Soil Compaction Study of 20 Timber-harvest Units on the Ouachita National Forest

Kenneth R. Luckow
USDA Forest Service, Ouachita National Forest, Hot Springs, Arkansas

James M. Guldin
USDA Forest Service, Southern Research Station, Monticello, Arkansas

A soil compaction study was performed on 20 timber harvest units on both rocky (15-35% by volume gravel) and non-rocky (<15% by volume gravel) surface soils of the Ouachita National Forest in Arkansas, to determine if these areas met the USDA Forest Service Southern Region (R8) soil quality standards for compaction and affected area extent. The compaction standard states bulk density cannot increase more than 15% from its natural (undisturbed) level and not more than 15% of an activity area can be adversely affected. Eight of the study units exceeded this standard. These eight units generally contained less than 15% rock fragments in the top 8 inches (20 cm) of soil, and seven of the eight had been harvested during the moist season (December-June) using rubber tire skidders. The non-rocky soil units, when harvested during the dry season (July-November), resulted in about 20-50% less compaction than when harvested during the moist season. Non-rocky soils with a sandy loam surface tended to compact less during dry season but more during moist season equipment operation than the non-rocky loam or silt loam soils. Compaction also averaged about 30-50% less on the rocky soils than on non-rocky soils. On the rocky soils, logging equipment operation during either the dry or moist season did not show a difference, and only native surface roads and log decks tended to have a greater than 15% bulk density increase. Compaction due to timber harvest activities that had occurred at least 15-20 years earlier averaged about 9% bulk density increase for the non-rocky soils and 7% for the rocky soils, and indicated that partial recovery had occurred. An analysis of surface infiltration rates found that a 15% density change resulted in more than 60% reduction in infiltration. This study also found that a 15% density change can be visually determined by change in soil structure.

Keywords: *compaction, bulk density, infiltration, soil structure, soil quality standard*

Introduction

Forest land managers are concerned with soil compaction and its effects on long term productivity of the land. Regionally and nationally there has been growing evidence to support this concern. On the Ouachita National Forest, Arkansas, little previous work has been done to determine the degree and extent of compaction that may occur on our soil types. Because the soils on the Ouachita National Forest are typically rocky, it has generally been concluded that compaction is not a serious problem.

Turton et al. (1997) analyzed compaction on six Phase II Ecosystem Management Research sites on the Ouachita, and found compaction to be significant only on multiple pass skid trails in single tree selection and group selection treatments, where soil rock content was relatively low. They found that those soils with the greater percentages of rock content resulted in lower amounts of soil compaction.

Kluender et al. (1994), in their assessment of impacts of alternative harvesting methods in mixed pine/hardwood stands on six harvest units on the Ouachita NF, found that compaction was significant only on the single tree selection treatment units. They attributed this result to the more concentrated traffic pattern or increased number of passes on fewer skid trails on these units. In another site impact study of five harvest treatments on 23 stands in the Phase II Ecosystem Management Research plots, Stokes et al. (1997) found the percent area extent in primary and secondary skid trails to be 22.4, 21.9, 20.5, 14.6 and 14.3 for the clear cut, seed-tree, shelterwood, group selection and single tree selection harvest treatments, respectively.

Froelich et al. (1980) found that the most critical period for compaction to occur is when soil moisture levels are between field capacity and saturation. This information is essential but still leaves the land manager with unanswered questions and situations when dealing with soil compaction at the operational level considering the various soils on the forest. Our study was designed to further our knowledge

M Furniss, C Clifton, and K Ronnenberg, eds., 2007. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004*, PNW-GTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

of compaction, its effects on surface infiltration and its degree and extent on the Ouachita's soils, and relate this to the USDA Forest Service Southern Region (Region 8) soil quality standard for compaction and area extent (UDSA Forest Service 2003). The compaction standard states that bulk density cannot increase more than 15% from its natural (undisturbed) level in the top 20 cm (8 inches) of soil, and that no more than 15% of the unit area can be affected.

Methods

Treatment units were initially selected for their compaction potential. A review of compaction research shows that soils and harvest units that show high amounts of compaction would have been subjected to intense heavy equipment activity, would contain low proportions of rocks, would probably be sandy loam textured soils, and would have been operated on during the moist season when soils would have a greater chance of being moist. Several units were selected that met these criteria. Similar soils and treatment units were also selected that had been harvested during the dry season, or that had a loam or silt loam surface texture, to help determine the importance of operating season or surface texture to compaction. To determine the influence of soil rockiness on compaction, treatment units were also selected that contained moderate percentages of rocks (approximately 15-35% gravel size rocks) in the top 20 cm (8 inches) of soil. Some of these rocky units had been harvested during the moist season and some during the dry season.

The study site soils are of the Carnasaw and Sherless Series. The Carnasaw soil is a clayey, mixed, thermic, Typic Hapludult, 100-150 cm (40-60 inches) deep, overlying soft shale bedrock with small amounts of sandstone. The Sherless soil is a fine-loamy, mixed, thermic, Typic Hapludult that is 50-100 cm (20-40 inches) deep over soft sandstone bedrock with small amounts of shale. For this study, those soils containing from 0-15% (field estimate by volume) rock content in the top 20 cm (8 inches) of soil are referred to as "non-rocky soils", and those soils containing from 15-35% rocks as "rocky soils". The density readings of the rocky soils were corrected for rock content differences among groups, and directly related to their non-rocky counterpart soils. The predominant rock size (which typically accounted for 50-100% of the rock present) was 2-19 mm and consisted mainly of sandstone fragments.

This study was performed on small, 0.8-2.0 ha (2-5 acre) subplots of timber harvest units. Most of the harvest units had been harvested within the past year with a few not yet harvested at time of selection. Treatments included single tree selection, group selection, shelterwood or seed tree harvest with harvest volumes mainly in the 23-35 m^3/ha (4,000-6,000 board foot/ac) range. Random transect monitoring was conducted using a Troxler 3440 moisture/density gauge to determine soil density within the 0-20 cm (0-8 inch) soil depth. Each day of use the gauge was tested for calibration and accuracy. To further validate the accuracy of the moisture/density gauge readings, and note any natural changes in the sample itself, the soil at each reading site was excavated by shovel, and field examined for USDA soil texture, estimated percent by volume rock fragments, and estimated amount of roots or buried debris present for possible gauge reading interference. In addition, an estimate of soil moisture at each reading site was made by feel. To further validate soil moisture readings from the Troxler gauge, selected soil samples of the 0-20 cm (0-8 inch) depth were collected and oven dried for 24 hours at 105°C. to gravimetrically determine moisture content. During the physical examination of each reading site, evidence of soil compaction was also recorded. This included noting changes in soil structure and the degree and depth of this structural change according to the 2002 NRCS Field Book for Describing and Sampling Soils (USDA NRCS 2002).

Random transects were set up using a tape with points measured at 3-m (10-foot) intervals and averaging about 75 sample points per unit. Each transect point was given one of six levels of visual disturbance ratings. These six levels included: undisturbed (or natural); evidence of previous impacts but not disturbed this entry (old disturbance); 1-2 pass tractor logging or other heavy equipment operation; 3 or more pass tractor logging not on the primary skid trail (these multi-pass areas are hereafter referred to as secondary skid trails); primary skid trail; and log deck or native surface road.

Identifying old disturbance sites required assessing such density gauge and field indicators as: (a) a site with a slight soil surface depression made from previous entry tire tracks; (b) a thinner layer of semi-decomposed litter relative to that of the natural undisturbed areas; (c) a change in soil structure from the natural state; and (d) greater density readings with no apparent cause other than prior disturbance. The final determination would typically include a combination of the above indicators with highest priority given to change in soil structure.

Surface infiltration measurements were performed on selected harvest units and sites of known degree of compaction to determine what effect density change may have on infiltration. Each infiltration measurement was made by carefully driving one 15-cm-tall x 10-cm-diameter x approximately 2-mm-thick steel ring, 3-5 cm into the soil by placing a short piece of 2 x 4 wood over the ring and using a 2-pound hammer. Water was then carefully applied to fill the rings while not disturbing the soil surface inside the ring. A period of 30 minutes was given for the water to soak into the soil, with additional water added to the ring and any leakage outside the ring stopped by soil mounding as needed. Readings were then recorded of water draw down inside the ring over time. The final surface infiltration recording was the average of the two or three individual ring recordings, and reduction in infiltration was the difference between those of the compacted sites vs. the undisturbed site infiltration recordings for each unit.

To determine whether bulk density values were different on individual treatment units between levels of disturbance, data were analyzed using one-way analysis of variance (ANOVA). To determine if these bulk density disturbance values were affected by the interaction from soil rockiness, season of equipment operation, or soil texture, data were analyzed using two-way analysis of variance (ANOVA), in which the classification variables of mean bulk density (BD) by texture, season of equipment operation, and soil rockiness were compared with the 'treatment', or disturbance variables. The analysis was conducted using the General Linear Models (GLM) procedure, with comparisons of means among classification and treatment interactions conducted with Sidak's test (SAS Institute 1989).

In instances where mean bulk density of the natural condition varied among classification variables, data were transformed by expressing all BD observations as a percentage of mean natural BD within each classification. ANOVA tests using Sidak's mean comparison test were then performed on the result, essentially a means of testing whether the percentage increases in BD above the natural conditions were significant between classification variables by treatment. Individual unit results are summarized in Table 1, and combined interaction unit results in Table 2.

Results

During this study additional data were collected to examine a number of variables including type of harvest method employed and volume per unit area removed. The analyses of these data were not found to be significant and therefore are not discussed here. Those variables that did prove to be significant included season of equipment operation, soil rockiness class, and surface texture class of the non-rocky soils. The fine sandy loam and loamy fine sand textured surface soils are hereafter referred to as sandy loam textured soils.

Table 1 shows bulk density means by individual harvest unit by two soil rockiness classes (non-rocky = <15%, and rocky = 15-35% gravel rock) where present, as measured against six different compactive disturbance levels. Also represented in this table is the average percent of area receiving 15% or greater soil density increase over that of the undisturbed condition by soil rockiness class, and the overall percent weighted area extent of each unit area receiving 15% or greater density increase from all data when both the non-rocky and rocky classes (if applicable) are combined. As the data show, eight harvest units did not meet the regional soil quality standard for compaction and area extent of impact (Table 1).

Soil Rockiness

Non-rocky soils compacted more, and with less effort, than the rocky soils. Nearly all units containing the rocky soils showed lower bulk density levels and smaller areas of excessive compaction relative to their non-rocky counterparts (Table 1). Of the 16 units that contained only or mostly non-rocky soil (see Table 1), eight exceeded the proposed compaction threshold. In contrast, none of the four units in which half or more of the area was made up of the rocky soils (shaded in Table 1) exceeded this threshold.

When data from these individual units are compared a clearer picture emerges. Figure 1 and Table 2A compare the mean bulk density and percent compaction of all the non-rocky soils to that of the rocky soils by disturbance level. Both the rocky soils and the non-rocky soils show significantly different mean bulk densities at all levels of disturbance, including old disturbance vs. their undisturbed levels. The data also show that rocky soils have significantly lower mean bulk densities than non-rocky soils on primary and secondary skid trails and areas receiving 1-2 equipment passes.

Mean bulk density change for the non-rocky soils, as compared to undisturbed areas, was about 22% on the landings and native surface roads, 19% on the primary trails, 13% on secondary trails, 7% on areas receiving 1-2 passes, and 9% from old disturbance areas. Analysis shows these densities to be different from the natural level at the 95% or greater confidence level. In contrast, the rocky soils show bulk density to be about 19% greater than natural levels on log decks and native surface roads. On primary skid trails, secondary skid trails and areas receiving 1-2 equipment passes this drops to about 10%, 8% and 5%, respectively. The old disturbance averaged about 7% above natural levels for rocky soils. Based on these data, the rocky soils appear to be 30-50% less compactable than the non-rocky soils for primary and secondary skid trails, and areas receiving from 1-2 equipment passes.

Total depth of the compacted soil layer was related to the level of disturbance and rock content of the soil.

Table 1. Comparison of mean bulk density (in g/cm³) by disturbance level, percent of area receiving greater than 15% increase by soil rockiness group, and percent overall weighted area exceeding the compaction standard of 15% change in bulk density. Shading indicates units where rocky soils predominate.

				Bulk Density Measurements[4] (g/cm³)						Change in Treatment Area (%)	
Unit ID	Surface texture	Season of operation	Soil rockiness	Undisturbed density	Old disturbance	1 to 2 passes	Secondary skidtrail	Primary skidtrail	Log deck/ temp. road	>15% change in density by class	>15% change in density, total area
1	fsl[1]	moist	non-rocky[3]	1.36a	1.45b		1.47b	1.57c		9	
			rocky	1.36a	1.43b	1.43b	1.41	1.45c		0	4
2	fsl	moist	non-rocky	1.38a	1.41a	1.51b	1.58	1.77c		22	22
3	fsl	dry*[2]	non-rocky	1.35a	1.45b		1.49c	1.52c		2	2
4	fsl	dry*	non-rocky	1.38a	1.44ab		1.47b			0	0
5[5]	fsl	moist	non-rocky	1.37a	1.48c	1.44b	1.50c	1.51c	1.49c	7	7
6	l	dry	non-rocky	1.28a	1.44	1.33b	1.40	1.51c	1.47c	13	
			rocky	1.28a		1.26a	1.33	1.45b		11	13
7	sil	moist	non-rocky	1.33a	1.39a	1.47b	1.50	1.58c		22	
			rocky	1.33a			1.40	1.52b		22	22
8	sil	dry*	non-rocky	1.32a	1.42b	1.41b	1.49c	1.48c	1.61d	6	6
9	l	dry	rocky	1.32a	1.40	1.37b	1.42	1.43bc	1.49c	9	9
10	sil	moist	rocky	1.31a	1.35ab	1.38b	1.44c		1.44c	8	8
11	sil	moist	non-rocky	1.34a	1.41ab	1.41ab	1.42	1.64c		14	
			rocky	1.34a			1.48b	1.41ab		8	11
12	sil	moist	non-rocky	1.34a	1.45b	1.43b	1.52	1.60d	1.65d	24	24
13	sil	moist	non-rocky	1.31a	1.37b	1.43c	1.48		1.55d	24	24
14	l	moist	non-rocky	1.31a	1.40b	1.40b	1.53c	1.55c		32	
			rocky	1.31a	1.30a		1.49			14	30
15	sil	dry	non-rocky	1.31a	1.47	1.4	1.53	1.54		26	
			rocky	1.31a		1.42b	1.47			7	16
16	sil	moist	non-rocky	1.28a	1.40b		1.37b			2	2
17	l	moist	non-rocky	1.30a	1.42	1.39b	1.47			11	
			rocky	1.30a	1.42	1.38b	1.44	1.46c	1.66d	17	13
18	fsl	moist	non-rocky	1.31a	1.45b	1.40b	1.54	1.62c	1.69d	28	28
19	fsl	dry	non-rocky	1.34a	1.45b		1.41b	1.53c		8	8
20	fsl	moist	non-rocky	1.34a	1.50b	1.49b	1.56bc	1.62c	1.74d	40	40

(Shaded on the page: units 1, 9, 10 and 17.)

[1] fsl = fine sandy loam; l = loam; sil = silt loam

[2] * indicates that unit was initially operated on when the soil was too wet, and logging operations were temporarily suspended until conditions improved.

[3] Non-rocky = 0-15% by volume gravel in surface 20 cm (8 inches); rocky = 15-35% by volume gravel in surface 20 cm.

[4] Bulk densities followed by different letters are significantly different at $P > 0.05$. Bulk densities without a letter had too few samples for statistical analysis

[5] This unit was logged using a team of mules instead of a rubber tire skidder.

Table 2. Mean bulk density values (in g/cm³) and significance for four levels of recent disturbance plus old disturbance as measured against undisturbed bulk density.

A. Comparison of non-rocky (0-15% gravel) soils to rocky (15-35% gravel) soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
non-rocky soil	1.32	1.41	1.49	1.57	1.61	1.44
rocky soil	1.32	1.38	1.43	1.45	1.57	1.42
signif. by soil rockiness:	ns	*	***	***	ns	ns
signif. by disturbance level:	a	b	d	e	f	c

B. Comparison of dry vs. moist season logging on non-rocky soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.32	1.38	1.47	1.51	1.55	1.45
moist season	1.33	1.43	1.5	1.6	1.67	1.44
significance by season of ops:	ns	**	**	***	***	ns
significance by disturbance level:	a	b	d	e	f	c

C. Comparison of dry vs. moist season logging on rocky soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.31	1.37	1.42	1.44	1.49	1.41
moist season	1.32	1.39	1.44	1.46	1.61	1.42
significance by season of ops:	ns	ns	ns	ns	*	ns
significance by disturbance level:	a	b	c	c	d	bc

D. Comparison of non-rocky sandy loam vs. non-rocky loam or silt loam soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
sandy loam	1.35	1.46	1.51	1.64	1.72	1.45
loam/silt loam	1.31	1.38	1.48	1.54	1.56	1.44
significance by soil texture:	ns	**	ns	**	**	ns
significance by disturbance level:	a	b	d	e	f	c

E. Comparison of dry vs. moist season logging on non-rocky loam or silt loam soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.30	1.36	1.45	1.51	1.55	1.43
moist season	1.32	1.40	1.49	1.55	1.59	1.44
significance by season of ops:	ns	*	**	*	ns	ns
significance by disturbance level:	a	b	d	e	e	c

F. Comparison of dry vs. moist season of logging on non-rocky sandy loam soils.

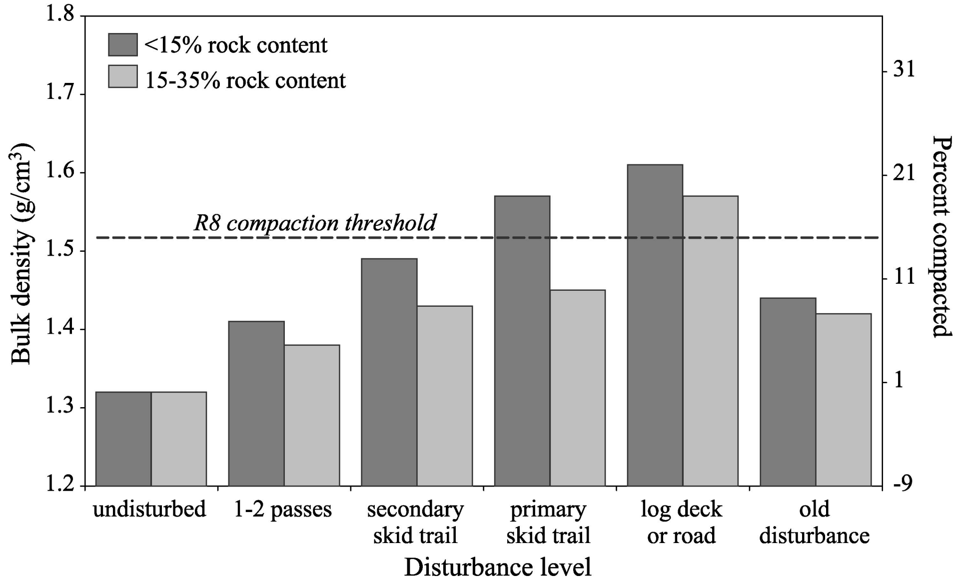
	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.36	1.46	1.49	1.52	no data	1.45
moist season	1.34	1.46	1.53	1.65	1.72	1.45
significance by season of ops:	ns	ns	**	*		ns
significance by disturbance level:	a	bc	c	d	e	b

G. Comparison of dry vs. moist season of logging on rocky loam or silt loam soils.

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.31	1.37	1.42	1.44	1.49	1.41
moist season	1.33	1.41	1.47	1.47	1.47	1.37
significance by season of ops:	ns	ns	ns	ns	ns	ns
significance by disturbance level:	a	b	c	c	cd	b

ns not significant
* significant at P > 0.05
** significant at P > 0.01
*** significant at P > 0.001
different letters following disturbance levels are significantly different at P>0.05.

Figure 1. Comparison of mean bulk density of non-rocky and rocky soils.



From visual observation only the first few inches tended to be compacted where 1-2 passes had been made. On primary skid trails, log decks and native surface roads this compacted layer would typically include the entire 20 cm (8 inches) of soil examined. The rocky soils tended to display a less prominent visual degree and depth of impact as compared to the non-rocky soils for the same levels of disturbance.

Season of Equipment Operation

Twelve of the 20 harvest units monitored were logged during the moist season (December-June), and eight during the dry season (July-November). Of the eight units in Table 1 exceeding the proposed compaction standard, seven were yarded during the moist season. Only one of the eight units harvested during the dry season (unit 15) did not meet the standard.

A review of Figures 2 and 3, and Tables 2B and 2C, shows that the non-rocky soils compact more than rocky soils and season of logging operation significantly affects bulk density on the non-rocky soils, but not for the rocky soils. Moist season logging operation proved to be significant for all recent levels of disturbance for the non-rocky soils, but was not significant at any level of disturbance for the rocky soils. Figure 2 shows mean bulk density for all non-rocky soils data (excluding areas where mule logging was used) by dry or moist logging operating season. This figure clearly indicates that moist season equipment operation results in the greatest change in bulk density. These analyses show changes in mean bulk density to be 20-50% smaller on the non-rocky soils on primary and secondary skid trails, and areas receiving 1-2 passes, when logging operations were conducted during the dry season. On the rocky soils, equipment operation performed during the dry season vs. the moist season showed only a slight and insignificant change in mean bulk density by disturbance levels.

Unit 5 (Table 1) was the only unit harvested not using conventional rubber tire skidders. This unit was logged using a team of mules. The log deck and native surface haul road were driven on by a 2-axle haul truck with a mounted log loader. This unit was one of the five non-rocky soil units harvested during the moist season that met the proposed soil quality standards for compaction. In fact, of the 7% area extent not meeting the compaction standard, more than half was due to old disturbance compaction caused from a previous entry or entries.

The most serious degree and extent of compaction were found on the non-rocky soil units that were harvested when these soils were very moist but not saturated. Examples of this situation were experienced with units 2, 14 and 18 (Table 1). Soil moisture conditions on these units were known to be very moist from personal field observation at the time of equipment operations. Similarly, on units 3, 4, and 8, where harvest activities were first commenced and then halted during very moist soil conditions (near saturated soil moisture) and later completed during the dry season, compaction did not show up as a serious problem. Instead, soil puddling or displacement became the major concern where deep tire tracks had been made earlier when the soils were too moist.

Units 10 and 13 (Table 1) were also harvested during very moist soil conditions. On these units no primary skid trails were present, as the tractor operator would often change trail routes in order to prevent further deep tire

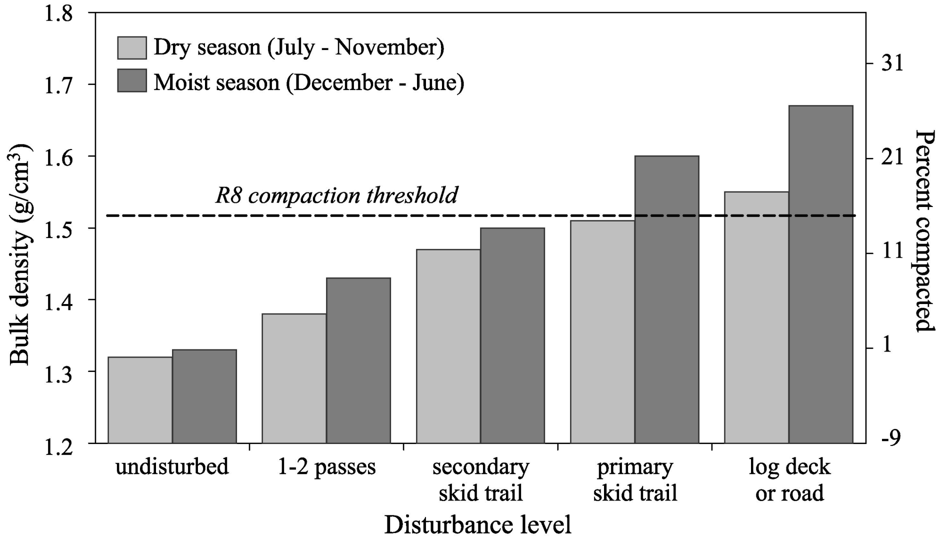


Figure 2. Comparison of mean bulk density of non-rocky soils by season of equipment operation.

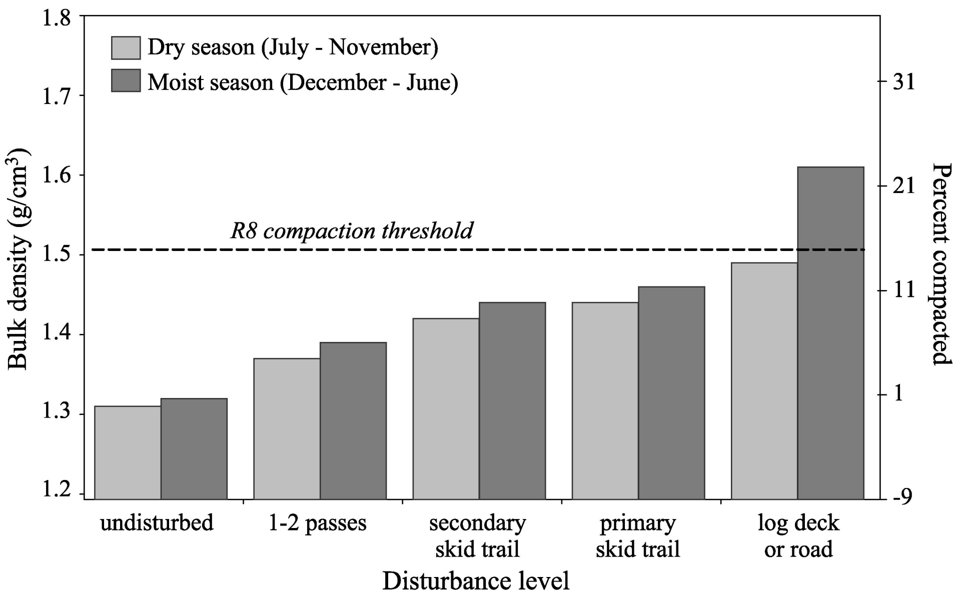


Figure 3. Comparison of mean bulk density of rocky soils by season of equipment operation.

tracks or other obvious damage to the soil resource. This highly dispersed equipment logging practice resulted in a greater area of impacts from the equipment. For unit 13, which contained non-rocky soil, 24% of the area received greater than 15% compaction. Unit 10, a rocky soil, faired much better. Only 8% of the unit area was greater than 15% compacted.

Soil Texture

Changes in surface texture on non-rocky soils affected the degree of compaction (Table 2D). The sandy loam textured soils suffered greater changes in density levels than the loam or silt loam textured soils at all four recent disturbance levels. Analysis shows density changes due to texture are significant for log decks and native surface roads, primary trails, and areas receiving 1-2 equipment passes.

When logging equipment operating season is also considered, the non-rocky loam and silt loam soils, and the non-rocky sandy loam soils, continue to show significant differences in bulk density both by disturbance level and season of operation (Table 2E and F). Moist season logging resulted in significant increases in compaction on primary and secondary skid trails from both textural groups. In addition, there was a significant density increase for 1-2 pass equipment operation for the loam and silt loam soils during moist season operation.

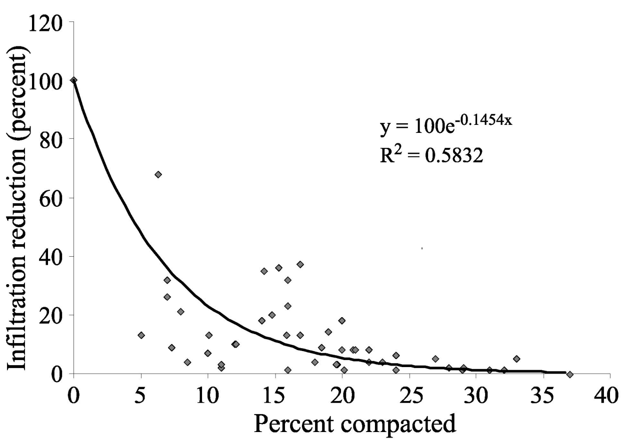
Analysis of all data found the percentage of samples exceeding the 15% compaction standard on loam and silt loam soils by dry season vs. moist season equipment operation to be 0% vs. 2% for 1-2 pass areas, 30% vs. 42%

for secondary trails, and 52% vs. 71% for primary trails, respectively. For the sandy loam soils, the numbers were 0% vs. 10% for 1-2 pass areas, 8% vs. 36% for secondary trails, and 33% vs. 82% for primary trails when logged during the dry vs. moist season, respectively. These data indicate that the sandy loam soils tend to compact less than the loam and silt loam soils during dry season equipment operation, but more during moist season operation. For the rocky soils with loam and silt loam surface textures our data indicated no significant differences by disturbance level between dry vs. moist season equipment operation (Table 2G).

Surface Infiltration

Surface infiltration measurements were performed on both undisturbed sites and selected disturbed sites within units 6, 8, 12, 14, 18 and 20 to determine the relative change in infiltration as a result of density change (Figure 4). Over 50 measurements were recorded from soils with density changes ranging from 5% to greater than 30% relative to the undisturbed density levels. This study found infiltration rates had been significantly reduced. Surface infiltration rates have dropped by over 60% from the undisturbed levels when density levels had increased by 15 percent or more (Figure 4).

Figure 4. Reduced surface infiltration caused by compaction.

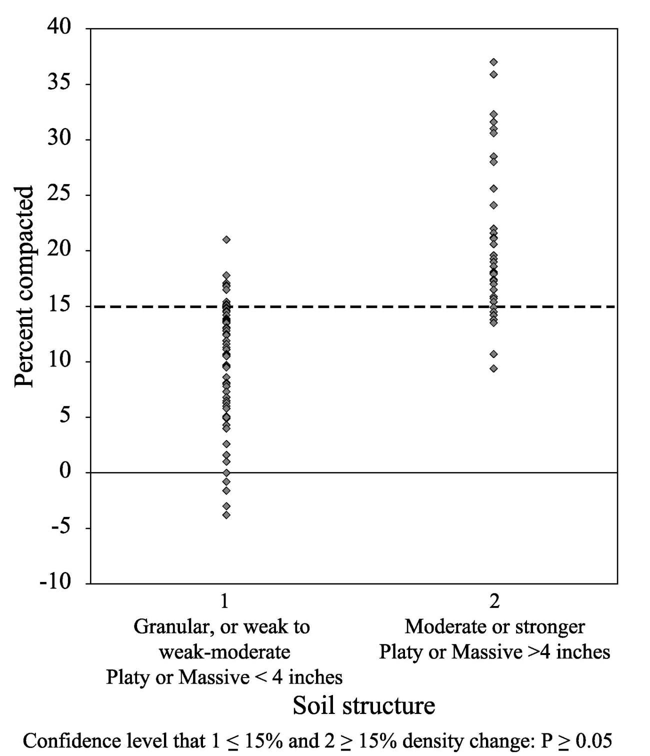


Soil Structure Change vs. 15% Compaction

Physical changes in soil structure were examined, including degree and depth of structural change, to determine if structure could be used to identify a 15% change in soil density. Soil structure had briefly been examined during data collection at all sites, but was more intensely examined on 113 sites during later follow-up work. These follow-up sites included both rocky and non-rocky soils and soils with sandy loam, loam or silt loam textures. On these harvest units the surface soils, in an undisturbed condition were granular in structure, and typically identified as a moderate medium granular structure (USDA NRCS 2002). Those surface soils in a strongly compacted condition (25% density change or greater) nearly always contained a moderate or strong platy structure which typically included the entire 20-cm (8-inch) depth being analyzed.

To determine whether the soil exceeded the Region 8 compaction threshold (15% density increase over the undisturbed level) required more detailed observation of structure. Those soils with a 5-15% density change typically contained a weak or weak-moderate (an inter-grade between weak and moderate) platy or massive structure that was less than 10 cm (4 inches) in total thickness beginning at the surface. In contrast, those soils with a 15-25% density change typically contained a moderate or moderate-strong (an inter-grade between moderate and strong) platy or massive structure that was greater than 10 cm (4 inches) in total thickness (Figure 5). This structure and affected depth combination resulted in a 95% probability of correctly determining whether the soil had either greater than, or less than, a 15% density change. Neither soil rockiness nor soil texture altered this structure or depth combination in relation to change in compaction.

Figure 5. Use of soil structure to determine 15 percent change in bulk density (Region 8 compaction threshold).



DISCUSSION

We found soil compaction to be a serious concern on some soils on the Ouachita National Forest, especially when silvicultural harvest operations using conventional rubber tire skidder logging equipment are conducted during the moist season, when antecedent soil moisture levels are high. Other studies have also found that moisture condition of the soil itself at the time of heavy equipment operation is the most important precursor to compaction (Day and Holmgren 1952; Froelich et al. 1980; Hatchell et al. 1970). Day and Holmgren (1952) using three different levels of compactive force, found the soil to be 2.4 to 3.0 times more compacted when these forces were applied to moist soil vs. dry soil. Our study comparing moist vs. dry season logging did not show as large a difference. This is probably due to the fact that antecedent soil moisture conditions fluctuate during both moist season and dry season. They tend, however, to remain generally wetter during the moist season and drier during the dry season.

Results from individual units in our study known to have very moist soils during equipment operation (units 2, 13, 14, and 18) indicate that the soils in these units were up to twice as compacted as similar dry units. These very moist soil units would be more in line with Day and Holmgren's (1952) findings above. During very moist soil conditions, equipment logging operations also tended to become more and more dispersed. This is typically done with the good intention of desiring to avoid unnecessary or severe impacts to the soil. This dispersal practice, however, has not worked well to reduce equipment impacts, particularly on non-rocky soils which are most susceptible to compaction, as demonstrated in unit 13 of our study.

Our study found that, for non-rocky soils during moist season equipment logging, a secondary skid trail exhibited about the same degree of change in bulk density as a primary skid trail did on the same soil during dry season logging (Table 3). Both of these mean bulk density changes (14%) are close to exceeding the compaction standard of 15%. Similarly, primary skid trails, log decks and temporary roads were about 50% more compacted during moist season equipment logging vs. dry season logging (Table 3). These findings are in line with those of Hatchell et al. (1970), who concluded that one equipment pass under moist soil conditions was equivalent to four equipment passes under dry soil conditions. The 20-50% decrease in mean density levels from dry season logging (relative to the moist season) found on our non-rocky soils indicates that managing the season of heavy equipment use can be an effective way to help minimize compaction on a forest wide scale.

Our results indicate that soil bulk density increases somewhat proportionately to increasing levels of disturbance. Figures 1-3 show a stair-step pattern of mean

Table 3. Change in mean bulk density (g/cm³) and percent compaction by disturbance level, by soil rockiness group and season of equipment operation.

Soil Rockiness Group	Dry Season Equipment Operation	Percent Increase in Bulk Density (% compacted)	Moist Season Equipment Operation	Percent Increase in Bulk Density (% compacted)
0-15% gravel rock soils "Non-Rocky"				
Natural (undisturbed)	1.32		1.32	
1-2 passes	1.38	5	1.42	8
Secondary trail	1.47	11	1.50	14
Primary trail	1.51	14	1.60	21
Log deck/road	1.55	17	1.67	27
Old disturbance	1.45	10	1.44	9
15-35% gravel rock soils "Rocky"				
Natural (undisturbed)	1.32		1.32	
1-2 passes	1.37	4	1.39	5
Secondary trail	1.42	8	1.44	9
Primary trail	1.44	9	1.46	11
Log deck/road	1.49	13	1.60	21
Old disturbance	1.41	7	1.42	8

density levels from the natural (undisturbed) levels to the greatest change at the log deck/native surface road disturbance level. On non-rocky soils, mean soil density increased from 5% at 1-2 passes, to 11% on secondary skid trails, and 14% on primary trails under dry season operations, versus 8%, 14% and 21% for these same disturbance levels, respectively, during moist season equipment operations (Table 3). This compares closely with Hatchell's (1970) findings where they found compaction to be twice as great on primary skid trails as on secondary trails on nine treatment units in South Carolina and Virginia.

When considering the use of rubber tire skidders in logging operations, for non-rocky soils we can expect log decks, native surface roads, and primary skid trails to be excessively compacted under most antecedent soil moisture conditions. Under moist soil conditions, however, secondary skid trails may similarly be excessively compacted. As Stokes et al. (1997) have shown from their study on area extent in primary and secondary skid trails for typical silvicultural systems on the Ouachita National Forest, operating logging equipment during dry soil conditions can make the difference if a unit passes or fails the Region 8 soil quality standard for compaction for harvest units having non-rocky surface soils.

We found that surface soils containing between 15-35 percent by volume of gravel rock content resulted in 30-50 percent less density change than soils containing from 0-15 percent by volume gravel rock. These results are in line with an unpublished independent follow-up study by Barkhimer (2000). Barkhimer used a modified Proctor Test to compare two levels of gravel rock content on loam and sandy loam soils collected from the Ouachita National Forest. He found that between antecedent soil moisture levels of permanent wilting point and field capacity, the soils were 0-20% less compactable when 15% by volume gravel rock was added, and 40% to more than 100% less compactable when 35% by volume gravel rock was added to these soils.

For rocky soils, our study found no significant differences between dry season vs. moist season equipment logging (Table 2). Neither season of equipment operation nor soil texture played a significant roll in soil compaction on rocky soils. Mean density levels exceeded the 15% compaction standard only on log decks and temporary roads during moist season logging operations (Table 3). Primary skid trails tended to exceed the compaction standard only under very moist soil conditions. Generally, however, the area extent of soil compaction itself did not exceed the soil quality standard. Other than for very moist soil conditions and high traffic areas such as log decks and temporary roads, the 15-35% rock content of these soils tended to be effective in buffering against excessive compaction. By extrapolating these results to soils containing greater than 35% rock content we would expect even less compaction to occur.

Old disturbance sites exhibiting compaction did not reflect the same lower dry season/higher moist season density fluctuation we typically found with current levels of disturbance (Tables 2 and 3). This is because season of equipment operation during prior entries could not be determined, as these records have long since been discarded. The result is that there is an equal chance this old disturbance could have occurred during either period. We would therefore expect to find little or no change in mean bulk density due to the current season of operation, as was typically the case. Average percent compaction found on old disturbance areas was about 9-10% for the non-rocky soils compared to about 7-8% for the rocky soils (Table 3). This represents an approximate 20% reduction in bulk density change on rocky soils as compared to that found on the non-rocky soils. Although this 20% change did not prove to be significant (Table 2), it is to be expected and supports the above findings that rocky soils are less compactable than non-rocky soils.

Surface infiltration was studied to determine what effect compaction might have on soil infiltration rates on this Forest. This work indicated that a relatively small increase in soil density caused by compactive forces will result in a large decrease in infiltration rate. Surface infiltration drops rapidly from undisturbed soil density levels to almost no infiltration as soil density increased to 25% or greater (Figure 4). This can have a negative impact on both soil productivity and the watershed's natural hydrologic functioning. A reduced infiltration rate can result in less water entering the soil profile for future plant uptake and growth. In addition, water not entering the soil adds to overland runoff, resulting in increased on-site erosion, channel destabilization and downstream flooding.

Our study found some evidence that old disturbance areas have partially self-mitigated since the previous harvest entry. The old disturbance compaction we observed in this study was caused from harvest equipment activities that occurred at least 15-20 years earlier. Old disturbance areas are composed of secondary or primary skid trails and areas that received 1-2 equipment passes. Temporary roads and log decks are not included in old disturbance level findings from this study, as these areas were reused again during the recent entry.

The amount of natural soil bulk density mitigation since the last disturbance can be estimated by comparing the average density change from the three current disturbance mean density levels of the primary and secondary skid trail densities and areas receiving 1-2 passes, to the old disturbance density level. By multiplying this difference by a 15-20 year recovery period, and relating this back to the current old disturbance density level, we estimate it would take from 50-80 years for skid trail soil density levels to recover to near natural density levels. This estimated recovery period is in line with other findings. Perry (1964) estimated a 40-year recovery period for reduced infiltration rates on old compacted woods roads to approach natural rates on a southern Arkansas soil. In the Pacific Northwest, it has been suggested that it would take 100 years or more for compacted areas to recover to near natural density levels (Froelich et al. 1980).

Our study also examined changes in soil structure vs. degree of compaction. Altered soil structure, as a result of compaction, has commonly been used to help determine when a soil has, or has not, exceeded a given compaction standard. Altered soil structure is visible in both degree and extent when examined with a spade. Our intent was to calibrate this structural change, degree and extent with soils on the Ouachita National Forest to equate to a 15% soil density change (our Region 8 soil compaction standard).

This study determined that there is a 95% probability that Ouachita National Forest soils exhibiting a moderate or stronger platy or massive structure, with a total affected depth of 10 cm (4 inches) or greater, equates to a 15% or greater density change. Conversely, those soils exhibiting a granular structure, or, a weak, or weak-moderate (intergrade between weak and moderate) platy or massive structure, with a total effected depth of less than 10 cm (4 inches), equates to less than 15% density change (Figure 5). This structural change information can be used as an indicator in future monitoring efforts in determining whether our forest land management practices meet the Region 8 soil quality standard for compaction.

Conclusion

Soil compaction has been shown to result in a rapid loss of surface infiltration. Compaction has been found to be a concern on the Ouachita National Forest on non-rocky soils where conventional harvest equipment logging occurs during moist antecedent soil conditions. Compaction can be minimized on non-rocky soils by logging during dry soil conditions. On rocky soils, logging during moist soil conditions is not as great a concern, as the soil rock content acts as a buffer to compaction. We have also shown that the Region 8 soil quality compaction standard of 15% density change can be detected visually by noting change in soil structure.

References

Barkhimer, JC. 2000. A study on the combined effects of rocks and moisture on soil bulk density. Honors program thesis. Monticello, AR: School of Forestry, University of Arkansas at Monticello. 15p. unpublished.

Day, PR, and GG Holmgren. 1952. Microscopic changes in soil structure during compression. *Soil Science Society of America Proceedings* 16(1): 73-77.

Froelich, HA, J Azevedo, P Cafferata, and D Lysne. 1980. Predicting soil compaction on forested land. Final project report to U.S. Forest Service Pacific Northwest Forest and Range Experiment Station and Missoula Equipment Development Center. Coop. Agreement #228. 120 p. Available from the USDA Forest Service PNW Research Station, 333 SW 1st Avenue, Portland, OR 97205.

Hatchell, GE, CW Ralston, and RR Foil. 1970. Soil disturbance in logging. *Journal of Forestry* 68: 772-775.

Kluender, RA, DA Lortz, and BJ Stokes. 1994. Production time, total costs, and residual damage at varying harvest intensities. In JB Baker, ed., Ecosystem management research in the Ouachita Mountains: Pre-treatment conditions and preliminary findings, Gen. Tech. Rep. SO-112. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station: 229-240.

Perry, TO. 1964. Soil compaction and loblolly pine growth. *USDA Forest Service Tree Planters Notes* 67. 9 p.

SAS Institute, Inc. 1989. SAS/STAT user's guide, version 6, fourth edition, volume 2. Cary, NC: SAS Institute, Inc. 846 p.

Stokes, BJ, RA Kluender, JF Klepac, DA Lortz. 1997. Harvesting impacts as a function of removal intensity. In: BJ Stokes, R Lauhanen, J Klepac, comps. Forest operations and environmental protection: Proceedings of a symposium organized by IUFRO Proj. Group P3.11.00 at the IUFRO World Congress; 1995 Aug. 6-12; Tampere, FI.. Auburn, AL: U.S. Dept. of Agriculture, Forest Service, Southern Research Station: 207-216.

Turton, DJ, LD Clendenen, WP Fowler, JL Michael. 1997. Effects of silvicultural operations on the bulk density of stony soils in the Ouachita Mountains. Oxford, MS: USDA Forest Service, Southern Forest & Experiment Station, Research Work Unit 4153; Final Report; Coop Agreement FS-SO-19-92-096. 17 p. Available from USDA Forest Service, Southern Research Station, Forest Hydrology Laboratory, 1000 Front Street, Oxford, MS.

USDA Forest Service. 2003. FSH 2509.18. Soil management handbook, Ch. 2. Soil quality monitoring. R8-2509-18-2003-1. 6 p. Available at *http://fsweb.r8.fs.fed.us/fsrecords/directives/fsh/2509.18/2509.18,2.doc*

USDA Natural Resources Conservation Service [USDA NRCS]. 2002. Field book for describing and sampling soils. Version 2.0. Lincoln, NE :National Soil Survey Center : 2-41 to 2-48. Available online at *http://soils.usda.gov/technical/fieldbook/*