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Soil compaction caused by timber harvesting in central Appalachian hardwood forests

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**SOIL COMPACTION CAUSED BY TIMBER HARVESTING IN
CENTRAL APPALACHIAN HARDWOOD FORESTS**

By

Mark W. Jones

**Thesis submitted to the Davis College of Agriculture, Forestry, and
Consumer Sciences
At West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Forestry**

Approved by

**Dr. Jingxin Wang, Committee Chairperson
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Dr. Pamela Edwards**

Wood Industries

Morgantown, West Virginia

2003

Abstract

SOIL COMPACTION CAUSED BY TIMBER HARVESTING IN CENTRAL APPALACHIAN HARDWOOD FORESTS

by Mark W. Jones

Two commonly used harvesting systems in central Appalachia were examined to determine the amount of soil compaction associated with each harvest type. A manual system of chainsaw and cable skidder, along with a mechanized system consisting of feller-buncher and grapple skidder were monitored in two central Appalachian hardwood forest sites. Examinations of soil bulk density (lbs/ft³) were made pre-harvest and post-harvest for each harvest unit. Observations were conducted along the skid roads in conjunction to distance from the landing. Sample points were also taken systematically through each harvest site. The physical condition was recorded using a nuclear density probe. Data were analyzed statistically to determine the effect of operational variables on soil impacts. Results indicate that timber harvesting does affect the soil compaction levels in the woods, as well as along skid roads. Soil compaction also varies by different soil moisture level and soil series.

Keywords: Soil compaction, logging, forest operations, Appalachian hardwood forest.

DEDICATION

I dedicate this project to my parents. I thank them for their moral and financial support, and their unconditional love. I just hope they are proud of my long and unorthodox journey to achieve my Master's degree.

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TABLE OF CONTENTS

Abstract	ii
Dedication.....	iii
Acknowledgements	iv
Table of contents	v
List of Figures.....	vi
List of Tables	vii
List of Symbols / Nomenclature	viii
INTRODUCTION	1
CHAPTER 1 LITERATURE REVIEW	4
1.1 Soil Characteristics	5
1.2 Soil Moisture	5
1.3 Residual Tree and Seedling Growth.....	7
1.4 Harvesting Methods and Systems	9
1.5 Objectives.....	10
CHAPTER 2 METHODS AND DATA	12
2.1 Sites.....	12
2.1.1 Manual Site.....	14
2.1.2 Mechanized Site	19
2.2 Methods.....	23
CHAPTER 3 DATA ANALYSIS AND RESULTS	32
3.1 Data Analysis.....	32
3.2 Results.....	35
3.2.1 Soil Bulk Density - Points in the Woods	35
3.2.2 Soil Bulk Density - Points on the Roads.....	37
3.2.3 First Ten Loaded Machine Passes	41
CHAPTER 4 DISSCUSSION AND CONCLUSION	46
REFERENCES.....	47

LIST OF FIGURES

Figure 2.1 Location Map for Harvest Sites	13
Figure 2.2 Manual Harvest Site	17
Figure 2.3 Soil Map for Manual Harvest Site	18
Figure 2.4 Mechanized Harvest Site	21
Figure 2.5 Soil Map for Mechanized Harvest Site	22
Figure 2.6 Manual Harvest Site Point Location	25
Figure 2.7 Mechanized Harvest Site Point Location.....	26
Figure 2.8 Example of sample points in the woods.....	27
Figure 2.9 Cross section of skid road layout	28
Figure 2.10 Manual Harvest Site Road Point Layout	29
Figure 2.11 Mechanized Harvest Site Road Point Layout	30
Figure 3.1 First ten loaded machine passes – Manual	45
Figure 3.2 First ten loaded machine passes – Mechanized.....	45

LIST OF TABLES

Table 2.1 Site conditions.....	14
Table 2.2 Cruise data for manual harvest site.....	15
Table 2.3 Manual harvest configuration	16
Table 2.4 Cruise data for mechanized harvest site.....	19
Table 2.5 Mechanized harvest configuration	20
Table 3.1 Statistics of observed variables for points in the woods	36
Table 3.2 Means and significant levels of bulk density for point in the woods	36
Table 3.3 Statistics for points in the roads	38
Table 3.4 Means and significant levels of bulk density on roads	38
Table 3.5 Mean and significant of ten loaded machine passes	40

LIST OF SYMBOLS / NOMENCLATURE

1.	ac.....	Acre
2.	AH.....	After Harvest
3.	BF.....	Board Feet
4.	bd.ft./ac.....	Board feet per acre
5.	BH.....	Before Harvest
6.	BMP.....	Best Management Practices
7.	BtE.....	Buchanan and Ernest stony soils
8.	DD.....	Dry Density
9.	DEP.....	Division of Environmental Protection
10.	GdE.....	Gilpin-Dekalb stony complex
11.	GkE.....	Gilpin-Dekalb stony complex moist
12.	GLM.....	General Linear Model
13.	GPS.....	Global Positioning System
14.	LyC.....	Lily loam
15.	psi	Pounds per square inch
16.	SAS.....	Statistical Analysis System
17.	WD.....	Wet Density

INTRODUCTION

The forest floor is a continuing source of available plant nutrients, which contributes to the water-holding capacity of the soil, prevented erosion, and contained a bank of buried seeds vital for regeneration (Bormann and Likens 1979). Logging operations cause surface soil disturbance ranging from removal of the protective organic litter to complete removal of top-soil (Dyreness 1965). Any access or entry into a stand has the potential to disturb the forest floor and soil (Ogden and Morris 1996).

The use of forest roads and equipment has been increased due to selective harvesting of timber. Harvesting machines used for thinning sometimes cause residual stem and root damage with additional soil compaction, rutting, and nutrient relocation on the site (McNeel and Ballard 1992). Recent advances in harvesting techniques and product utilization have resulted in increasing occurrence of removing the entire aboveground biomass of trees. These methods are efficient, but require the use of heavy equipment, which may reduce site productivity by compacting the soil and/or disturbing the litter layer (Steinbrenner and Gassel 1955, Lull 1959, Froehlich 1979, Donnelly and Shane 1986). As extraction equipment has evolved from crawler-type tractors to wheel skidders and as felling machines have progressed from chain saws to mechanical harvesters, the percentage of disturbance has increased (Martin 1988).

Regardless of the type of timber harvest or silvicultural treatment, logging always changes the site. These changes may include alterations of the litter layers, hydrology, erosion, growth rates, soils, and visual appearance.

Factors that influence soil disturbance and compaction include the amount and distribution of surface litter and slash, soil texture and structure, soil moisture, the weight and function of a machine, wheel size and slip, equipment speed, type of load, operator skill, topography, and weather (Burger 1983, Sirois et al. 1985). Trafficking, or the number of loaded machine is another major factor that can influence the soil compaction, over an area. Vehicular traffic associated with forest harvesting operations has the potential to compact and/or puddle forest soils (Hatchell et al. 1970, Aust et al. 1993).

The physical properties of the soil, texture and moisture have an effect on the level of soil disturbance. Soil compaction varies with soil texture and effects the operability of harvesting equipment. Erosion or sedimentation during and after logging also reflected in the type of harvest employed, because equipment greatly affects the amount of soil disturbance to the forest floor. Soil compaction affects the growth of seedlings and residual trees (Foil and Ralston, 1967), reduces the amount of air-filled pore space, and increases the proportion of micropores. The latter two factors decrease oxygen diffusion rates in soil, and increases soil moisture tension (Reisinger et. al. 1988).

During the past decade, forest harvesting methods available for the central Appalachian hardwood forests have evolved. Increased rates in worker's compensation, along with the demand for more production, have led to more

mechanized harvesting systems throughout the central Appalachians. Soil changes caused from a mechanized system are unknown at this time due to the variability of soil types, site conditions, harvest types, harvest systems, and season of the year. While mechanized trafficking is believed to cause soil compaction or other effects to the soil the variability throughout the central Appalachian hardwood forest also makes the degree of change uncertain. Evaluations of the soil impacts among harvesting systems, silvicultural treatments, soil types, and soil conditions seem necessary in the region.

CHAPTER 1 LITERATURE REVIEW

1.1 Soil Characteristics

Soil type can affect how soil is disturbed or compacted during a harvesting operation. Gent et al. (1984) reported a 17% increase in surface soil bulk density (from 1.16 to 1.36 Mg/m³) after whole-tree harvesting and a 36% increase (from 1.12 to 1.52 Mg/m³) on skid trails in a sandy clay loam with a moisture content of 27% at the time of harvesting. However, no increase in bulk density was observed on a sandy clay loam Piedmont soil at 15-cm depth following trafficking by a rubber-tired skidder or crawler (Burger et al. 1985).

Pote (2000) demonstrated that sandy soils in the inland zone show much less variability in the number of annual working days at the different probability levels. At least 233 predicted workdays were expected half the time on sandy soils, and at least 216 predicted workdays were expected in 9 out of 10 years. On loamy soils, the equivalent values for the inland zone were 183 days and 141 days, respectively. Pote (2000) also found that the clay soils in the coastal zone showed more variability in the number of workdays. In at least 50% of the years, 122 work days were expected, while in 9 out of 10 years (90% level), at least 7 workdays were anticipated. On sandy soils in that zone, the expected workdays were 252 and 225, respectively. Loamy soils had equivalent values of 172 and 108 days.

1.2 Soil Moisture

Soil moisture is a major factor in controlling soil disturbance or compaction during a harvesting operation. Weaver and Jamison (1950) reported that compaction increased with moisture content throughout the moisture range of 6-12 percent in Davidson loam soil. Soil moisture at the time of trafficking also had a major influence on reduction and redistribution of pore space as soils were compacted (Seixas and McDonald 1997). Although a wide variety of site and machinery factors influence the soil disturbances, the likelihood of soil disturbance was enhanced on moist to saturated soils (Moehring and Rawls 1970, Greacen and Sands 1980, and Aust et al. 1995). Soils that are too wet to support heavy equipment would be compressed and rutted during harvesting, which could lead to increased bulk density, loss of soil macroporosity, increased erosion, decreased availability of water, and potential loss of productivity (Rachael and Karr 1989). Rutledge and McHardy (1968) reported that the soil was not tractable when soil moisture was near or above field capacity. Their study indicated a record high value of soil bulk density in an area that was harvested under conditions of relatively high soil moisture, as necessitated by the time constraints of the salvage effort. Conditions such as high moisture content above satisfactory levels would result in significant damage to the soil structure. Volumetric water contents increased as the level of disturbance increased (Aust et al. 1993). Rutting of the soils is a visual and physical impact and is common while harvesting timber, especially in wet or moist conditions.

The impacts of harvesting under wet site conditions on soil physical properties and residual tree growth were examined in natural loblolly pine stands (Reisinger et al. 1994). They found that shallow rutting of corridors when soil conditions are wet is not necessarily detrimental to overall site productivity in spite of the visual impressions immediately after harvesting. Thinning operations should be planned when soil conditions are dry so as to minimize rutting, but if thinning must be done under wet conditions, the operations should be stopped when machine traffic creates deep ruts (Reisinger et al. 1994). The severity of soil disturbance from mechanized timber harvesting seems to be strongly related to soil wetness and drainage class. There is some evidence that soils in poorer drainage classes might be more severely disturbed during spring, summer, or autumn harvesting when soil is not frozen (Case and Donnelly 1979, Hatchell et al. 1970). The amount of undisturbed and severely disturbed soil on the harvested site differed among drainage classes (Turcotte et al. 1991). There was less undisturbed soil on poorly drained than on moderately well drained soil; somewhat poorly drained soils had intermediate amounts of soil disturbance. There were more mineral ruts with severe disturbance on somewhat poorly and poorly drained soil than on moderately well drained soil. Soil moisture differences among drainage classes during harvesting operations apparently affect the extent of soil disturbance on drier soils. However, during wet conditions some wheel-rutting could be expected on all soils (Turcotte et al. 1991).

Dickerson (1976) reported that bulk densities of wheel-rutted Coastal Plain soils were increased about 20% in northern Mississippi, ranging in texture from loamy sand to silty clay loam. Aeration porosity (the air-filled pore space at a tension of 60 cm of water) was reduced by 68% after seven passes with a rubber-tired machine skidding tree-length logs. He also found the soils between the ruts that were compacted by the movement of logs had a 10% increase in bulk density and a 38% decrease in aeration porosity.

1.3 Residual Tree and Seedling Growth

Soil compaction affects the growth of trees and seedlings. Since partial cuts and thinnings are increasingly used, foresters have been concerning the effects of soil compaction on the growth of residual trees. Mechanized harvesting equipment commonly used for thinning southern pine stands might damage the soil and/or residual trees, thus negate the potential benefits of the thinning treatment (Reisinger et al. 1994). Soil nutrient availability was altered by changes to soil physical properties caused by the removal of forest floor and compaction during harvesting and site preparation (Hamlet et al. 1990, Briars et al. 1995, Mo et al. 1995, Huang et al. 1996, Worrell and Hampton 1997). Soil compaction and loss of organic matter from the forest floor directly influences mineral weathering rates, nutrient mineralization and consequently plant growth (Zabowski et al. 1994, Worrell and Hampson 1997). The forest floor was very susceptible to disturbance by harvesting operations (Turcotte et al. 1991). Mechanical disruption of the forest floor might have an adverse impact on site

productivity because the forest floor is a major source of nutrients for shallow rooted spruce and fir seedlings (Hoyle 1965, Shaw et al. 1987). Growth of planted Douglas-fir seedlings on compacted tractor roads was significantly lower than seedlings in other cutover locations (Youngberg 1959). Several researchers have suggested that such disturbances might have long-term consequences for the management of pine plantations (Foil and Ralston 1967, Scheerer et al. 1995).

Some soil disturbances can be beneficial to seedling growth or regeneration. In two areas with naturally regenerated loblolly pine, secondary skid trails had an initial establishment of seedlings equal to, or greater than that on undisturbed soils, and shoot growth was less than that on undisturbed soil during the first two years (Hatchell et. al. 1970). Pine stocking during the first year was greater on secondary skid trails than on adjacent undisturbed soils, probably because skidding exposed the mineral soil. However, in one area, height growth on secondary trails was significantly less than that on disturbed soils. Reduced stocking and retarded height growth were also observed on primary skid trails, and detrimental effects were particularly severe on the finer textured soil. Seedlings in primary skid trails were less than half as tall as seedlings in undisturbed soil. Establishment and growth of pines were hampered to an even greater extent on log decks, which were more severely compacted and puddled than the primary skid trails.

1.4 Harvesting Methods and Systems

All harvesting operations cause some compaction, but the degree of compaction varies with harvesting equipment, techniques, and intensity, and soil properties, especially moisture content and texture (Reisinger et. al. 1988).

Silvicultural treatments coupled with harvesting technique have an influence on how an area is disturbed and the severity. Soil disturbance averaged 17% in selection cuts and 28% in strip and patch clearcuts of northern hardwoods (Nyland et al. 1977). Dickerson (1968) reported that 21% of the soil in a clearcut stand was disturbed compared to 14% for an area with selective cut. He also found twice as much severely disturbed soil (barred, rutted, and compacted) on the clearcut site as on selective site. Willis (1971) found a similar result in a clearcut in Georgia. Approximately 5 to 10 percent of these areas, usually composed of log decks and primary skid trails, were considered seriously compacted. Hatchell et al. (1970) surveyed nine tractor skidder logged areas in South Carolina and Virginia and reported that 34% of the area was disturbed and 14% of the 34% (primary skid trails and log decks) classified as compacted.

Many studies compared the area disturbed by conventional logging with a tractor or skidder to a skyline system. Garrison and Rummell (1951) found mineral soil was exposed about 20.9% in tractor-logged areas, 15.2% of the total area where cables were used, and 11.8 % in horse-logged areas in eastern Oregon and Washington. Steinbrenner and Gessel (1955) also studied tractor logged areas in

western Washington and found 26% of the total area occupied by tractor skid roads. Wooldridge (1960) observed 29.4% of the ground surface was disturbed in a tractor logged area while only 11.1% was disturbed in the skyline area. Dyrness (1965) found a tractor-logged unit had about three times more area in the compacted disturbance class than did a high lead unit. Kochenderfer (1977) reported roads and landings accounted for 10.3% of skidder-logged area, and 7.8% for jammer-logged areas. McMinn (1984) found that a small skyline yarding operation disturbed only 1% of the total area compared to 37% and 16 % of disturbance in two skidded areas excluding landings. A similar study in Mississippi found that a cable yarding required 2% less area in landings than skidding, and yarding corridors occupied 12% less area than skid trails (Miller and Sirois 1986).

1.5 Objectives

There are several problems associated with ground-based skidding in the central Appalachian hardwood forests. The single most important step to avoiding unnecessary road construction is proper harvest and road planning. As road density and miles of road increase, ground disturbance increase. The introduction of the feller-buncher in this region has also influenced how loggers harvest timber. The feller-buncher has increased production and improved logger's safety, but effects on soils may have worsened. However, since the introduction of the feller-buncher in the central Appalachians, no studies have been conducted on the

machine's effects on soil compaction, nor have feller-buncher effects been compared to other commonly used harvesting systems from perspectives of soil compaction and or soil disturbance. Therefore, the objectives of this study are to:

- (1) Examine if the occurrence of soil compaction is significantly different between two commonly-used ground-based harvest systems in central Appalachian hardwood forests,
- (2) Physically examine the amount of soil compaction on the skid roads and across the site by soil type, soil moisture, site condition, and harvest system, and
- (3) Statistically analyze the amount of soil compaction associated with the harvest system, soil type/moisture, and site conditions.

CHAPTER 2 METHODS AND DATA

2.1 Sites

All harvest sites were located on Mead-Westvaco's forest in Randolph County, West Virginia (Figure 2.1). Harvesting plans in these areas were determined by Mead-Westvaco in context with their long-term forest management goals. The two study sites were similar in size and volume of wood removed per acre (Table 2.1). Average slope varied between the two harvested sites. The mechanized site was flatter with 5-20% slope, while the manual system was employed on relatively steeper slopes ranging from 30 to 40%.

Figure 2.1 Location Map for Harvest Sites

Table 2.1. Site conditions.

	Manual Site	Mechanized Site
Harvest Method	Manual	Mechanized
Harvest Type	Selection	Clearcut
terrain slope (%)	35-45	15-25
aspect	Northeast	North
Time of Harvest	Summer	Summer
Tract Size (ac)	31	34
Volume (BF/ac)	3,595	5,765
Species Composition	Mixed Hardwoods	Mixed Hardwoods

(1) Manual Site

The manual harvesting site was located in the School Craft watershed, on the property of Mead-Westvaco. The tract was 31 acres in size. Tree volume removed was 3600 BF per acre with the primary species including red oak (*Quercus rubra*), red maple (*Acer rubrum*), black birch (*Betula nigra*), chestnut oak (*Quercus prinus*), and basswood (*Tilia Americana*) (Table 2.2). The study area with north-facing slope was moderately steep (approximately 30 to 40 percent). Some scattered places in this tract were with $\geq 50\%$ slope. The elevation ranges from 2600 ft. at the creek buffer to 3010 ft. at the ridge top (Figure 2.2).

Soils for the manual harvest site are primarily Gilpin series (GkE), though it is Buchanan (BtE) near the valley bottom. The Gilpin series is found on ridge

tops, benches, side slopes, which consists of a well-drained and moderately deep soil. Slopes range from 3 to 70%. Gilpin soils commonly are formed in acid material weathered from interbedded shale, siltstone, and sandstone. The Buchanan series is colluvial consisting of deep, moderately well drained, acidic soils. The Buchanan series is common on foot slopes, drainage ways, benches, and in coves. Slopes range from 3 to 35%, but occur dominantly slopes from 15 to 35 percent (Pyle et al. 1967). Soil distribution in the manual harvest site is illustrated in Figure 2.3.

Table 2.2. Cruise data on the manual harvest site.

Species	Volume (BF/Acre)	Total Volume (BF)	Percent (%)
Black Cherry	135	15,000	4
Red Oak	1189	132,000	33
Black Walnut	0	0	0
Hard Maple	189	21,000	5
Soft Maple	613	68,000	17
Ash	144	16,000	4
Black Oak	0	0	0
White Oak	18	2,000	1
Poplar/Cuc	243	27,000	7
Scarlet Oak	0	0	0
Basswood	270	30,000	8
Chestnut Oak	333	37,000	9
Hickory	27	3,000	1
Black Birch	342	38,000	10
Beech	36	4,000	1
Black Locust	9	1,000	0
Y. Birch	27	3,000	1
Misc. Hdwd.	18	2,000	1
TOTAL	3,595	399,000	100

The manual harvesting system consisted of two timber fellers using chainsaws, one rubber-tired cable skidder, and one bulldozer. Table 2.3 illustrates the system configuration

Table 2.3. Manual harvesting system configuration.

Operation	Felling	Skidding	Other
Machine	Chainsaw	TJ 460D cable skidder	Case 650C dozer
No. of machines	2	1	1

Figure 2.2 Manual Harvest Site

Legend

(2) Mechanized Site

The mechanized harvesting site was located along Flatbush Fork, on the Mead-Westvaco property. The harvest area was 34 acres. Volume removed per acre was 5,765 BF, 196,000 BF in total. Primary species were poplar (*Liriodendron tulipifera*), soft maple (*Acer rubrum*), red oak (*Quercus rubra*), and chestnut oak (*Quercus prinus*) (Table 2.4).

Table 2.4. Cruise data for the mechanized harvest site.

Species	Volume (BF/Acre)	Total volume (BF)	Percent (%)
Black Cherry	0	0	0
Red Oak	1265	43,000	22
Black Walnut	0	0	0
Hard Maple	29	1,000	1
Soft Maple	1353	46,000	23
Ash	147	5,000	3
Black Oak	0	0	0
White Oak	265	9,000	5
Poplar/Cuc	1559	53,000	27
Scarlet Oak	29	1000	1
Basswood	0	0	0
Chestnut Oak	676	23,000	12
Hickory	0	0	0
Black Birch	118	4,000	2
Beech	0	0	0
Magnolia	59	2,000	1
Misc. Hdwd.	265	9,000	5

The mechanized site was north facing with approximately 10-20% of slope. Elevation ranged from 2440 ft at the creek buffer to 2600 ft at the southern boundary (Figure 2.4). Soils for the mechanized harvest site consists of Buchanan (BtE), Gilpin (GdE), and Lily (LyC) series. The Buchanan and Gilpin series were described earlier. The Lily series consists of deep, well-drained soils that formed

from acid material weathered from sandstone and some interbedded siltstone and shale. The Lily soils exist primarily on ridge tops and benches. Slopes range from 3 to 15%. Lily soils are on the landscape of well-drained Gilpin soils, and are less deep than Buchanan soils (Pyle et. al. 1967). The soil survey on the mechanized harvest site is illustrated in Figure 2.5.

Feller-buncher and grapple skidder were the two major machines in the mechanized system. The configuration of this system is listed in table 2.5.

Table 2.5. Mechanized harvesting system configuration.

Operation	Felling	Skidding	Other
Machine	Timbco feller-buncher	JD 648II grapple skidder	-
No. of machines	1	2	-

Figure 2.4 Mechanized Harvest Site

2.2 Methods

A completely randomized design (CRD) was employed for data collection in this study, which consisted of one block and two treatments. The block was defined as the timber harvest sites. Two harvesting sites were assumed similar in terms of stand and terrain conditions. The two treatments applied were manual harvesting system and mechanized harvesting system. Manual harvesting system employed chainsaw felling and a cable skidder while mechanized harvesting system consisted of a feller-buncher and grapple skidder. The mechanized system usually has no workers on the ground and makes it safer for the loggers.

Soil sample plots were pre-determined prior to harvest. Soil samples were taken on skid roads and throughout two harvested sites. Points were systematically located in the harvest sites, while the points on the skid roads were randomly placed. A GPS unit was used to map, record, and relocate the sample locations.

Thirty sampling locations were installed in each of two harvesting sites (Figure 2.6 and 2.7), which were systematically laid out using a grid of 3 by 3 chains. Four samples were taken at each location at random direction and distance (Figure 2.8). The core points taken across the site (not on the skid trails) were also recorded and mapped using the GPS unit. The direction was determined much like using your second hand on a wrist watch and the distance

will be a random length up to 15 feet, which was determined using a program called “Randomizer” (www.randomizer.org) (Figure 2.8).

Figure 2.6 Manual Harvest Site Point Location

Figure 2.7 Mechanized Harvest Site Point Location

Compaction on skid roads is directly related to the number of passes on the trail. Road closer to landing has more traffic, while it has considerably less traffic if the road is farther away from the landing. Consequently, the measurement locations were identified relative to the proximity of the landing. Six samples were taken at a cross section on the road (Figure 2.9). A total of 60 points were measured at 10 cross sections on the skid road in manual harvesting site (Figure 2.10) while 84 points were recorded at 14 cross sections on the road in mechanized site (Figure 2.11).

Figure 2.9 Cross section of skid road layout

**Figure 2.10 Manual Harvest Site
Road Point Location**

Figure 2.11 Mechanized Harvest Site
Road Point Location

The soil compaction associated with the first ten-loaded skidder passes were recorded at the first four cross section samples on the skid road in each site. The locations of the samples in relation to the log landing also were measured. Samples closer to a log landing generally have a greater number of loaded machine passes than those further away from the landing.

A Troxler density and moisture gauge was used to measure the soil density and soil moisture, which allows to take more samples and provide more accurate measurement. The Troxler can measure bulk density and soil moisture from 2 inches deep to 12 inches deep in increments of 2 in. Samples were measured six inches from the top of the surface to obtain soil bulk density in this study.

The independent variables measured were harvest type, harvest status (pre-harvest and post-harvest), soil types, and soil moisture. The quantitative measurements for the variables included wet density (lb/ft^3), and dry density (lb/ft^3). The wet density is the actual weight of the soil and water per unit volume. The dry density is the weight of the soil per unit volume. The soil compaction was computed by differentiating dry soil bulk densities after and before harvests.

Mean soil compaction was compared to determine if a difference between harvesting systems by harvesting status. The general linear model (GLM) was used to test if the significant differences of soil density or compaction exist among harvest system, harvest status, and soil moisture levels. Tests were performed using Duncan's multiple-range test at 0.05 level.

CHAPTER 3 DATA ANALYSIS AND RESULTS

3.1 Data Analysis

Data were analyzed using Statistical Analysis Systems (SAS). A GLM model was performed to determine if any differences of soil bulk densities/compaction existed on three datasets: points in the woods, points in the roads, and first ten loaded machine passes.

(1) Points in the woods

The GLM model for soil bulk density for points in the woods is expressed as:

$$D_{ijk} = \mu + HS_i + HT_j + HS_i * HT_j + e_{ijk}$$

$$i = 1,2$$

$$j = 1,2$$

$$k = 1,2 \dots n$$

Where D_{ijk} represents the k^{th} observation of the soil bulk density (DD or WD); μ is the mean of each response variable; HS_i is the effect of the i^{th} harvest system; HT_j is the effect of the j^{th} harvest status; e_{ijk} is an error component that represents uncontrolled variability; and n is the number of observations within each treatment. Interactions between harvest system and harvest status were also considered in the model.

(2) Points in the road

This is the GLM model used for points on the roads:

$$D_{ijk} = \mu + HS_i + HT_j + HS_i * HT_j + e_{ijk}$$

$$i = 1,2$$

$$j = 1,2$$

$$k = 1,2,\dots,n$$

Where D_{ijk} represents the k^{th} observation of the soil bulk density (DD and WD); μ is the mean of each response variable; HS_i is the effect of the i^{th} harvest system; HT_j is the effect of the j^{th} harvest status. Interactions between harvest system and harvest status were also considered in the model.

(3) Ten Loaded Machine Passes

A generic GLM for analyzing soil bulk densities associated with the first ten loaded machine passes is expressed as:

$$D_{ijkl} = \mu + HS_i + NP_j + SM_k + HS_i * NP_j + HS_i * SM_k + NP_j * SM_k + e_{ijkl}$$

$$i = 1,2$$

$$j = 1,2, \dots, 10$$

$$k = 1,2,\dots,n$$

Where D_{ijk} represents the k^{th} observation of the soil bulk density (DD and WD); μ is the mean of each response variable; HS_i is the effect of the i th harvest system; NP_j is the effect of the j th number of loaded machine passes; SM_k is the effect of the k th soil moisture; e_{ijkl} is an error component that represents uncontrolled variability; and n is the number of observations within each treatment.

Interactions among harvest system, number of loaded machine passes and soil moisture were also considered in the model.

3.2 Results

3.2.1 Soil Bulk Density - Points in the Woods

On the manual harvest site, the mean pre-harvest soil bulk densities were 65.75 lb/ft³ DD and 84.44 lb/ft³ WD, respectively, while mean post-harvest soil bulk densities were 67.00 lb/ft³ DD and 90.41 lb/ft³ WD. The mean bulk density showed an increase after the timber harvest was completed. An increased compaction level of 6.08 lb/ft³ was present on the manual harvest site (Table 3.1).

On the mechanized harvesting site mean pre-harvest soil bulk densities were 59.31 lb/ft³ DD and 80.46 lb/ft³ WD, respectively. Mean post-harvest soil bulk densities were 59.48 lb/ft³ DD and 77.62 lb/ft³ WD. The mechanized harvesting site showed an increased compaction level of 1.82 lb/ft³ DD after harvest (Table 3.1).

Both DD ($F = 40.20$; $df = 1, 479$; $P = 0.0001$) and WD ($F = 66.85$; $df = 1, 479$; $P = 0.0001$) were significantly different between harvesting systems (Table 3.2). However, there was no significant difference for DD ($F = 0.43$; $df = 1, 479$; $P = 0.5147$) and WD ($F = 2.32$; $df = 1, 479$; $P = 0.1283$) between harvest statuses. Soil moisture did significantly affect the soil bulk density or compaction. Both DD and WD decreased as soil moisture level increased from 15% to 70%.

Table 3.1 Statistics of observed variables for points in the woods.

Harvest status	Variable	Mean	Std. Dev.	Min.	Max.
Manual harvesting system					
Pre-harvest	DD	65.74	10.40	45.00	97.60
	WD	84.44	8.71	64.10	110.70
	Smoist	29.76	10.72	7.40	60.00
Post-harvest	DD	67.00	13.91	39.80	114.00
	WD	90.41	13.55	59.20	135.80
	Smoist	36.74	11.34	12.80	72.80
	DD compaction	6.08	8.97	0.00	42.40
Mechanized harvest system					
Pre-harvest	DD	59.31	12.05	32.30	97.40
	WD	80.47	11.10	56.40	110.40
	Smoist	36.74	11.34	12.80	72.80
Post-harvest	DD	59.49	11.59	31.30	99.10
	WD	77.62	11.05	50.60	108.20
	Smoist	32.13	11.76	8.90	73.50
	DD compaction	1.82	3.01	0.00	16.90

Table 3.2. Means and significant levels of bulk density *

Dry Density		Wet Density
Harvest System		
Manual	66.37A	87.43A
Mechanized	59.40B	79.05B
Harvest Status		
Before Harvest	62.53A	82.46A
After Harvest	63.24A	84.02A
Soil Moisture (%)		
0-15	83.52A	93.52A
16-30	70.56B	87.27B
31-45	59.89C	81.92C
46-60	51.42D	77.10D
61-70	41.72E	69.59E

* Means with the same letter are not significantly different at alpha = 0.05 (ANOVA)

3.2.2 Soil Bulk Density - Points on the Roads

Mean pre-harvest soil bulk densities on the roads in the manual site were 85.88 lb/ft³ DD and 105.34 lb/ft³ WD. The mean bulk densities of DD and WD showed an increase after harvest. Mean post-harvest soil bulk densities were 93.16 lb/ft³ DD and 112.21 lb/ft³ WD, showing an increased compaction level of 9.35 lb/ft³ on the manual harvesting site (Table 3.3).

On the mechanized harvesting site mean pre-harvest soil bulk densities were 81.88 lb/ft³ DD and 98.73 lb/ft³ WD. Mean post-harvest soil bulk densities were 86.16 lb/ft³ DD and 103.88 lb/ft³ WD, showing an increased compaction level of 7.88 lb/ft³ (Table 3.3).

For the points on the road, both DD ($F = 15.39$; $df = 1, 287$; $P = 0.0001$) and WD ($F = 36.28$; $df = 1, 287$; $P = 0.0001$) were significantly different between harvesting systems (Table 3.4). Similarly, there was no significant differences of DD ($F = 16.01$; $df = 1, 287$; $P = 0.0001$) and WD ($F = 23.00$; $df = 1, 287$; $P = 0.0001$) between harvest statuses. The interaction between harvesting system and harvest status showed a significant effect on both DD ($F = 1.14$; $df = 1, 287$; $P = 0.2874$) and WD ($F = 0.49$; $df = 1, 287$; $P = 0.4849$). Soil moisture groups showed a trend that the lower the soil moisture the higher the soil bulk density. However, the higher the soil moisture the higher the soil compaction level. Soil moisture did significantly affect the compaction levels.

Table 3.3. Statistics for points in the roads.

Variable	Mean	Std. Dev.	Min.	Max.
Manual harvest system - Pre-harvest				
DD	85.88	11.46	60.60	103.60
WD	105.34	11.15	77.90	124.40
Smoist	23.32	7.93	11.20	52.00
Manual harvest system - Post-harvest				
DD	93.16	9.99	68.60	110.20
WD	112.21	7.64	92.70	125.30
Smoist	21.15	8.00	8.80	45.60
DD compaction	9.35	9.98	0.00	38.30
Mechanized harvest system - Pre-harvest				
DD	81.88	12.79	51.00	110.20
WD	98.74	11.35	74.90	124.30
Smoist	21.66	9.52	5.20	61.80
Mechanized harvest system - Post-harvest				
DD	86.16	11.98	52.30	111.60
WD	103.88	10.45	66.30	126.00
Smoist	21.45	9.13	5.40	70.30
DD compaction	7.88	8.69	0.00	31.60

Table 3.4. Mean and significant levels of bulk density on roads*.

	Dry Density	Wet Density
Harvest System		
Manual	89.52A	108.77A
Mechanized	84.02B	101.30B
Harvest Status		
Before Harvest	83.55B	101.49B
After Harvest	89.08A	107.349A
Soil Moisture Group		
0-15	91.99A	109.61A
16-30	89.60A	107.74AB
31-45	85.29A	107.38AB
46-60	75.40AB	95.20BC
61-70	67.70B	92.53C

* Means with the same letter are not significantly different at alpha = 0.05 (ANOVA)

3.2.3 First Ten Loaded Machine Passes

The mean pre-harvest soil bulk density was 88.32 lb/ft³ on the manual harvesting site, which increased as the number of loaded machine passes increased (Figure 3.1). A decrease in soil compaction was shown after three or four passes. This might be attributed to the rutting observed after three or four loaded machine passes. As the soil was displaced, the bulk density decreased some. Then, as the soil displacement minimized, the bulk density increased as the number of loaded machine passes increased. The soil bulk density increased to 97.20 lb/ft³ after 10-loaded machine passes.

The soil bulk density on the mechanized harvesting site indicated a similar increasing trend as the number of loaded machine passes increased (Figure 3.2). However, as in the manual system a decrease in soil compaction was noticed as soil displacement occurred. A smaller decrease in soil density was recorded as rutting occurred. In addition, as the displacement minimized the bulk density increased as the number of loaded machine passes increased. An average bulk density of 78.22 lb/ft³ before harvest on the mechanized harvest site was observed and it increased to 88.75 lb/ft³ after five machine passes and 95.60 lb/ft³ after ten passes.

The DD for the first ten loaded machine passes showed a significant difference among machine passes ($F = 4.01$; $df = 10, 86$; $P = 0.0007$) (Figure 3.7). The DD ($F = 29.51$; $df = 1, 86$; $P = 0.0001$) was significantly different between harvest systems. Likewise, there was a significant difference for the DD ($F = 19.14$; $df = 4, 86$; $P = 0.0001$) among soil moisture groups. The interaction

between harvest system and number of loaded machine passes did not significantly affect the DD ($F = 0.81$; $df = 10, 86$; $P = 0.6164$). No significant difference was identified in the interaction between the number of loaded machine passes and soil moisture groups ($F = 0.30$; $df = 18, 86$; $P = 0.9958$). Similarly, there was a significant difference for DD ($F = 4.42$; $df 2, 86$; $P = 0.0014$) by the interaction between harvest system and soil moisture group.

Table 3.7. Means and significant levels of ten loaded machine passes.

	Dry Density	Wet density
Harvest System		
Manual	89.52A	108.77A
Mechanized	84.02B	101.31B
Soil Moisture Group		
0-15	97.33A	117.98A
16-30	95.94A	113.03A
31-45	95.60A	112.17A
46-60	93.49AB	94.27B
61-70	85.60B	89.50B
Loaded Machine Passes		
0	83.27B	103.60B
1	90.30A	111.90A
2	91.50A	112.91A
3	91.67A	112.92A
4	92.40A	113.15A
5	93.09A	113.37A
6	94.30A	113.71A
7	94.77A	114.83A
8	95.25A	115.00A
9	95.81A	115.35A
10	96.40A	116.44A

* Means with the same letter are not significantly different at $\alpha = 0.05$ (ANOVA)

Figure 3.1 First ten loaded machine passes - Manual

Figure 3.2 First ten loaded machine passes - Mechanized

CHAPTER 4 DISCUSSION AND CONCLUSIONS

The manual harvesting system caused more soil compaction than the mechanized system. However, the compaction varied by soil types, harvest type, slope percent, operators experience and weather conditions. There are three reasons why the mean dry bulk density is lower on the mechanized harvest site than that on the manual harvest site. The manual harvesting operation started in the late spring and experienced approximately 6.5 inches of rainfall, while the mechanized system began in late July and finished in two weeks and had no rainfall. Secondly, the mechanized harvest site was preplanned and skid roads were put in two to three weeks prior to harvesting operations. There were no points in the woods that fell on the skid road system on the mechanized site. On the manual harvesting site, however, the skid roads were built as the operation progressed. Therefore, five locations for points in the woods were ultimately located on a skid road. Harvesting conditions such as the slope, can also contribute to this as well as preplanning or lack of planning. Finally, operator experience contributes to the amount of ground disturbance. The crew for the mechanized harvest system had no wasted motion. The feller-buncher bunched trees and the skidder got all the bunched trees in one turn. However, the cable skidder operator on the manual harvesting site sometimes skidded logs from the same point along the skid road three or four times before moving to another location.

It would be interesting to compare the two systems in the same harvest type, harvest site and same time of the year. In addition, the comparison should be made for two ground-based systems with the same level of decision making by the loggers. There was a great deal of difference in the equipment and operators between the two harvesting systems, these factors might cause some compaction variability between the two systems.

The lower the soil moisture level the higher the mean bulk density. This is consistent with findings in previous studies. The soil moisture groups that made up of most of the samples were between 15 and 45 percent soil moisture. The mean bulk densities for these soil moisture groups are comparable on the two harvest sites.

Higher soil bulk densities were also observed on the skid roads in the manual harvesting site as compared with the densities on the skid roads in the mechanized site. The reasons are as follows: (1) the ground pressure for the TimberJack 460 cable skidder used in the manual site was 7.2 (psi), while the ground pressure for the John Deere 648GII grapple skidder in the mechanized site was 6.4 (psi); (2) the manual harvesting site had more precipitation during the harvest; and (3) the operator of the John Deere 648GII cut tracks while skidding, on the mechanized site. This means the machine never ran in the same place twice. The skidder operator used the whole width of the road instead of traveling in the same wheel tracks.

The mean bulk density between the two harvest systems was significantly different between harvest statuses. This is expected when the roads were

measured before any loaded machine passes versus the completion of the harvest. The bulk density on the roads gained approximately 7 lb/ft³ from before harvest to after harvest. Although this increase in density is significantly different, this is not a large amount of compaction.

The soil moisture in the road seems to have an inverse effect on soil compaction. Most of points were observed in the soil moisture levels of 0 – 15 percent and 16– 30 percent. These two soil moisture groups contained the highest mean bulk densities. All samples with soil moisture from 31 percent up to 70 percent seemed to have a lower soil bulk density. There were fewer points recorded in the higher soil moisture levels for the harvest systems on the skid roads and the higher soil moisture groups had the lower soil bulk density.

The bulk density on the manual harvesting site increased a 9.35-lb/ft³ from before harvest to after harvest, while the mechanized site experienced a 7.88 lb/ft³ increase. Even though the tire size made a difference in ground pressure between the two systems the final compaction on the skid road was not significantly different between harvesting systems. It seems that the compaction on skid road does not directly relate to the harvesting system.

The higher the soil moisture the more likely the soil is to be compacted. Although, the lower soil moisture groups have a higher mean bulk density, the lower soil moisture resulted in the lower compaction. The soil compaction was not significantly different among soil moisture groups. The soil moisture tends to be low after road construction. The moisture dried out after the road was established. The loggers running the manual harvest system built roads as the

harvest progressed, therefore, the soil moisture was higher than in the pre-planned roads on the mechanized system. This might have contributed to a higher compaction level on the skid roads.

Both harvesting systems showed an increase in soil compaction with the number of loaded machine passes. A small decrease in soil compaction was recorded as rutting began to occur for both harvest systems. For both systems, the soil compaction increased as the rutting stopped. However, more samples might help to improve the accuracy of this observation.

The silvicultural treatments (selection cut and clearcut) showed a difference for compaction, especially for points measured in the woods. However, further study is needed to evaluate these two silvicultural treatments using the same harvesting system. A comparison of the two harvest systems and two silvicultural treatments may produce a different result. The most ironic finding for this study was that the mechanized system along with a clearcut did not have as much compaction as the manual system on a selection cut. This finding can give a new base line for future studies. A selection harvest with the mechanized may result in more compaction than a clearcut.

Soil compaction on the roads was not significantly different comparing harvest systems as was expected. However, road planning will reduce the roads by area can be beneficial to soil compaction in a forest stand.

Future monitoring should also include evaluating the fate of compacted soil on the skid roads. Soil bulk density should be evaluated each year or even every six months to determine how long it takes the soil to return to its original bulk density. Compaction did occur on skid roads, however, trees have grown on old skid roads. It would be beneficial to continue to evaluate the soil density for productivity purposes.

Soil compaction on different soil types was monitored during this research. However, the differences in the soil types for each site made it impossible to compare. Similar harvest sites with the same soil types would be beneficial for determining soil compaction by soil types. The BtE soil type was found on both sites in this study and presented similar compaction level. It was noticed that the BtE soil was easily compacted than other types. The GkE, which was on the manual site, and the GdE, which was on the mechanized site, also showed similar results in compaction.

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