	0.490	0.458	0.438	0.422
			2	0.481	0.478	0.464	0.438	0.423
LL	30-40	1	1	0.469	0.437	0.412	0.385	0.365
			2	0.459	0.438	0.412	0.373	0.350
		2	1	0.499	0.487	0.466	0.456	0.447
			2	0.485	0.458	0.439	0.432	0.423
		3	1	0.477	0.472	0.441	0.434	0.428
			2	0.491	0.480	0.439	0.431	0.416
		4	1	0.520	0.520	0.487	0.477	0.471
			2	0.481	0.475	0.452	0.443	0.442

Table B.2. Volumetric water content at -10, -20, -33, -100, and -1500 kPa soil water pressures for Logged Area-Recent (LA-R), Logged Area-Historic (LA-H), Logging Road (LR), and Log Landing (LL) treatments; (SS = sub-sample).

| Tmt | Depth | Replicate | SS | Soil Water Pressure (kPa) | | | | |
				-10	-20	-33	-100	-1500
	Cm			---------------------cm^3 cm^{-3}----------------------				
LA-R	0 – 10	1	1	0.381	0.352	0.339	0.273	0.189
			2	0.339	0.310	0.307	0.194	0.127
		2	1	0.362	0.336	0.336	0.248	0.146
			2	0.377	0.340	0.310	0.204	0.113
		3	1	0.357	0.331	0.270	0.160	0.070
			2	0.389	0.364	0.294	0.186	0.080
		4	1	0.333	0.297	0.284	0.202	0.150
			2	0.328	0.299	0.241	0.169	0.120
LA-R	10– 20	1	1	0.343	0.317	0.254	0.141	0.120
			2	0.344	0.314	0.281	0.170	0.137
		2	1	0.330	0.308	0.273	0.132	0.109
			2	0.348	0.322	0.261	0.151	0.107
		3	1	0.336	0.303	0.249	0.123	0.048
			2	0.362	0.326	0.249	0.127	0.045
		4	1	0.270	0.240	0.133	0.094	0.053
			2	0.271	0.235	0.153	0.110	0.055
LA-R	20-30	1	1	0.348	0.328	0.305	0.186	0.115
			2	0.370	0.325	0.316	0.185	0.110
		2	1	0.353	0.321	0.298	0.172	0.074
			2	0.359	0.327	0.305	0.161	0.068
		3	1	0.371	0.331	0.285	0.164	0.067
			2	0.385	0.359	0.278	0.149	0.078
		4	1	0.314	0.294	0.163	0.130	0.085
			2	0.322	0.308	0.216	0.164	0.116
LA-R	30-40	1	1	0.356	0.344	0.301	0.244	0.175
			2	0.376	0.353	0.304	0.241	0.172
		2	1	0.346	0.320	0.268	0.181	0.100
			2	0.355	0.332	0.261	0.176	0.105
		3	1	0.353	0.325	0.252	0.150	0.066
			2	0.363	0.282	0.275	0.142	0.066
		4	1	0.435	0.422	0.266	0.226	0.154
			2	0.323	0.308	0.246	0.207	0.140

Table B.2 (continued).

Tmt	Depth	Replicate	SS	-10	-20	-33	-100	-1500
						Soil Water Pressure (kPa)		
	cm					$cm^3\ cm^{-3}$		
LA-H	0 – 10	1	1	0.391	0.356	0.282	0.193	0.115
			2	0.376	0.339	0.297	0.188	0.136
		2	1	0.386	0.360	0.324	0.240	0.144
			2	0.433	0.400	0.298	0.241	0.161
		3	1	0.460	0.425	0.326	0.251	0.125
			2	0.432	0.400	0.316	0.294	0.134
		4	1	0.382	0.346	0.323	0.181	0.123
			2	0.387	0.370	0.337	0.234	0.128
LA-H	10– 20	1	1	0.357	0.334	0.197	0.138	0.054
			2	0.354	0.318	0.261	0.126	0.057
		2	1	0.357	0.334	0.276	0.171	0.096
			2	0.375	0.352	0.280	0.171	0.093
		3	1	0.366	0.352	0.266	0.170	0.096
			2	0.347	0.330	0.253	0.164	0.087
		4	1	0.390	0.364	0.221	0.158	0.059
			2	0.368	0.332	0.212	0.149	0.061
LA-H	20-30	1	1	0.328	0.305	0.286	0.142	0.057
			2	0.331	0.308	0.285	0.143	0.061
		2	1	0.341	0.327	0.319	0.215	0.132
			2	0.401	0.384	0.282	0.208	0.151
		3	1	0.382	0.368	0.259	0.205	0.137
			2	0.376	0.362	0.288	0.203	0.129
		4	1	0.360	0.339	0.274	0.169	0.084
			2	0.349	0.324	0.301	0.153	0.066
LA-H	30-40	1	1	0.329	0.309	0.266	0.176	0.108
			2	0.337	0.320	0.255	0.180	0.118
		2	1	0.461	0.446	0.294	0.206	0.164
			2	0.402	0.384	0.305	0.252	0.188
		3	1	0.392	0.382	0.280	0.220	0.163
			2	0.413	0.402	0.287	0.212	0.165
		4	1	0.367	0.352	0.271	0.212	0.147
			2	0.369	0.355	0.266	0.209	0.152

Table B.2 (continued).

Tmt	Depth	Replicate	SS	Soil Water Pressure (kPa)				
				-10	-20	-33	-100	-1500
	cm			----------------------cm^3 cm^{-3}----------------------				
LR	0 – 10	1	1	0.344	0.321	0.189	0.119	0.063
			2	0.322	0.294	0.170	0.130	0.063
		2	1	0.374	0.355	0.231	0.174	0.069
			2	0.402	0.379	0.308	0.205	0.093
		3	1	0.362	0.339	0.226	0.169	0.147
			2	0.372	0.344	0.273	0.178	0.144
		4	1	0.294	0.262	0.196	0.096	0.080
			2	0.328	0.300	0.192	0.097	0.095
LR	10– 20	1	1	0.316	0.298	0.219	0.143	0.085
			2	0.273	0.257	0.188	0.146	0.078
		2	1	0.340	0.326	0.245	0.158	0.068
			2	0.342	0.325	0.248	0.162	0.070
		3	1	0.363	0.343	0.248	0.207	0.122
			2	0.393	0.370	0.253	0.200	0.131
		4	1	0.262	0.244	0.176	0.136	0.063
			2	0.277	0.258	0.189	0.153	0.068
LR	20-30	1	1	0.328	0.312	0.255	0.163	0.126
			2	0.344	0.329	0.255	0.210	0.142
		2	1	0.400	0.380	0.309	0.218	0.137
			2	0.397	0.377	0.291	0.207	0.138
		3	1	0.428	0.416	0.352	0.291	0.226
			2	0.453	0.440	0.383	0.337	0.212
		4	1	0.398	0.389	0.372	0.321	0.250
			2	0.389	0.380	0.310	0.241	0.174
LR	30-40	1	1	0.443	0.429	0.355	0.292	0.217
			2	0.456	0.444	0.352	0.308	0.237
		2	1	0.378	0.361	0.286	0.235	0.145
			2	0.392	0.379	0.296	0.242	0.169
		3	1	0.431	0.417	0.337	0.286	0.203
			2	0.474	0.464	0.343	0.278	0.225
		4	1	0.408	0.398	0.364	0.296	0.216
			2	0.447	0.421	0.402	0.311	0.258

Table B.2 (continued).

Tmt	Depth	Replicate	SS	-10	-20	-33	-100	-1500
						Soil Water Pressure (kPa)		
	cm					$cm^3\ cm^{-3}$		
LL	0 – 10	1	1	0.330	0.300	0.188	0.134	0.070
			2	0.317	0.294	0.197	0.142	0.076
		2	1	0.340	0.320	0.216	0.159	0.085
			2	0.349	0.326	0.237	0.178	0.099
		3	1	0.360	0.336	0.217	0.175	0.099
			2	0.374	0.351	0.243	0.186	0.115
		4	1	0.387	0.357	0.225	0.172	0.149
			2	0.375	0.352	0.222	0.162	0.136
LL	10– 20	1	1	0.318	0.299	0.243	0.167	0.102
			2	0.367	0.333	0.233	0.154	0.100
		2	1	0.405	0.394	0.260	0.193	0.117
			2	0.371	0.348	0.263	0.202	0.134
		3	1	0.356	0.335	0.261	0.162	0.082
			2	0.369	0.352	0.256	0.210	0.129
		4	1	0.314	0.288	0.194	0.147	0.084
			2	0.353	0.329	0.247	0.182	0.096
LL	20-30	1	1	0.331	0.316	0.272	0.157	0.106
			2	0.314	0.298	0.287	0.157	0.102
		2	1	0.390	0.376	0.314	0.244	0.179
			2	0.408	0.379	0.330	0.260	0.192
		3	1	0.373	0.359	0.316	0.263	0.186
			2	0.319	0.305	0.300	0.265	0.186
		4	1	0.412	0.398	0.340	0.352	0.222
			2	0.412	0.397	0.353	0.296	0.197
LL	30-40	1	1	0.350	0.332	0.255	0.182	0.129
			2	0.334	0.315	0.240	0.174	0.125
		2	1	0.439	0.407	0.317	0.255	0.175
			2	0.418	0.402	0.312	0.263	0.184
		3	1	0.423	0.413	0.304	0.261	0.178
			2	0.411	0.399	0.334	0.280	0.197
		4	1	0.468	0.455	0.372	0.327	0.224
			2	0.440	0.433	0.327	0.278	0.208

Table C.1. Saturated hydraulic conductivity (K_{Sat}) and bulk density for Logged Area-Recent, Logged Area-Historic, Logging Road, and Log Landing treatments at four soil depths.

Treatment	Depth	Replicate	Sub Sample	K_{Sat}	Bulk Density
	cm			cm h^{-1}	g cm^{-3}
Logged Area-R	0 – 10	1	1	47.46	0.86
			2	41.40	0.87
		2	1	43.65	0.92
			2	19.21	0.92
		3	1	13.93	1.12
			2	18.62	1.07
		4	1	15.65	1.03
			2	30.60	1.11
Logged Area-R	10 – 20	1	1	1.19	1.19
			2	2.84	1.10
		2	1	5.23	1.16
			2	8.40	1.08
		3	1	0.35	1.17
			2	0.63	1.24
		4	1	1.18	1.34
			2	5.88	1.41
Logged Area-R	20 – 30	1	1	5.60	1.28
			2	18.24	1.04
		2	1	2.24	1.17
			2	1.59	1.18
		3	1	0.35	1.29
			2	0.04	1.46
		4	1	2.30	1.40
			2	0.20	1.41
Logged Area-R	30 – 40	1	1	2.47	1.32
			2	8.14	1.19
		2	1	2.89	1.24
			2	1.70	1.28
		3	1	0.11	1.40
			2	0.075	1.50
		4	1	0.001	1.40
			2	0.008	1.51

Table C.1 (continued).

Treatment	Depth	Replicate	Sub Sample	K_{Sat}	Bulk Density
	cm			cm h^{-1}	g cm^{-3}
Logged Area-H	0 – 10	1	1	9.20	1.05
			2	5.44	0.98
		2	1	49.74	1.06
			2	0.33	1.09
		3	1	2.28	0.99
			2	1.14	1.01
		4	1	5.04	1.03
			2	12.35	0.87
Logged Area-H	10 – 20	1	1	0.12	1.36
			2	0.33	1.28
		2	1	0.107	1.39
			2	14.18	1.29
		3	1	0.36	1.48
			2	3.64	1.23
		4	1	0.27	1.33
			2	0.70	1.22
Logged Area-H	20 – 30	1	1	2.20	1.51
			2	0.60	1.44
		2	1	0.136	1.29
			2	0.24	1.32
		3	1	0.187	1.44
			2	2.63	1.49
		4	1	0.23	1.46
			2	0.75	1.46
Logged Area-H	30 – 40	1	1	0.89	1.49
			2	0.211	1.48
		2	1	0.014	1.29
			2	0.017	1.29
		3	1	0.056	1.41
			2	0.006	1.45
		4	1	5.29	1.38
			2	0.143	1.38

Table C.1 (continued).

Treatment	Depth	Replicate	Sub Sample	K_{Sat}	Bulk Density
	cm			cm h^{-1}	g cm^{-3}
Logging Road	0 – 10	1	1	0.051	1.49
			2	0.25	1.43
		2	1	0.15	1.39
			2	0.78	1.26
		3	1	0.14	1.42
			2	0.28	1.30
		4	1	0.35	1.37
			2	0.18	1.44
Logging Road	10 – 20	1	1	0.24	1.61
			2	0.21	1.71
		2	1	0.11	1.56
			2	0.035	1.60
		3	1	0.64	1.44
			2	0.50	1.43
		4	1	0.27	1.66
			2	0.64	1.61
Logging Road	20 – 30	1	1	0.40	1.48
			2	0.15	1.46
		2	1	0.17	1.39
			2	0.140	1.45
		3	1	0.012	1.36
			2	0.002	1.31
		4	1	0.003	1.40
			2	0.004	1.48
Logging Road	30 – 40	1	1	0.37	1.20
			2	0.009	1.20
		2	1	0.63	1.30
			2	0.005	1.29
		3	1	0.042	1.32
			2	0.006	1.32
		4	1	0.004	1.37
			2	0.002	1.32

Table C.1 (continued).

Treatment	Depth	Replicate	Sub Sample	K_{Sat}	Bulk Density
	cm			cm h^{-1}	g cm^{-3}
Log Landing	0 – 10	1	1	0.91	1.58
			2	1.83	1.41
		2	1	0.022	1.50
			2	0.231	1.49
		3	1	0.41	1.46
			2	0.28	1.41
		4	1	1.72	1.28
			2	1.96	1.28
Log Landing	10 – 20	1	1	0.18	1.55
			2	0.104	1.54
		2	1	0.01	1.36
			2	0.53	1.41
		3	1	0.13	1.50
			2	29.48	1.22
		4	1	1.13	1.51
			2	14.31	1.35
Log Landing	20 – 30	1	1	0.79	1.52
			2	0.17	1.54
		2	1	0.045	1.39
			2	0.003	1.34
		3	1	15.93	1.30
			2	0.17	1.33
		4	1	0.41	1.32
			2	0.17	1.37
Log Landing	30 – 40	1	1	0.12	1.41
			2	0.33	1.43
		2	1	0.001	1.33
			2	0.002	1.37
		3	1	0.027	1.39
			2	0.025	1.35
		4	1	0.003	1.28
			2	0.003	1.38

VITA

Langston A. Simmons was raised in Fairfield, a western suburb of Birmingham, Alabama. As a child growing up he had a vivid imagination and knew there was a great world outside of his neighborhood and that someday he would be involved in and play a key role within it.

Growing up in the western suburbs of Birmingham, Alabama, his generation of youth was, and youth there today still are, introduced to crime and other detrimental activities frequently and at an early age. The Boy Scouts of America helped Langston to connect with nature and at the same time develop a sound character. His father, as the Scoutmaster, kept him, his two brothers, and many other boys involved and saw to it that many young men reached the highest rank of Eagle Scout. Langston was awarded a United States Department of Agriculture (USDA) / 1890 Land Grant Universities Scholarship to Tennessee State University (TSU) in 2001.

Following graduation from TSU in 2005, he moved to Fulton, MO to work as a Biological Scientist with the USDA Forest Service. Upon moving to Mid-Missouri, Langston soon became comfortable in the community, joining and participating in several local organizations. He served as a mentor to middle school boys in a program called TEAM (Together Everyone Achieves More) Challenge. He was as a trustee at a local church and an active member of the Fulton branch of the National Association for the

Advancement of Colored People. Additionally, he was the Chapter Advisor for the

Lincoln University undergraduate chapter of Iota Phi Theta Fraternity, Inc., of which he

is a member.   Meanwhile, back in his hometown of Birmingham, AL the times continued

to change from his childhood there. Over half of the males who went to high school with

him were being killed or sent to jail. When his best friend, Damien Sherrod, from middle

school was killed in January of 2009 it hit Langston hard. He decided he needed to make

a change to be more of a positive influence on society. It is his belief that everything in

life is interconnected in a web. A future with poor soils will cause food and timber

shortages which in turn will cause more poverty and more friends being murdered. His

friend's death, along with encouragements from his undergraduate professors and his

mother among others, persuaded him to further his knowledge in his discipline of soils.