

SOIL COMPACTION EFFECTS OF FORWARDING AND ITS RELATIONSHIP WITH 6- AND 8-WHEEL DRIVE MACHINES

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A B S T R A C T

A study was done to determine the impact, if any, of a range of drive train options on the soil compaction effects of forwarders. The purpose of the study was to evaluate the cost of optional forwarder equipment versus its ability to reduce detrimental soil physical property changes. Tests were done on forwarders equipped with wide and narrow tires, rear steel tracks, and 6 or 8 tires. The configurations differed, at the extremes, by a factor of about 2 in expected ground pressure. Despite that, results showed little difference in bulk density, soil strength, rut formation, or porosity changes (**pre-** vs. **post-traffic**) between any of the tested options. The implication was that, for the moisture conditions encountered in the study, the use of the tested options did not alter soil compaction impacts substantially. A drop in macroporosity was observed, however, which may have been evidence that traffic affected soil structure without compacting it by a detectable amount.

Impacts to soils resulting from heavy equipment operation within forested ecosystems are of great concern to timber managers. Research has documented changes in site characteristics associated with operating harvest machinery on soils, including infiltration and erosion potential (3,7), hydrologic factors (1,2), and tree growth (11,15,20).

Soil compaction is another site impact associated with forest harvesting that, in the case of tree-length equipment systems, has been studied extensively (5,6,9). The conventional ground-based harvesting machinery systems used in the Southeast typically include **feller-bunchers**, grapple skidders, and mechanical processors. Using these harvesting machines for thinning sometimes results in residual stem and root damage with additional soil compaction, rutting, and nutrient relocation on the site (14). Soil moisture at the time of trafficking has a major influence on reduction and redistribution of pore space as soils are compacted. Dry soils are more resistant

to changes in pore size distribution and this resistance is reduced as soil moisture increases (4). If soil moisture increases, the resistance to compaction decreases until the **lower** plastic limit is reached and maximum compaction occurs. Above the lower plastic limit, near the saturation point for a given type of soil, moisture increases result in a density reduction, perhaps causing destruction of soil **structure** (17,19).

Impacts of cut-to-length (CTL) systems in thinnings, however, have not been as well documented, especially in southern U.S. conditions. Studies have

shown some advantage for CTL systems in reducing soil impacts (10,21), but the influence of specific equipment design factors on compaction have not been documented. For example, sales literature for forwarders often lists estimated ground pressure for various configurations, with machines equipped with wide tires or tracks showing distinct advantages over the standard option. It is difficult to predict, however, to what extent this change in ground pressure will influence compaction on a given site.

Managers and equipment operators, therefore, do not have all the relevant information to make informed decisions regarding the effects of CTL equipment on soils. The lack of data means choices made regarding tire size and equipment configuration are **often** based on incorrect assumptions, leading to expense or soil impacts that are potentially greater than necessary. The objective of this study was to investigate some of the factors that can control the level of impacts associated with **CTL** harvesting systems on soils in a given set of conditions.

Other than timing of operations, there are relatively few alternatives available to managers that influence the level of potential impacts. These options are mainly related to how the machine is configured

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TABLE 1. — Soil characteristics for the test sites.

Experiment	Soil series	Site index	Depth	Organic matter	Texture		
					Sand	Silt	Clay
6/8 Wheel + Wide/Narrow Tires Reps 1,2	Bayboro	74	(25-yr basis)	(% by weight)	----- (%) -----		
			0 to 5	16.4	49	30	21
			15 to 20	6.1			
6/8 Wheel + Wide/Narrow Tires Reps 3,4	Leaf	74	0 to 5	12.3	60	24	16
			15 to 20	3.6			
			30 to 35	1.9			
Tracks, All Reps	Leaf	72	0 to 5		45	34	21

with respect to its drive train, including number of axles/bogies or tire size. These were the main factors investigated in this study. Specific objectives were to: a) compare the impacts of 6-wheel (rear bogie) and 8-wheel forwarders (front and rear bogie) in the same soil conditions; b) measure the effect of standard and wide tires; and c) compare the impacts associated with wide tires and steel tracks.

METHODOLOGY

STUDY SITE CHARACTERIZATION

The study was done in three phases corresponding to the three objectives. The experimental designs for testing each objective varied only in number of replicates, the treatment applied, and plot location. Location of the study plots varied with the treatment, with comparisons of 6- and 8-wheeled machines and wide and narrow tires at one site, and tracks and wide tires at another site approximately 5 km away. The change in location was made to take advantage of higher moisture contents (MCs).

The study sites were located in Beaufort County, N.C., in a large area of pine plantations owned by Weyerhaeuser Corp. Terrain in this area is nearly flat and is subject to periodic flooding and high water tables. The study sites were installed in bedded stands approximately 25 years old. Stands had been phosphate fertilized at establishment, and a water management system was used to regulate the water table to some extent. They had been thinned at about age 17 (fifth row removal with selection between rows).

TREATMENTS

A randomized complete block design was used for all experiments. Experimental plots for all treatments were established in the fifth row corridors and were set up in a consistent fashion for all tests, with a few exceptions. Each was about 1.5 m long by 5 m wide and was

TABLE 2. — Equipment used in the comparison of 6- and 8-wheeled forwarders.

Machine	Total weight	Tires	
		Front	Rear
	(t)		
Timberjack 910 6WD	20.5	700/55-34.00	48 x 31.00-20
Rottne Rapid 8WD	22.4	600/55-26.5	48 x 31.00-20

cleared of slash and surface litter. Plots ran lengthwise parallel to adjacent rows of trees, with the center of the plot situated along the center of the previously removed row. Because the stand had been bedded, the midline of the plot was its highest point, with wheel tracks evident from the previous thinning on either side.

Soil measurements. — Measurements consisted of bulk density and cone penetrometer samples taken at each of five transects spaced at 2-m intervals along the length of the plot. Surface profiles were measured at three additional transects using the methods reported in a study by McDonald et al. (12).

Bulk density samples were extracted using a slide-hammer method at 2 or 3 depths, depending on the experiment. Cores were oven-dried for 72 hours at 105°C to determine MC and dry weight. Soil strength was measured using a cone penetrometer, with a 1-cm tip diameter. Readings were taken at either 15- (Rimik CP20) or 35- (Bush Recording Penetrometer) mm intervals to a depth of about 50 cm.

Post-treatment sampling of bulk density and soil strength was identical to pre-treatment except for sampling location. Post-treatment measurement transects were offset by about 1 m from the pre-treatment locations. Bulk density cores were removed from the traffic rut centerline, and cone resistance measurements were made across the width of the

tire, four penetrations per transect/rut combination (a total of 40 measurements per plot). Saturated hydraulic conductivity was evaluated using a falling head method (8) and macropore space was evaluated using pressure plates (18).

6- and 8-wheeled forwarders. — Tests to measure the difference in compaction between 6- and 8-wheeled forwarders were run in November of 1994. Four replicates of the two machinery treatments were installed in two distinct areas about 0.5 km apart within a single stand. The areas had similar soil types, with the first having Bayboro series soils (clayey, mixed, thermic Umbric Paleaquult), and the second Leaf series (clayey, mixed thermic Typic Albaquult). Organic matter by depth and soil texture at a 12.5-cm depth are shown in Table 1. Each area had two blocks, and each block consisted of two treatment plots installed in either the same or adjacent fifth row corridors. Plots within the same fifth row were separated by about 5 m.

Equipment used in the test is summarized in Table 2. The two forwarders were run across the plots six times at about 3.5 km per hour, these values were chosen to be representative of operational conditions. The same load of logs was used on both forwarders. The wider (48 x 31.00-20) tires were normally used on the 6-wheeled forwarder but were temporarily mounted on the 8-wheeled machine (normally running 700/55-

TABLE 3 — Equipment used in the comparison of wide and narrow tires.

Machine	Loaded weight		Tires	
	Front	Rear	Front	Rear
	----- (t) -----			
Timberjack 910	5 62	1562	700/55-34.00	600/55-26.5 (narrow)
	5 62	15 51	700/55-34.00	48 x 31.00-20 (wide)

TABLE 4. — Summary of equipment used in the comparison of wide tires and tracks.

Machine	Loaded vehicle weight	Tires
	(kg)	
Timberjack 910 6WD	6,850 F	700/55-34.00 F
	11,230 R	48 x 31.00-20 R (wide)
Rottne SMV Rapid 6WD	7,340 F	700/70-34 F
	14,640 R	54 x 37.00-25 R (wide)
Rottne Rapid 8WD	5,200 F	600/55-26.5 F
	14,870 R	600/55-26.5 R (wide)

w/Olofsfors EcoMagnum Tracks

TABLE 5. — Pre- and post-treatment bulk density and size of ruts following traffic with a 6- and 8-wheeled forwarder.

Machine	Depth	Bulk density		Moisture	Rut size	
		Pre	Post		Depth	Area
	(cm)			(%)	(cm)	(cm ²)
Timberjack 910	5 to 10	0.99	1.02	31.1	2.38	510.5
- 6WD	15 to 20	1.54	1.62	17.5		
	30 to 35	1.68	1.66	18.1		
Rottne Rapid	5 to 10	0.96	0.91	34.4	2.83	566.2
8WD	15 to 20	1.51	1.49	20.5		
	30 to 35					

26.5) to remove any effect of rear tire size.

Bulk density samples were taken at three depths: 5 to 10, 15 to 20, and 30 to 35 cm. The Bush Recording cone penetrometer was used for soil strength measurements, providing averaged force readings over a 35-mm interval to a depth of 50 cm.

Rear tire width. — Tests of tire width effects were made during September 1995. Equipment used is summarized in Table 3. The site and experimental procedures were identical to that for the 6- and 8-wheel tests, with a few exceptions. Moisture content of the soil was somewhat higher than in the wheel number experiments because of rain immediately prior to the test. A Rimik CP20 cone penetrometer was used in place of the Bush, providing averaged pressure readings at 15-mm intervals to a depth of 40 cm. Bulk density samples were taken at 2 depths: 5 to 10 and 15 to 20 cm. Additional soil cores were taken for measure-

ment of changes in saturated hydraulic conductivity and macropore space as a function of tire treatment.

Wide tires and tracks. — Three forwarders, each with a different capacity and drive configuration, were tested for changes in post-traffic soil bulk density, rut formation, and soil strength (Table 4). Two forwarders were equipped with wide tires, one with tracks. All machines were loaded with the same logs. The experiment was located about 5 km from the other test site in an area with somewhat wetter soils. Soil type was identified as Leaf series, with texture and organic matter contents as in Table 1. The intention was to assess the wide tires and tracks under the extreme conditions in which they were designed to operate, but this proved to be impossible. Generally, operations are shut down for a time during the winter in that part of North Carolina because of rutting problems resulting from wet conditions. Unfortunately, the winter of 1995 was very dry in east-

em North Carolina and conditions were never ideal for making a comparison of the systems in very wet soils.

The experimental design was a randomized complete block with two replicates of three plots each. Plots within the blocks were arranged linearly along a removed row corridor and were randomly assigned a treatment. There was approximately 5 m space between consecutive plots. The ground surface was cleared of slash and litter. Sampling procedures were identical to those used in the other tests. Bulk density measurements were made at two depths: 0 to 5 and 7.5 to 12.5 cm. Cone penetrometer measurements were made with the Bush system.

An equipment breakdown forced a delay during the tests and there was a difference of 1 week in the measurements for the two machines with tires and the tracked machine. There was rainfall just prior to the tests with tire-equipped machines. In order to, as nearly as possible, duplicate the conditions in which the tire-equipped machines were tested, plots for the track-equipped machine were artificially watered the evening before applying the treatment.

DATA ANALYSIS

All values for bulk density and cone resistance were evaluated as differences in pre- and post-treatment measurements. The bulk density data points were paired by sampling location within the plot. There were 10 sampling locations in each plot: 1 in each tire rut at 5 transects. The paired differences were evaluated for the effects of initial bulk density and MC. For the 6- and 8-wheel and wide/narrow tire tests, the additional effect of soil type (plot location) was included but found non-significant.

For cone resistance, there were also 10 sampling locations in each plot, arranged as in the bulk density samples. Four penetrations were made at each location, then averaged to make one observation. The pre- and post-treatment values for a given location were then subtracted and the result tested for statistical difference from 0.

Rut sizes were evaluated using measures of depth and cross-sectional area. Depth was generally defined as the largest average deflection in the soil surface over the width of one tire (or track). This value was calculated by scanning the difference in pre- and post-traffic soil pro-

files for the smallest (or largest negative) sum of consecutive values over a given number of samples. The number of samples was fixed as the tire width divided by 3.5 cm, the horizontal resolution of the profile gauge. Cross-sectional area was separated into positive and negative components, or upwards and downwards relative to the original soil surface.

RESULTS AND DISCUSSION

6- AND 8-WHEELED FORWARDERS

Table 5 summarizes pre- and post-traffic bulk density and rut depth/area. There were no differences found in bulk density following traffic with either machine at any depth. The pre-treatment bulk densities observed at depths greater than 15 cm were all higher than 1.5 Mg/m³ on average. This suggested a high degree of compaction resulting from either the first thinning done in the stand, with little recovery during the intervening time, or perhaps a residual effect of oscillations in the water table. It was not surprising, therefore, that there was no additional compaction in the deeper portions of the profile from the traffic levels used in this study.

Bulk density closer to the surface averaged about 1.0 Mg/m³, considered good for tree growth and within the range of bulk density in which other studies have found compaction. On average, however, no compaction resulted from either treatment imposed. Figure 1 shows a plot of the change in bulk density as a function of initial density for soil samples in the 5- to 10-cm depth range. A linear regression between bulk density change and initial density (Fig. 1.) was significant ($p < 0.001$, $r^2 = 0.45$). Net change of zero occurred at an initial density of about 1.0 Mg/m³, and the slope of the line was near -1.0 (-0.78). This implied that the net change in bulk density as a result of either traffic treatment was a convergence toward a final density of 1 Mg/m³. A Proctor test done on the soil indicated that, for an MC of 30 percent, the ultimate compaction level was close to 1.0 Mg/m³. This may imply that, although the traffic caused no compaction, some change of soil structure occurred.

Plots of cone resistance as a function of depth are shown in Figure 2. The curves are pre- and post-treatment cone penetrometer resistance averaged over all locations sampled in all replicates. The curves show that there was an increase in soil strength over a range of

depths from 7 to 20 cm. This increase was significantly different from zero for the range of 10.5 to 17.5 cm depth ($p < 0.01$). The increase in this range averaged 0.8 and 1.0 MPa for the 6- and 8-wheeled forwarders, respectively. Sands and oth-

ers (16) suggested 3.0 MPa as a limiting soil strength for root penetration. The dashed vertical line in Figure 2 is at 3.0 MPa. The treatments lowered the depth at which soil strength exceeded 3.0 MPa by about 2 cm, to a level only about 10

TABLE 6. — Pre- and post-treatment Sulk density and size of ruts following traffic with a 6-wheeled forwarder, with wide or narrow tires.

Tires	Depth (cm)	Bulk density		Moisture (%)	Rut depth (cm)
		Pre	Post		
48 x 31.00-20 (wide)	5 to 10	1.28	1.09 ^a	28.0	8.40
	15 to 20	1.54	1.59	21.1	
600/55-26.5 (narrow)	5 to 10	1.32	1.24	29.0	8.94
	15 to 20	1.56	1.60	21.1	

^a * indicates a post-traffic bulk density mean significantly different from pre-traffic at the same depth. $\alpha = 0.05$.

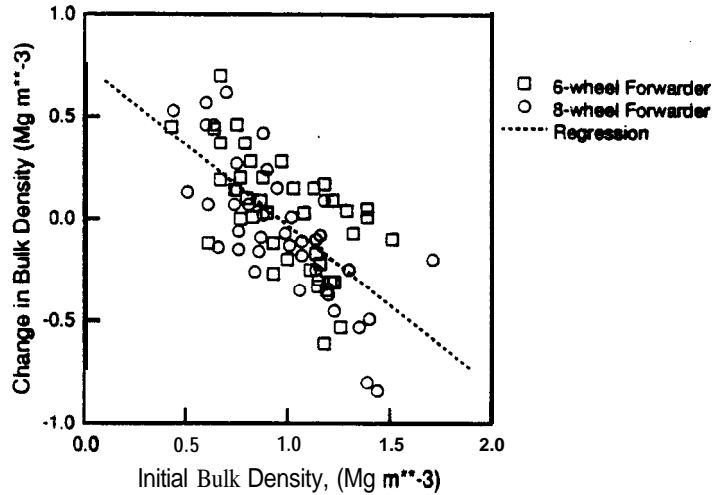


Figure 1. -Change in bulk density as a function of initial bulk density, 6- and 8-wheel tests.

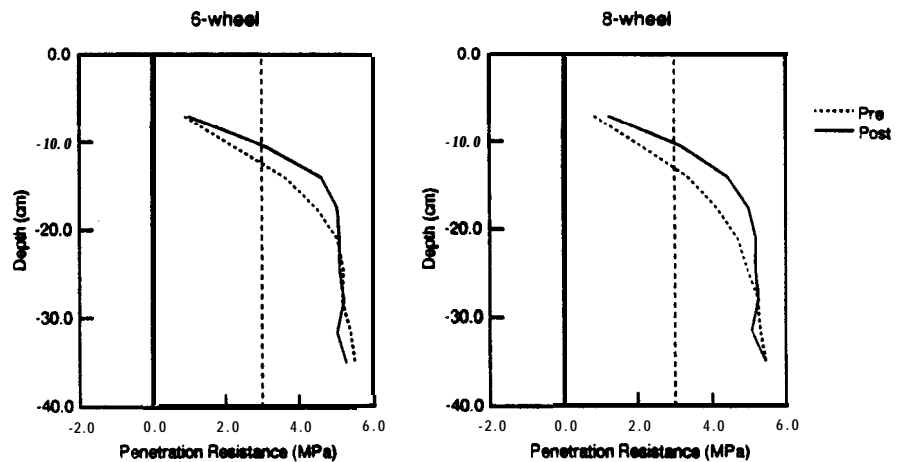


Figure 2. — Plot of pre- and post-treatment cone resistance, 6- and 8-wheel tests.

cm below the soil surface. This implied that the change in soil strength was probably the result of rut formation. Post-traffic penetration measurements were taken within the ruts, which averaged about 2 cm in depth. Whatever the cause of the increase, the soil volume capable of supporting root growth shrank within the trafficked areas.

WIDE AND NARROW TIRES

Table 6 shows pre- and post-traffic means of bulk density and rut depths for a 6-wheel forwarder with wide or narrow tires. For both tire sizes, traffic caused a slight increase in bulk density at the 15 to 20 cm depth, and a decrease in bulk density at 5 to 10 cm. The decrease was

significant ($p < 0.05$) for the wide tires. There were no differences in rut depth between the tires, but the ruts were about three times deeper on average than those observed in the tests of 6- and 8-wheel machines.

Change in bulk density following traffic was again modeled as a function of initial bulk density and the results were very similar to those observed in the 6- and 8-wheel tests. Figure 3 shows a plot of the change in bulk density with initial bulk density for soils in the 5 to 10 cm depth range. The response was linear, and again the net effect was to force the post-traffic bulk density toward 1.0 Mg/m^3 . No changes were detected in

saturated hydraulic conductivity following traffic, but a drop in macroporosity was observed (about 25%). The change, however, was not significant. This is further evidence that traffic, in these particular conditions, perhaps affected soil structure without compacting it.

Figure 4 shows the pre- and post-traffic penetration resistance for both tire widths. There was a significant increase ($p < 0.05$) in soil strength in the range from 3 to 7.5 cm in depth. The increase averaged 600 and 670 kPa for the narrow and wide tires, respectively. These increases were both lower in magnitude and shallower than observed in the tests of 6- and 8-wheeled forwarders. Pre-traffic soil strength peaked at about 3.0 MPa between 10 and 20 cm depth, and about 7 cm shallower following traffic. This again was probably due to the formation of ruts.

TRACKS AND WIDE TIRES

Table 7 summarizes average changes in bulk density and rut cross-sectional area with traffic for the three systems tested. Average bulk density increased with traffic at both depths and for all tire combinations. This is in contrast to the other tests, but was probably a result of the higher MCs. The increase was significant only in the 7.5-to-12.5-cm depth range and it was statistically the same for all treatments. The increase averaged 0.29 Mg/m^3 at 7.5 to 12.5 depth, and 0.07 Mg/m^3 at 0 to 5 cm.

The change in bulk density, ΔB_j (Mg/m^3), at both depths (0 to 5 and 7.5 to 12.5 cm), resulting from treatment j was modeled as:

$$\Delta B_j = t_j + a_j M + b B \quad [1]$$

where:

M = soil MC (%)

B = initial soil bulk density (Mg/m^3)

t_j , a_j , and b = regression terms

The model was found to be significant ($p < 0.001$) with $r^2 = 0.94$. Table 8 shows model parameter estimates and comparisons between treatments. Estimated model parameters for the two tire treatments were statistically the same. Parameters for the tracks, however, were significantly different from both tire treatments. Both the intercept (t_j) and MC (a_j) effects were smaller for the tracks than for the tire treatments. Over the range of measured MC and initial

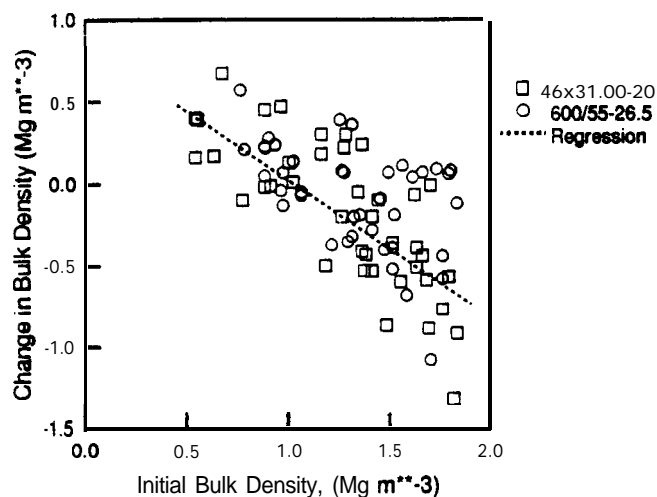


Figure 3. — Change in bulk density as a function of initial bulk density, wide (48 x 31 .00-20) and narrow (600/55-26.5) tires.

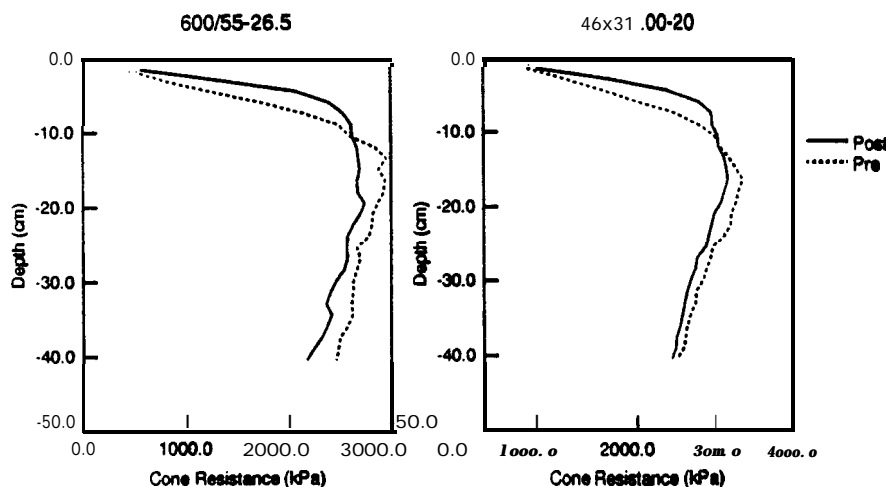


Figure 4. — Pre- and post-traffic soil penetration resistance, wide (48 x 31 .00-20) and narrow (600/55-26.5) tires.

bulk density. however, there was little difference in bulk density response between the treatments despite the significance of the differences in model parameters. Any difference in response between the tires and the tracks was well outside the range of realistic MC or bulk density. The effective response was the same as in the other tests, i.e., that the post-traffic bulk density tended to a value of 1.0 Mg/m^3 .

Rut cross-sectional areas were highest for the tracks and lowest for the $48 \times 31.00-20$ tires. The difference, however, was not significant. Results are similar to those in skidders (12), where wider tires tended to cause shallower ruts but larger total soil movement.

Graphs of the difference in pre- and post-traffic cone resistance are shown in Figure 5. Increases were significantly greater than 0 for all treatments for depths from 10.5 to 24.5 cm. The increase in soil strength averaged 0.7, 1.2, and 0.8 MPa for the $48 \times 31.00-20$ tires, $54 \times 37.00-25$ tires, and tracks, respectively, over that range of depths. Differences were highest for the $54 \times 37.00-25$ tires and were significantly greater than the $48 \times 31.00-20$ tires for depths from 7 to 25 cm, and from 10.5 to 14 cm for the tracks.

DISCUSSION

The results showed no clear advantages in the studied situation for the use of either wide tires or tracks. Few changes in soil bulk density were noted, and what changes were observed were generally uniform among treatments. Most of the significant changes in soil characteristics were detected in soil strength properties. These were confined to relatively shallow depths and were probably the result of a shift in the ground surface following traffic rather than a true increase in cone resistance. For most conditions tested, there were essentially no changes in soil physical properties as a result of traffic and therefore, no effect due to treatment was detectable.

There were, however, indications of changes in soil structure with traffic. For all tests, forwarder traffic changed bulk density of surface-layer soils in a repeatable manner. The bulk density in post-traffic soils tended to converge to 1.0 Mg/m^3 , the final bulk density achieved for the measured MC in a standard Proctor test. This suggested a change in soil

TABLE 7 — Pre- and post-treatment bulk density and size Of ruts following traffic with two sizes of wide tires and tracks.

Tires	Depth (cm)	Bulk density		Moisture (%)	Rut cross-sectional area (cm^2)
		Pre	Post		
$48 \times 31.00-20$	0 to 5	1.21	1.31	49.7	473
	7.5 to 12.5	1.62	1.88**	33.0	
$54 \times 37.00-25$	0 to 5	1.12	1.19	53.1	632
	7.5 to 12.5	1.52	1.78*	38.4	
Tracks	0 to 5	1.01	1.04	58.8	698
	7.5 to 12.5	1.41	1.61*	41.4	

* Indicates a post-traffic bulk density mean significantly different from pre-traffic at the same depth. $\alpha = 0.05$.

TABLE 8. — Parameter estimates for the model of change in bulk density (ΔB_i) as a function of soil moisture and initial bulk density.

Tire	t	a	h
$48 \times 31.00-20$	1.81 A=	-0.0145 A	-0.384
$54 \times 37.00-25$	1.77 A	-0.0139 A	
Tracks	1.62 B	-0.0109 B	

Means in the same column with the same capital letter are not significantly different.

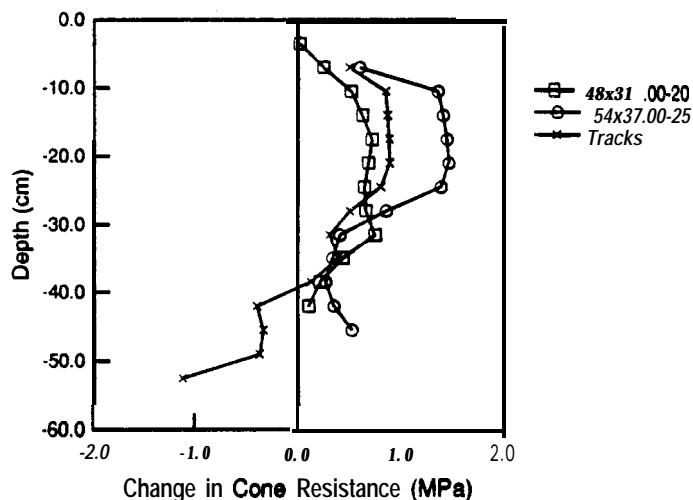


Figure 5. — Plot of the change in cone resistance, wide tires ($48 \times 31.00-20$ and $54 \times 37.00-25$) and tracks.

structure, and a non-significant decrease in soil macroporosity was noted. However, more tests are needed to establish the extent of the change.

The lack of any difference in impact because of machine configuration was surprising given the large variation in ground pressure exerted by the systems tested. Estimated ground pressures can vary by a factor of 2 to 3 between a standard-equipped forwarder and one with tracks. Ground pressure is often

cited by manufacturers in defining the relative impact of a given machine configuration, yet the results found in this study would suggest that no relationship exists. One possible explanation for this result was that the test sites, located in a previously thinned stand, were already compacted to a maximal level.

In studies of the effect of tire width in skidder soil impacts, McDonald and others (13) concluded that wide tires reduced rut depths, but they did not reduce

total soil displacement (rut cross-section area) or changes in physical properties. It would seem, therefore, that wide tires would provide their greatest benefit under conditions that would promote the formation of deep ruts, ordinarily very wet conditions. Operating in these wet conditions, however, may be detrimental. Further research is needed to establish the magnitude of soil impacts in the conditions these technologies were designed to handle.

CONCLUSIONS

This investigation examined the soil impacts of forwarders equipped with standard and wide tires and tracks. Results indicated that there were some changes resulting from forwarder traffic, mainly in apparent soil strength, and to some extent in surface soil structure. A non-significant drop in macroporosity was observed. This might have been evidence that traffic, in these particular conditions, affected soil structure without causing significant compaction. There were few differences in the soil impacts attributable to the drive train configuration. The effectiveness of these technologies in reducing impacts seems to be very specific to a particular soil type and moisture condition and a site should be examined carefully in order to determine what equipment is most suitable.

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