Soil bulk density changes caused by mechanized harvesting: A case study in central Appalachia

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Abstract

A mechanized harvesting system consisting of a feller-buncher and a grapple skidder was examined to quantify soil bulk density changes in a central Appalachian hardwood forest site. Soil bulk density was measured using a nuclear gauge pre-harvest and post-harvest systematically across the harvest unit and on transects across skid trails. Bulk density also was measured in the skid trails in a subset of the transects after the first 10 loaded machine passes. Post-harvest soil bulk density of 954.4 kg/m^3 was not significantly different from the pre-harvest bulk density of 925.2 kg/m^3 across the site. Grapple skidding resulted in significant bulk density changes in the skid trails. Results suggest that most of the soil bulk density changes in the skid trails occurred after the first loaded machine pass. Our findings suggest that the use of tracked feller-bunchers to fell and bunch the trees results in the minimum changes to soil bulk density across a harvest site.

Harvesting operations can cause some degree of soil compaction, depending on harvesting equipment, techniques, traffic intensity, soil properties, and especially moisture content (MC) and soil texture (Reisinger et al. 1988). Whenever soil is disturbed/compacted on steep slopes, there is a chance for erosion along with subsequent sedimentation of nearby streams (Martin and Hornbeck 1994). As extraction equipment has evolved from crawler-type tractors to wheel skidders, and as felling has progressed from manual chain saws to mechanized feller-bunchers or harvesters, the spatial extent of disturbed soil areas has increased (Martin 1988).

Soil disturbance and compaction are influenced by several factors, including the amount and distribution of surface litter and slash, soil texture and structure, soil moisture, the weight and function of the machine, wheel size and slip, equipment speed, type of load, operator skill, terrain, and weather (Sirois et al. 1985). Although a wide variety of site and machinery factors influence the degree of soil disturbance/compaction, the likelihood of soil disturbance/compaction is enhanced on moist to saturated soils (Moehring and Rawls 1970, Greacen and Sands 1980). Heavy equipment compresses and ruts soil during harvesting, which can lead to increased bulk density, loss of soil macroporosity, increased erosion, decreased availability of water, and potential loss of site productivity. Vehicular traffic associated with forest harvesting operations also has the potential to compact and/or puddle forest soils (Hatchell et al. 1970, Aust et al. 1993). Soil moisture at the time of trafficking has a major influence on reduction and redistribution of pore space as soils are compacted (Seixas and McDonald 1997).

Several studies have examined the relationship between compaction, tire size, and associated number of loaded machine passes. The greatest change in bulk density occurs during the first few passes over an area (Froehlich et al. 1981, Greene and Stuart 1985, Shetron et al. 1988), but using lighter machines or larger tires can reduce soil compaction (Greene

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Table 1. — Site and harvest information for the mechanized harvesting system.

Item	Value
Site and stand	
Tract size (acres)	34
Volume removed (BF/acre)	5,765
Species composition	Mixed hardwoods
Slope (%)	15 to 25
Aspect	North
Harvest	
Silvicultural method	Clearcut
Felling machine	Timbco 445C feller-buncher
Skidding machine	JD 648G grapple skidder
Skidder tire size (in)	30.5 to 32
Weight of skidder (lb)	33,400
Skidder payload (BF)	518

and Stuart 1985). McDonald et al. (1995) found that the number of skidder passes was the most significant factor influencing rut formation. The first pass accounted for half the average rut depth and area. Wider tires reduced the potential for traffic-related changes in soil properties.

Foresters have long considered the effects of soil compaction on the growth of residual trees and seedlings. Soil compaction and disturbance can have long-term negative consequences on forest management (Foil and Ralston 1967, Shaw et al. 1987). Soil nutrient availability is altered by changes to soil physical properties caused by compaction and the removal of forest floor organic matter during harvesting and site preparation (Hamlett et al. 1990, Briars et al.1995, Huang et al. 1996). Soil compaction and loss of organic matter from the forest floor directly influence mineral weathering rates, nutrient mineralization, and subsequent plant growth (Zabowski et al. 2000). However, some seedling growth and regeneration can benefit from some soil disturbance (Hatchell et al. 1970).

During the past decade, forest harvesting methods available in central Appalachian hardwood forests have evolved substantially. Increased worker's compensation rates along with the demand for greater wood production have led to more mechanized harvesting systems throughout the region. Research on the soil impacts of mechanized systems appears to be limited in this region. Accordingly, in this study we wanted to quantify and document soil bulk density change levels for a mechanized system in central Appalachian hardwood forests.

Methods

The study site was located on a north-facing slope of about 15 to 25 percent sideslope in Randolph County, West Virginia. The elevation ranged from 2,440 feet at the creek bottom to 2,600 feet at the southern uppermost boundary. The tract harvested was 34 acres in size, and the volume of wood removed per acre was 5,765 board feet (BF) (**Table 1**). The primary species on the tract were yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), red oak (*Quercus rubra*), and chestnut oak (*Quercus prinus*). The soils on the site are mapped as Buchanan, Gilpin, and Lily series (**Fig. 1**). Lily soils are deep and well drained, and formed from weathering of acid sandstones and some interbedded siltstones and shales. Lily soils occur primarily on ridge tops and benches (U.S. Soil Survey Division 2001).

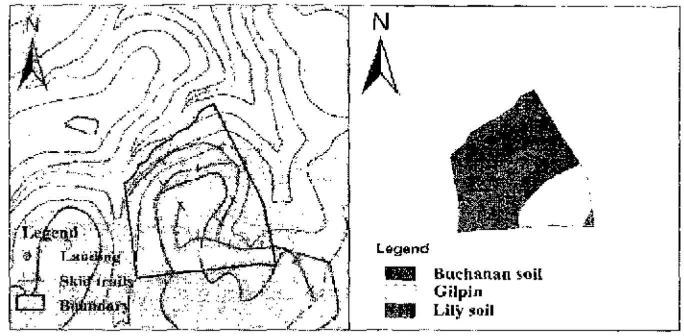

Figure 1. — Tract layout and soil distribution for the study site.

A tracked Timbco 445C feller-buncher and a John Deere 648G grapple skidder were the machines employed. The harvest was preplanned and skid roads were constructed 2 to 3 weeks prior to harvesting. The study began in late July of 2002, was finished 2 weeks later, and had no associated rainfall.

Soil bulk density and soil moisture were measured within the harvest unit and on transects in the skid trails. The pre- and post-measurements were made at the same locations. A Troxler Model 3440 surface density and moisture gauge was used to take the measurements at a 6-inch depth in the soil. The Troxler meter determines wet and dry bulk density, but only dry bulk density is reported in this paper as this is the standard way to express bulk density. The instrument uses the measured soil moisture value to calculate dry bulk density from the wet bulk density measurement. Thirty measurement points were located systematically in a 3- by 3-chain grid throughout the harvesting unit prior to treatment. Four measurements were taken around each point at random directions and distances up to 15 feet from that point. An additional 6 measurements were taken across 14 randomly located transects in the tract (n = 84 total measurements). Bulk density associated with the first 10 loaded grapple skidder passes was monitored on the 4 skid trail transects closest to the log landing. Locations for skid trail sample points were selected close to the log landing because the skid trail used by the loaded machines generally experiences more passes close to a log landing than farther from the landing. A GPS unit and wood poles were used to map, record, and relocate bulk density sample locations for post-measurements throughout the harvest unit and on the skid trails.

Soil bulk density change was computed as the difference between post-harvest and pre-harvest bulk densities, post-use and pre-use bulk densities of skid trails used by the loaded machine, and those associated with the first 10 loaded machine passes. A t-test was used to test if significant differences existed in soil bulk density changes. Soil moisture was also determined to quantify compaction levels on skid trails associated with the number of loaded machine passes.

Results

Measurements across the harvest unit

Pre-harvest soil MC averaged 37.7 percent. Soil bulk density was between 502.2 and 1562.5 kg/m^3 with an average of 925.2 kg/m^3 before harvesting, and increased to 954.4 kg/m^3. The mean increase in bulk density across the site was 29.2 kg/m^3 (**Table 2**). However, there was no statistically signifi-

Table 2. — Descriptive statistics for pre-harvest and post-harvest points across the site.

		Mean	SD[a]	Minimum	Maximum
Pre-harvest	Soil moisture (%)	37.7	12.6	12.5	74.6
	Bulk density (kg/m^3)	925.2	183.5	502.2	1562.5
Post-harvest	Soil moisture (%)	32.1	11.8	8.9	73.5
	Bulk density (kg/m^3)	954.4	185.9	502.2	1589.8
	Bulk density change[b] (kg/m^3)	29.2	48.4	0	271.1

[a]SD = standard deviation.
[b]Difference between post-harvest and pre-harvest bulk densities.

Table 3. — Descriptive statistics for pre-use and post-use points in the skid trails.

		Mean	SD[a]	Minimum	Maximum
Pre-use	Soil moisture (%)	21.7	9.5	5.2	61.8
	Dry bulk density (kg/m^3)	1313.6	205.2	818.2	1767.9
Post-use	Soil moisture (%)	21.5	9.5	5.4	70.3
	Dry bulk density (kg/m^3)	1440.0	178.6	940.1	1790.3
	Bulk density change[b] (kg/m^3)	126.4	139.4	0	506.9

[a]SD = standard deviation.
[b]Difference of bulk densities between post-use and pre-use of skid trails.

Table 4. — Significance level of soil bulk density comparisons by the number of machine passes[a].

No. of	No. of loaded machine passes										
passes	0	1	2	3	4	5	6	7	8	9	10
0	--										
1	0.0239	--									
2	0.0280	0.8979	--								
3	0.0274		0.8995	--							
4	0.0160			0.7916	--						
5	0.0142				0.9714	--					
6	0.0030					0.5280	--				
7	0.0028						0.9931	--			
8	0.0005							0.5501	--		
9	0.0002								0.7827	--	
10	0.0001									0.8034	--

[a]Test if the means of soil bulk densities were significantly different at $\alpha = 0.05$ level among machine passes.

cant difference between post-harvest and pre-harvest soil bulk densities at the measurement points across the site (df = 238; t = 0.12; $p = 0.9084$).

Transects in the skid trails

Pre-use soil MC averaged 21.7 percent in the skid trails (**Table 3**). The skid trail bulk density increased from an average of 1313.6 kg/m^3 before use to 1440.0 kg/m^3 after skid trail use was completed. Soil bulk density in the skid trails increased an average of 126.4 kg/m^3 (**Table 3**). The soil bulk density of post-use skid trails differed significantly from the bulk density of pre-use trails (df = 166; t = 2.24; $p = 0.0262$).

First 10 loaded-machine passes

Soil bulk density change was not significantly affected by soil moisture on the skid trails by the number of loaded machine passes (df = 1, 42; F = 0.02; $p = 0.8801$). Additional statistical comparisons using a t-test showed that the bulk density after the first loaded pass was significantly different from the initial bulk density without any loaded passes ($p = 0.0239$) (**Table 4**). However, the soil bulk density changes were not significantly different between two consecutive passes after the first pass ($\alpha = 0.05$ level). For example, the bulk density after two passes did not differ significantly from the bulk density after the first pass ($p = 0.8979$) and the density after three passes was not significantly different from the density after two passes ($p = 0.8995$) (**Table 4**). These results suggest that most of the soil bulk density changes occurred after one loaded machine pass in the skid trails.

Average bulk density increased with the first two loaded passes; then leveled out through about pass three (**Fig. 2**). If we assume that essentially 100 percent of the bulk density change that could occur did occur by pass 10, approximately 50 percent of the bulk density change occurred after one loaded machine pass (**Fig. 3**). About 57 percent of the bulk density change occurred after two loaded machine passes. After five passes, the bulk density change level was 60 percent on the skid trails.

Discussion

On the site, the feller-buncher cut and gathered trees and the grapple skidder secured and moved all of the bunched trees in one turn. The John Deere 648G grapple skidder used in the study had a ground pressure of 6.4 psi. The grapple skidder operator used the whole width of the trail instead of traveling repeatedly in the same wheel tracks. Although heavy equipment traversed over a large portion of the area, there was no statistically significant difference indicated in soil bulk density changes between post-harvest and pre-harvest across the site. However, significant bulk density changes were found in the skid trails after the use of skid trails was completed.

Soil bulk density increased on the skid trails as the number of loaded machine passes increased. The small decreases in bulk density change measured after three or four passes were unlike most previously reported soil bulk density studies in which bulk density generally has been reported to increase or remain constant with increasing numbers of passes (Greene and Stuart 1985, Shetron et al. 1988). The results from this case study confirm that mechanized harvesting operations do not significantly change soil bulk density across the site. The skidding operation does increase bulk density in the skid trails. The greatest proportion of bulk density change on skid trails occurred after only a single loaded pass – more than 50 percent.

Although we only examined one logging system on one site, our results support the recommendations of state forestry best management practices (BMPs) to focus skidding to a few

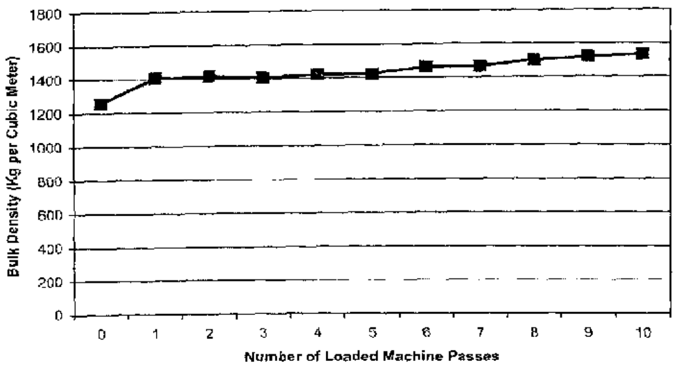

Figure 2. — Average soil bulk densities prior to using skid trails and for 10 loaded machine passes at the measurement point.

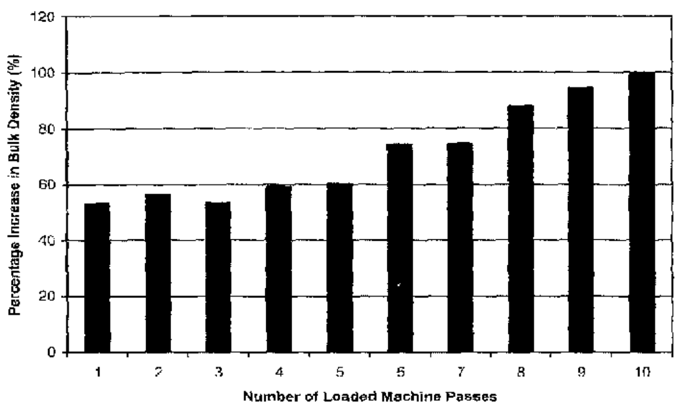

Figure 3. — Percentage increase in bulk density through 10 loaded machine passes at the measurement point.

well-developed designated skid trails and minimize trafficking across the general harvest area to protect water quality and reduce negative impacts to forest soil productivity. Loggers may want to consider the use of tracked feller-bunchers to harvest timber in areas where the minimum of change to bulk density is desired. Our results also confirm that skid trail construction and subsequent skidding on these trails should be constrained, if possible, to times when soil moisture is at a minimum.

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