The Taringatura Study: The Effects of Harvest Machine Traffic and Tillage on a Forest Soil in New Zealand

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ABSTRACT

A selection of the results from a comprehensive field and laboratory study on the impact of mechanised harvesting operations on a forest soil in New Zealand are presented. The season during which machine trafficking took place ("dry" and "wet"), machine type, and number of passes (from 1 to 30) were the input variables. Soil response was measured with pedological and geotechnical field and laboratory testing procedures. It was determined that although the soil was in some treatments heavily disturbed, it was not compacted, given that the natural water content was well above the laboratory determined optimum water content for compaction. Practical implications are discussed.

Keywords: *soil disturbance, compaction, density, water content, cone penetration tests, Shelby tubes, nuclear testing, Proctor moisture/density test.*

INTRODUCTION

The impacts of mechanised ground-based forest harvesting on soil physical properties, including compaction, erosion, and, with time, loss of site productivity, have been widely reported [8, 25]. Generally, the largest changes in soil structure occur following only a small number of machine passes [4, 7, 12], though overall soil response varies with (a) soil conditions such as water and organic matter content, and texture [8], (b) machine design [4, 22] and (c) the intensity of the machine loads applied to the ground surface [7, 12].

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Controlling the impacts of harvesting on site and soil quality remains one of forest management's greatest challenges. Improvements in machine design and a growing awareness of machine-soil-forest interactions, including the identification of soil physical constants above which root and/or tree growth begin to be affected, represent ways of limiting some of the adverse impacts described above. More commonly, soil cultivation treatments such as ripping, mounding, or discing provide a means of reversing any potential reduction in soil quality and site productivity, though given the complexities of soil and vegetation response, the results can be highly variable [6, 10].

Mechanisation of forest harvesting in New Zealand has been considerable since the mid 1980s [19], and previous studies have demonstrated that New Zealand is no exception to the site and soil disturbance associated with the use of heavy forest machinery [1, 2, 17, 18, 24]. As a result, Murphy *et al.* [18] suggested that considerable productivity losses may have already resulted from poorly managed harvesting operations.

Rayonier NZ Ltd. expressed a need for decision support when selecting harvesting machinery, and the timing of harvesting operations relative to ground conditions. In response, a study was undertaken in New Zealand's Southland, a region where operations typically are conducted under wet ground conditions. The study's hypothesis was that the rate and amount of soil disturbance depend on the season of operation, the machine type, and the number of passes made by the machine.

This paper summarises a selection of the results of the study, which is covered in much greater detail in a formal report made to Rayonier NZ Ltd. [27]. Note that a thorough treatment of the soil density determination methods has already been published in Wood *et al.* 2004a [26].

THE STUDY

The study constituted a classical experiment with replicates. Independent variables were:

- season ("dry" season – November 2001 – Trial 1; "wet" season – June 2002 – Trial 2)
- machine (Timberjack 1710 forwarder, John Deere 648G-II skidder, Caterpillar 525 skidder)
- number of passes by machine (0, 1, 3, 10, and 30 passes)

The forwarder and two skidders used in the project are shown in Figure 1. Nothing is to be taken as significant about the choice of machines other than the fact that they

Figure 1. Machines used in the study: (a) Timberjack 1710 forwarder, (b) John Deere 648G-II skidder, (c) Caterpiller 525 skidder.

were typical of the equipment used in the region and no endorsements or criticisms are implied. Machine characteristics are given in Table 1.

Site description

The test site was located in Taringatura Forest, approximately 50 km north of Invercargill, on New Zealand's South Island (Figure 2). It was a relatively flat area in rolling hills, sitting at approximately 430 m above sea level, with a southerly aspect (Table 2). The site was established with a planting of Radiata pine in 1972 at a spacing of approximately 3 x 3 m. Pedologically, the soil at the site was described as stony silt-loam in texture, typical of the broader forest area (Tables 2 and 3).

Prior to harvest in September 2001, two parallel strips of ground, 170 x 20 m and 310 x 20 m, approximately 80 m apart, were laid out (Figure 3). An area considered typical of the forest block's soil and terrain was selected. Care was taken to avoid wind-thrown stems, drains and streams. The forest immediately surrounding the two strips was first harvested mechanically, the remaining strips were then felled motor-manually and the stems lifted out mechanically to ensure no trafficking of the ground. The two untrafficked strips were divided into 48 plots, each 10 m x 20 m (Figure 4).

Five of the 48 plots were not used – three due to waterlogging and two due to accidental trafficking prior to the trials. As a result, a number of trafficking treatments had to be omitted: Trial 1 – CAT 525 (30 passes, replicates 1 and 2), Trial 2 – John Deere 648G-II (30 passes, replicate 2) and CAT 525 (30 passes, replicates 1 and 2).

METHODS

All the trafficking for a given trial was carried out on the same day on randomly allocated plots. The direction of travel along each plot varied: the forwarder was able to move forwards and backwards, but the two skidders had to pass through the plot in one direction only. The equipment was loaded during all passes. During the second trial, the 30-pass treatment by the forwarder in one plot was stopped after 17 passes when deep uneven rutting rendered the machine unstable.

On completion of trafficking, a visual assessment was made of the ground conditions along the trafficked areas relative to the un-trafficked areas of each plot. Disturbance classes 1 through 4 were assigned according to the designations in Table 4. In addition, to provide a quantitative measure of ground disturbance associated with each treatment, cross-sections of the ground surface

Table 1. Machine characteristics.

	Forwarder	Skidders	
	Timberjack 1710B	John Deere 648G-II	Cat 525
total length (m)	10.85	7.25**	5.55**
width	3.04	3.25	3.11
operatingtare weight (kg)	19000	12500	13600
measured payload (kg)*	12700	4900	4300
tyre/track width (m)*	0.70	0.80	0.80
traction aids	steel band tracks, front and rear bogies	steel chains, front wheels	steel chains, front wheels

figures based on manufacturer's literature, except where stated:
*authors' assessment from scaling and standard taper equations,
**not including grapple

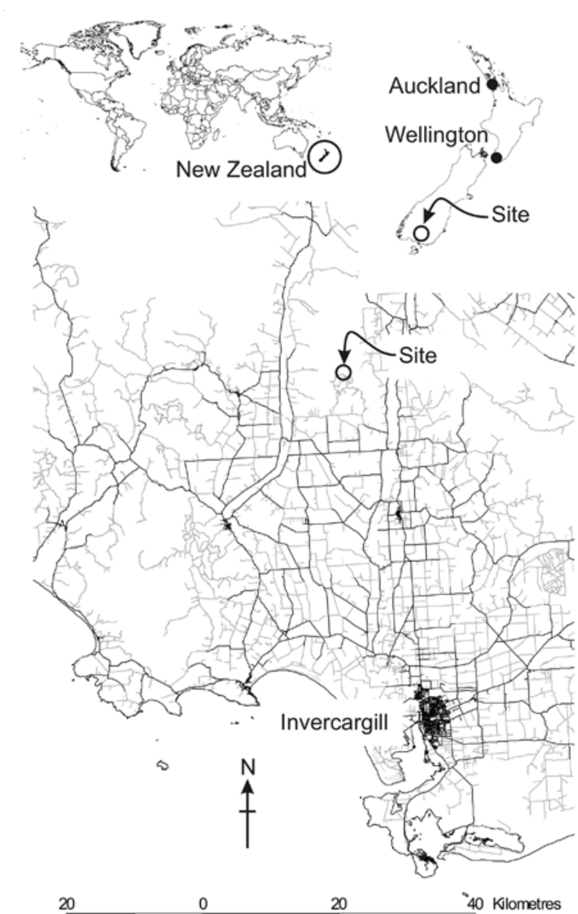

Figure 2. Study site location.

Table 2. Area site description.

soil series	Kaiwera
soil texture	stony silt loam
New Zealand soil classification	Acidic Allophanic Brown
International soil classification	Humic Dystrudept
location (NZ Map Grid)	2140950, 5461700 (± 50 m)
elevation	430 m
slope	5º
aspect	180º
annual rainfall	1000 mm/yr
drainage	good, water table at 2.0 m
vegetation	*Pinus radiata* stumps, coprosma, bracken
parent material	greywacke and loess
geological substrate	greywacke
topsoil depth	0.2 m
total rooting depth	0.7 m
limiting horizon	bedrock

pers. comm: T. Webb, Soil Scientist, Landcare Research New Zealand (Unpublished data).

Table 3. Soil profile description for Block 308, Taringatura Forest.

Horizon		Description
LFH	8-0 cm	dark reddish brown (5YR3/2); abrupt wavy boundary
Ah	0-10 cm	brown to dark brown (10YR4/3) silt loam; strongly developed peds; many distinct (10YR5/4) and common distinct (10YR3/3) mottles; few fine and many extremely fine roots; no voids; indistinct smooth boundary
AB	10-20 cm	dark yellowish brown (10YR4/4) silt loam; strongly developed peds; many distinct (10YR5/5) and common indistinct (10YR4/3) mottles; few fine and many extremely fine roots; no voids; indistinct wavy boundary
Bw1	20-35 cm	yellowish brown (10YR5/8) silt loam; strongly developed peds; common extremely fine roots; no voids; diffuse smooth boundary
Bw2	35-56 cm	yellowish brown (10YR5/8) silt loam; strongly developed peds; common extremely fine roots; no voids; abrupt wavy boundary
R	56-100+cm	greywacke

pers. comm: T. Webb, Soil Scientist, Landcare Research New Zealand (Unpublished data).

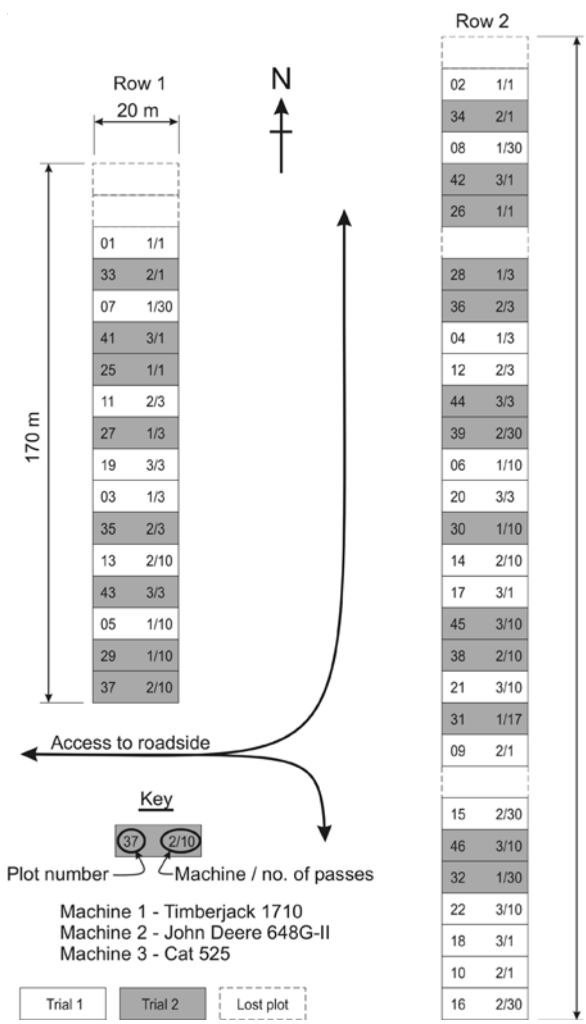

Figure 3. Layout of study site (not to scale).

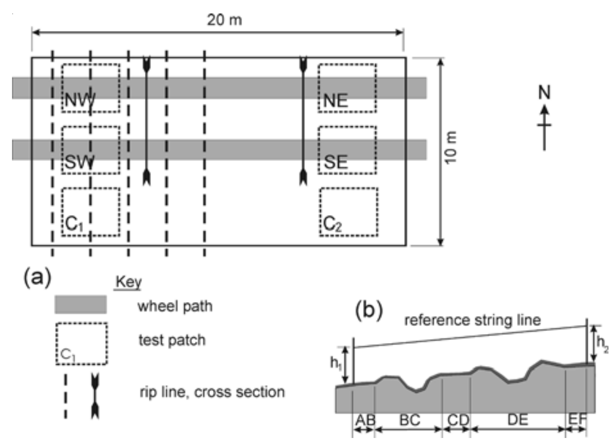

Figure 4. (a) Test plot layout (not to scale), (b) rut depth and disturbance index determination from cross sections, h1 = h2 (not to scale).

Table 4. Ground disturbance severity.

Level	Description
1	litter / duff layer largely intact
2	litter / duff layer extensively torn and displaced, often mixed with organic soil layer
3	displacement of organic soil layer, rut-to-heave total < 20 cm
4	displacement of mineral soil layer, rut-to-heave total > 20 cm

were measured at two locations along each plot. For each cross-section, the distance between the ground surface and a reference string line was measured at 10 cm intervals (Figure 4). The measurements for the disturbed ground (widths BC and DE in Figure 4) were extracted, and the standard deviation used as a measure of ground disturbance for each width. The average of the eight standard deviations was then obtained for each treatment (2 replicates x 2 cross sections per plot x 2 wheel paths per cross section).

To examine soil physical properties during Trials 1 and 2, 0.75 m x 1.50 m test patches within each plot were located so as to avoid obvious rocks and large roots (Figure 4). The ground at each test patch was prepared by removing any loose litter and logging debris to expose the upper soil surface. Measurement of soil physical properties was undertaken within two weeks of trafficking. Following completion of each soil test, the area disturbed during testing was marked on the ground with weather-proof paint to avoid re-using the ground during subsequent soil testing.

Subsequent to Trials 1 and 2, observations on the effects of ripping to a depth of approximately 75 cm on soil physical properties were made for a selection of the machine treatments. Ripping took place in July 2002 using a Komatsu 220LC tracked excavator equipped with a boom amounted winged ripping tine of approximately 75 cm length. Rip lines were orientated from north to south at approximately 2 m spacing (Figure 4). The machine treatments chosen for the ripping trial were the 1- and 10 pass treatments of the Timberjack 1710 forwarder and John Deere 648G-II skidder applied under both dry (Trial 1) and wet (Trial 2) conditions.

Measurement of Soil Physical Properties

A summary of soil properties measured and the methods employed is given in Table 5. Statistical analyses were limited to t-test comparisons (P = 0.05). Cone penetration resistance and dry density data were measured to provide information on basic soil impacts, values were later compared those cited in previous studies as limiting root and tree growth (see Discussion). Additional factors relating to soil quality as a growing medium such as moisture content, organic matter content and particle size distribution, were also measured. Liquid and plastic limits, and soil compactibility were determined to provide further information when interpreting soil response.

A full treatment of the methods used for penetration resistance, density and water content determination, including a discussion of the Shelby tube method and comparison of all methods used, is provided in Wood *et al.* (2004) [26], and will not be repeated at length here.

Cone penetration resistance was measured using a recording portable unit with a detachable conical tip (30° point angle, basal diameter 12.8 mm). During Trial 1, cone penetration resistance was measured in the untrafficked test patches (C_1 and C_2, Figure 4) of eight randomly chosen plots, and then in all the trafficked test patches (NE, SE, SW and NW, Figure 4) of all 22 plots. During Trial 2, cone penetration resistance was measured in the untrafficked test patches of all 21 plots (C_1 only, Figure 4), and then in all the trafficked test patches of each plot (NE, SE, SW and NW, Figure 4). In each test patch, six penetrations were

Table 5. Soil properties measured and methods used.

Property	Method	Depth range and (increment), cm	Pre-trial	Trial 1	Trial 2	Reference
organic matter	loss on ignition	0-20 (5)	Y			[13]
particle size distribution*	hydrometer	0-20 (5)	Y			[3]
liquid limit*	Casagrande apparatus, fall cone	0-20 (5)	Y			[3]
plastic limit*	3mm threads	0-20 (5)	Y			[3]
compactability*	Proctor testing	0-20 (5)	Y			[3]
water content	manual core sampler	0-20 (5)		Y		
	Shelby tube sampler	0-30 (5)			Y	
	Hydrosense soil water meter	0-12 (12)		Y	Y	
penetration resistance	soil penetrometer	0-45 (5)		Y	Y	
density	manual core sampler	0-20 (5)		Y	Y	
	Shelby-tube sampler	0-30 (5)			Y	
	nuclear density gauge	0-20 (10)			Y	

*based on bulk soil samples collected from the 0-5 cm, 5-10 cm, 10-15 cm and 15-20 cm depths from the untrafficked area of a single randomly chosen plot.

made and combined to provide a mean value for each depth increment.

After the site was ripped, cone penetration resistance was measured at the untrafficked/unripped, untrafficked/ripped, trafficked/ripped and trafficked/unripped test patches of each plot (C_1, C_2, NW and NE respectively, Figure 4). Measurement was performed on the 1-pass and 10-pass treatments of the Timberjack 1710 forwarder and John Deere 648G-II skidder, applied originally under both dry (Trial 1) and wet (Trial 2) conditions. In each test patch, six penetrations were made and combined to provide a mean value for each depth increment. Based on observations during Trials 1 and 2 regarding the shallow and stony nature of the soil, testing was limited to a depth of 30 cm.

During Trial 1, gravimetric water content and dry density were measured using a manual soil sampler. Soil samples of known volume were collected from the untrafficked test patches (C_1, Figure 4) of eight randomly chosen plots at 0-5 cm, 5-10 cm, 10-15 cm and 15-20 cm. Laboratory determination of water content and dry density for each sample was based upon weighing and drying at 105°C until a constant mass was achieved. Water contents were also obtained in the field using a time domain reflectometry (TDR) unit. During Trial 1, the TDR unit was used in the untrafficked test patches (C_1 and C_2, Figure 4), of eight randomly chosen plots, and during Trial 2, in the untrafficked test patches (C_1 only, Figure 4) of all 21 plots. In each test patch, four samples were taken and then averaged. Given the shallow and stony nature of the soil, only the unit's shorter (12 cm) probes could be used.

During Trial 2, water content and dry density were measured in selected untrafficked and trafficked test patches using a Shelby tube sampler of known volume [26]. In each of the 21 plots, tube samples were collected from the untrafficked test patches (C_1 only, Figure 4) and trafficked test patches (NE and SW only, Figure 4). In the laboratory, water content and dry density were calculated for continuous 5 cm slices of the extracted soil. These data were combined and presented for 10 cm depth increments to facilitate broad comparison with additional density values determined with a nuclear moisture-density gauge. Nuclear testing was performed according to the manufacturer's recommended procedures [11] in the same untrafficked and trafficked test patches sampled with the Shelby tubes.

RESULTS AND COMMENTS

The pre-trial values of the soil's physical properties are given in Table 6. The initial water contents and organic

Table 6. Pre-trial physical properties of soil (mean | standard deviation | number of samples).

<table>
<tr><th>Depth interval, cm</th><th></th><th>0-5</th><th>5-10</th><th>10-15</th><th>15-20</th><th>0-12</th></tr>
<tr><td>Water content, %*</td><td>(Trial 1)</td><td>55|8.62|8</td><td>46|4.09|8</td><td>42|5.45|8</td><td>42|3.88|8</td><td>-</td></tr>
<tr><td></td><td>(Trial 2)</td><td>67|11.73|21</td><td>49|10.21|21</td><td>44|8.39|20</td><td>41|9.40|20</td><td>-</td></tr>
<tr><td>TDR water content, %**</td><td>(Trial 1)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>41|7.03|8</td></tr>
<tr><td></td><td>(Trial 2)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>52|10.06|20</td></tr>
<tr><td>Organic content, %</td><td></td><td>22|0.24|4</td><td>18|0.30|4</td><td>16|0.25|4</td><td>15|0.15|4</td><td>-</td></tr>
<tr><td>Texture, fraction < gravel sizes:</td><td>% Sand</td><td>27|0.82|4</td><td>28|1.83|4</td><td>30|0.50|4</td><td>28|3.77|4</td><td>-</td></tr>
<tr><td></td><td>% Silt</td><td>30|1.50|4</td><td>32|1.83|4</td><td>30|0.50|4</td><td>30|2.52|4</td><td>-</td></tr>
<tr><td></td><td>% Clay</td><td>43|1.26|4</td><td>40|0.00|4</td><td>40|0.00|4</td><td>43|2.87|4</td><td>-</td></tr>
<tr><td>Liquid limit***</td><td></td><td>67</td><td>62</td><td>56</td><td>57</td><td>-</td></tr>
<tr><td>Plastic limit***</td><td></td><td>not plastic</td><td>not plastic</td><td>not plastic</td><td>not plastic</td><td></td></tr>
<tr><td>Standard compaction: $\tilde{a}_{dry\ max}$ (kN/m^3) @ OMC%***</td><td></td><td>11.2 @ 37</td><td>12.2 @ 32</td><td>12.9 @ 30</td><td>12.9 @ 30</td><td>-</td></tr>
</table>

*based upon soil samples collected with the manual sampler (Trial 1) and Shelby tubes (Trial 2) from the untrafficked test sites

** 0-12 cm depth increment only

***a single test was performed in each case (OMC% - optimum water content).

contents reflected anticipated trends. The organic content was high, and decreased with depth. The water contents were appropriate for the organic contents observed. They decreased with depth, as organic content decreased, and showed variability with the season, being wetter in the wet season, with the variability decreasing with depth. Texture was evidently independent of depth to 20 cm. The silty nature of the soil resulted in the relatively high liquid limits. The soil was non-plastic: no plastic limit could be determined. Relatively low standard Proctor maximum dry unit weights were determined. The Proctor unit weights increased with depth, as expected, given the decreasing organic contents.

Ground disturbance by class for the three machines during the two trials is shown in Figure 5. Disturbance increased as the number of passes increased, and as expected, more disturbance was observed during the trial conducted in wet conditions. The same trends were displayed in the graphs of ground disturbance index, Figure 6. The observed disturbance class of the soil began to climb with between 3 and 10 passes. It was generally one class higher in the wet season, all other things being equal. Some distrust of the disturbance class approach led to the development of the disturbance index, the standard deviation of the rut depth measurements. Standard deviation was selected as it removes the effect of the arbitrary and differing heights of the reference string line from cross section to cross section. In the end, it bore out the disturbance class observations, with, after 30 passes, the index for trafficking during the wet season being nearly four times the index for a single pass.

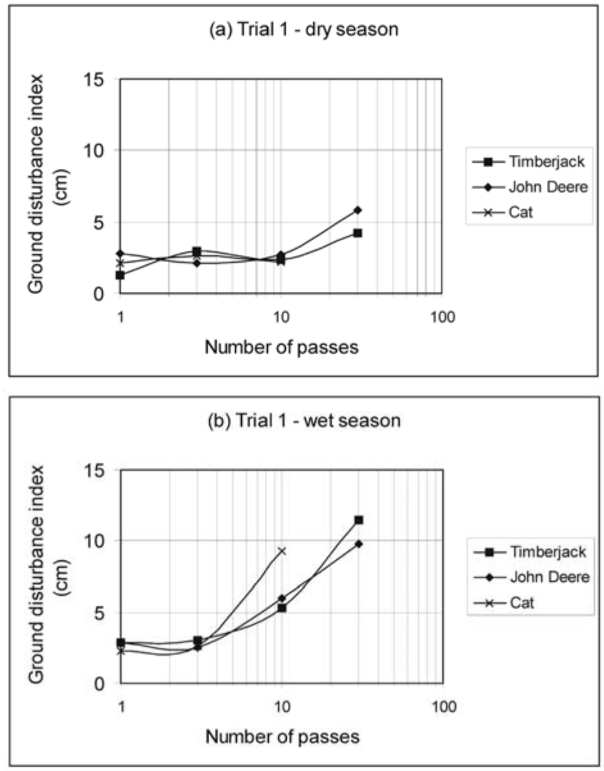

Figure 6. Ground disturbance index observations.

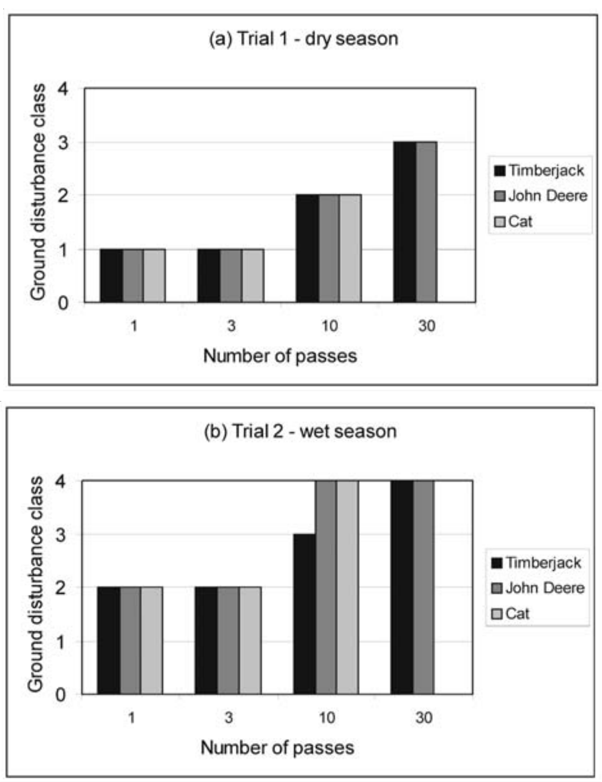

Figure 5. Ground disturbance class observations.

All cone penetration data is shown for the dry season tests (Trial 1) and the wet season tests (Trial 2) in Figures 7 and 8, respectively. Typical cone penetration data collected after the site was ripped is shown in Figure 9. Despite broad trends, differences in cone penetration resistance data between all treatments were rarely significant (t-test, $P = 0.05$).

During the dry season (Trial 1), the penetration resistance began from about 0.5 to 1.0 MPa at the surface (Figure 7), where the soil was unconfined, increased linearly to a depth of perhaps 20 cm, and then maintained a constant value below that depth, to a depth of 50 cm at which tests were terminated. There was a great deal of scatter in the data below a depth of about 20 cm, caused by the rocks and roots the cone encountered, with the recorded penetration resistance ranging from about 2.0 to 2.5 MPa, with one exception. Down to a depth of about 20 cm, within the linearly increasing range, there did seem to be a general trend of increasing penetration resistance with increasing number of passes. However, that trend broke down into scatter below a depth of about 20 cm.

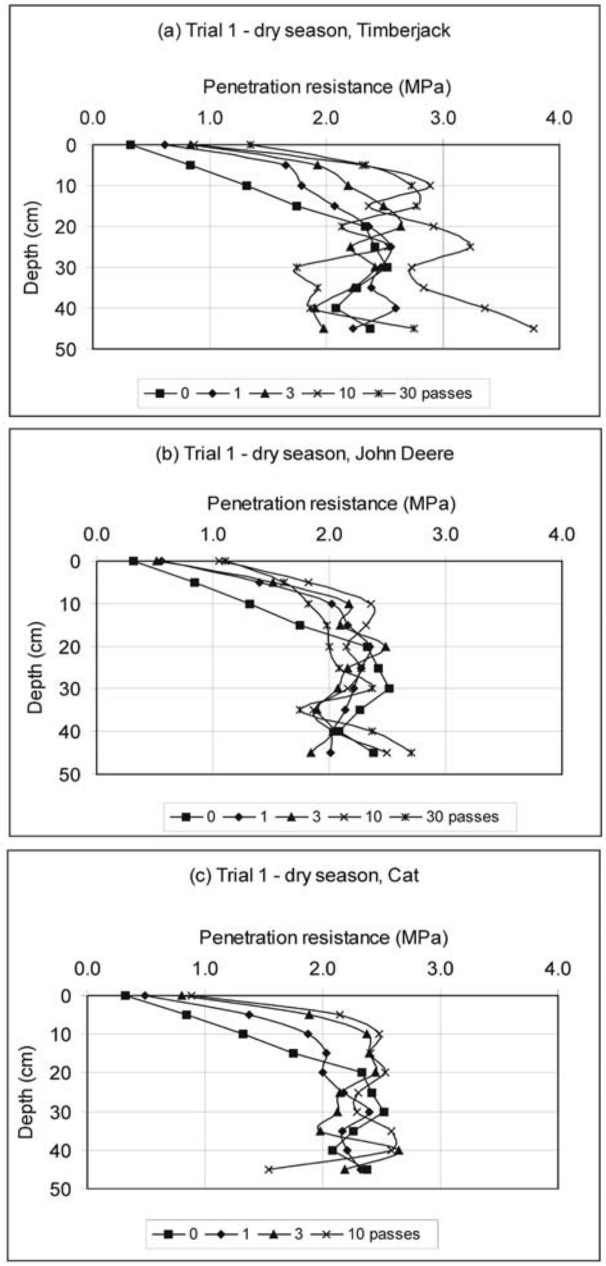

Figure 7. Penetration resistances, dry season.

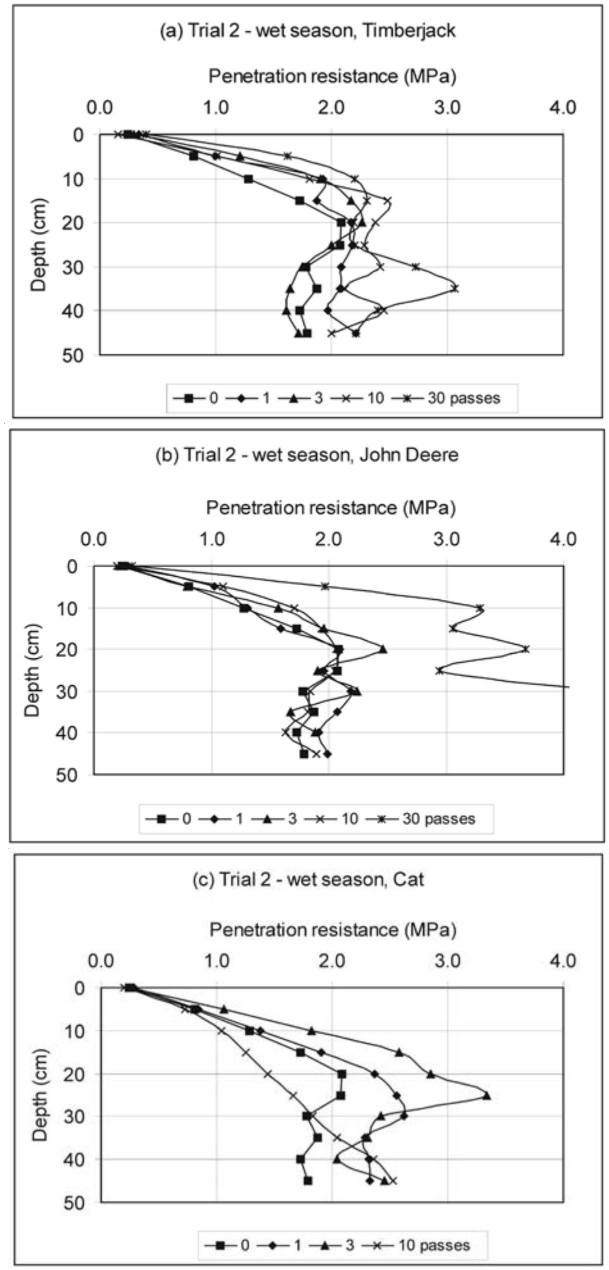

Figure 8. Penetration resistances, wet season.

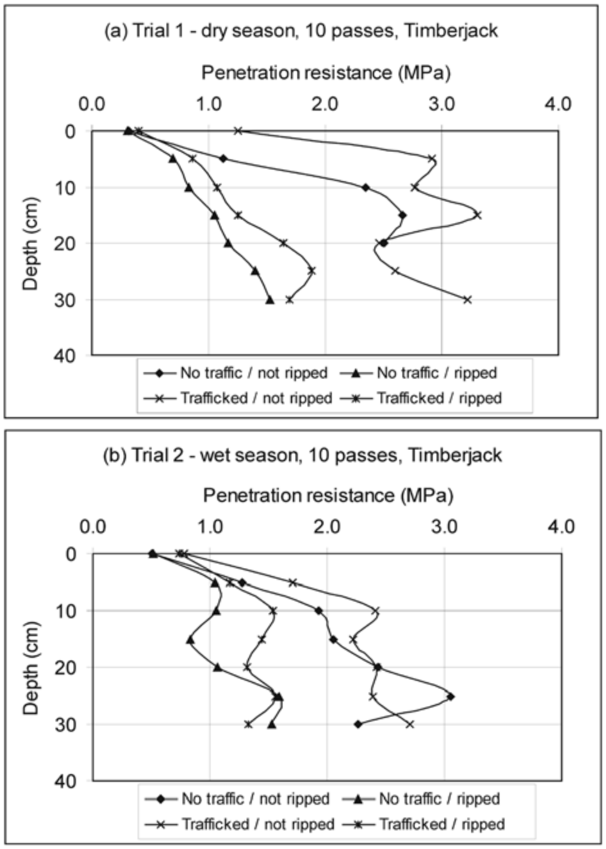

Figure 9. Typical penetration resistances before and after ripping.

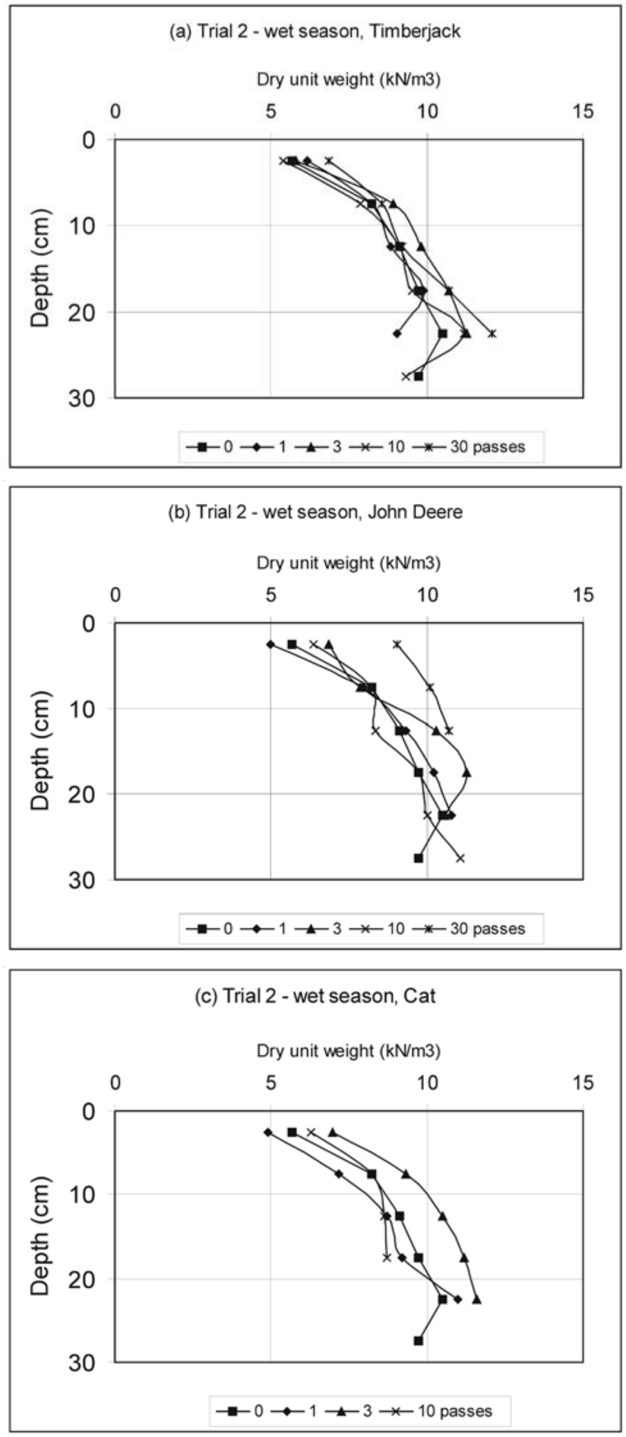

Figure 10. Dry unit weights from Shelby tube test data, wet season.

Similar observations were made for the results recorded during the wet season (Trial 2, Figure 8). The zero depth penetration resistance was about half the dry season values due to the wetter soil, ranging from about 0.2 to 0.4 MPa. Again it increased linearly with depth, to a depth of about 20 cm. The penetration resistance was relatively constant below that depth, varying from about 1.8 to 2.5 MPa, with a couple exceptions. Again, the data was quite scattered below about 20 cm. In contrast to the dry season results, there did not seem to be a consistent trend of increasing penetration resistance for increasing number of passes, at shallow depth of less than about 20 cm.

The trends were far more clearly delineated when penetration resistance before and after ripping was observed, and Figure 9 is typical of all the data. Clearly ripping decreased the penetration resistance markedly, for both the trafficked and untrafficked pairs. The differences were always greater for a change from “not ripped” to “ripped” than they were for a change from “not trafficked” to “trafficked”.

The set of dry unit weight measurements obtained from the Shelby tube sampling in Trial 2 is given in Figure 10.

Dry unit weights were approximately linear with depth, to a depth of about 20 cm. Very close to the surface, the dry unit weights were observed to range from approximately 5 to 7 kN/m^3 with one exception. No significant trend in density with increasing numbers of passes, or machine type, could be detected (t-test, P = 0.05). Table 7 presents the density results of nuclear and Shelby tube testing for Trial 2. In only one case was there a significant difference between the pre- and post-trafficking dry unit weights (t-test, P = 0.05).

DISCUSSION

At first glance, the penetration and density test results appear to be at odds with the disturbance class and index observations, and also, the findings typical of previous studies where considerable increases in soil density and/or strength took place after only a few machine passes [4, 7, 12]. In the dry season, the penetration resistances did show a mild increase with increasing numbers of passes, for all machines, but that relationship was not observed in the high quality Shelby tube density test results. There were no consistent trends of penetration or density with machine type and weight.

However, there clearly was an increase in the disturbance and rutting as the number of passes increased, for just a few passes, and that increase was exacerbated by wet weather. How can density and/or penetration resistance not go up – or not go up significantly with traffic, if disturbance and rutting do so emphatically?

While the soil did not densify under traffic, and therefore did not offer greater penetration resistance, it did move around dramatically under the action of the tyres or tracks. A clue as to why can be found in the water content data, when compared to the Proctor compaction test results. Proctor testing gave optimum water contents for compaction of from 37% to 30%, for depths from 0-5 cm down to 15-20 cm (Table 6). The corresponding field water contents, whether determined from the manual sampler specimens, the Shelby tube samples or the TDR testing, were all significantly above those values (Table 6, Figure 11). Thus the soil was much wetter than the optimum water content for compaction, rendering it much less compactable (Figure 12). At the same time, the high water content reduced the shear strength considerably, in turn reducing the bearing capacity offered to the tyres and tracks. As a consequence, the soil shifted around considerably under traffic, but did not become denser.

The message in the data is that large amounts of soil disturbance are not necessarily accompanied by detrimental compaction, particularly if the soil is well above the optimum water content for compaction as determined in the Proctor compaction test. The action of harvesting equipment would have little impact in the sense of densification of the soil. Hence, although in this case the soil could be heavily disturbed, it would offer no more resistance to root penetration after trafficking, as the new crop begins to grow. In terms of site productivity, threshold values of soil resistance to penetration of 2.5 – 3.0 MPa [9, 13, 14, 21] and dry bulk density of 1.2 – 1.5 g/cm^3 [5, 15, 16, 23, 28] have been demonstrated to affect root and tree growth subject to species and soil type. In this study, soil properties seldom approached these limiting values.

It must be remembered, however, that large ruts lead to pooling of water, and the augmented tendency for erosion and sediment transport. Tillage, such as the ripping used in this study, can not only beneficially loosen up the soil, but also restore a more even surface which is less prone to erosion, and presents better planting conditions for the next crop.

CONCLUSIONS

The conclusions that can be drawn from the study are made within the following bounds:

- work took place on one large site in Southland, New Zealand
- testing took place in two seasons, “dry” and “wet”
- three particular machines were used in the tests, one forwarder and two skidders
- number of passes up to 30

In the study, cone penetration resistances were linear with depth, to approximately 20 cm. Below that depth, they were relatively constant with depth to the extent of testing at about 50 cm, but there was a wide scatter in values.

Penetration resistances increased somewhat with the number of passes, when observed during the dry season. During the wet season, that pattern was not evident. Penetration resistance was independent of which of the three machines did the trafficking.

Tilling the soil by ripping it produced a significant decrease in cone penetration resistance.

Soil disturbance, as reflected by the disturbance class or measured with the disturbance index (standard deviation of rut depth measurements) increased markedly over the first 10 or so passes. The level of disturbance was strongly affected by which season the trafficking was done

Table 7. Pre- and post-trafficking densities, Trial 2 (wet season) (mean | standard deviation | number of samples).

<table>
<tr><th></th><th>Passes</th><th>Nuclear gauge
0 – 10 cm</th><th>Shelby tubes
10 – 20 cm</th><th>
0 – 10 cm</th><th>
10 – 20 cm</th></tr>
<tr><td>Control</td><td>0</td><td>0.84 | 0.10 | 21</td><td>1.10 | 0.11 | 20</td><td>0.71 | 0.17 | 21</td><td>0.96 | 0.14 | 20</td></tr>
<tr><td>Timberjack 1710</td><td>1</td><td>0.86 | 0.03 | 3</td><td>1.11 | 0.02 | 3</td><td>0.74 | 0.07 | 3</td><td>0.96 | 0.01 | 3</td></tr>
<tr><td></td><td>3</td><td>0.86 | 0.04 | 4</td><td>1.14 | 0.04 | 3</td><td>0.75 | 0.10 | 4</td><td>1.05 | 0.02 | 3</td></tr>
<tr><td></td><td>10</td><td>1.03 | 0.19 | 2</td><td>1.30 | 0.29 | 2</td><td>0.73 | 0.04 | 2</td><td>1.03 | 0.21 | 2</td></tr>
<tr><td></td><td>30</td><td>0.99 | 0.08 | 4*</td><td>1.18 | 0.05 | 4</td><td>0.79 | 0.07 | 4</td><td>1.02 | 0.05 | 4</td></tr>
<tr><td>John Deere 648G-II</td><td>1</td><td>0.79 | 0.03 | 4</td><td>1.09 | 0.12 | 4</td><td>0.66 | 0.08 | 4</td><td>0.99 | 0.15 | 4</td></tr>
<tr><td></td><td>3</td><td>0.92 | 0.08 | 4</td><td>1.21 | 0.08 | 3</td><td>0.75 | 0.23 | 4</td><td>1.14 | 0.21 | 3</td></tr>
<tr><td></td><td>10</td><td>0.99 | 0.11 | 4</td><td>1.17 | 0.24 | 4</td><td>0.75 | 0.13 | 4</td><td>0.92 | 0.30 | 4</td></tr>
<tr><td></td><td>30</td><td>1.08 | 0.18 | 2</td><td></td><td>0.98 | 0.32 | 2</td><td></td></tr>
<tr><td>Cat 525</td><td>1</td><td>0.80 | 0.06 | 3</td><td>1.08 | 0.05 | 3</td><td>0.62 | 0.07 | 3</td><td>0.91 | 0.04 | 3</td></tr>
<tr><td></td><td>3</td><td>0.96 | 0.05 | 3</td><td>1.21 | 0.06 | 2</td><td>0.83 | 0.06 | 3</td><td>1.09 | 0.15 | 2</td></tr>
<tr><td></td><td>10</td><td>0.98 | 0.12 | 4</td><td>1.15 | 0.11 | 4</td><td>0.74 | 0.14 | 4</td><td>0.89 | 0.13 | 4</td></tr>
<tr><td></td><td>30</td><td></td><td></td><td></td><td></td></tr>
</table>

*difference between pre-trafficked and post-trafficked mean significant at P = 0.05 (Students T-test assuming unequal variances).

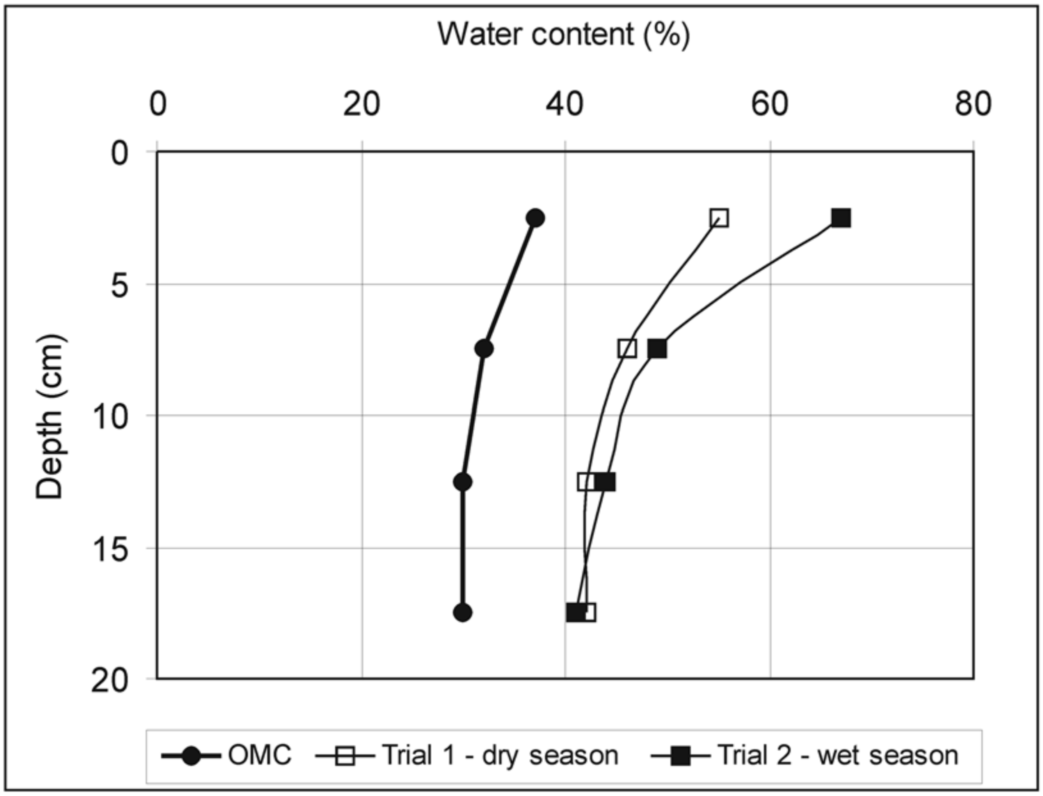

Figure 11. Water contents from Proctor compaction tests in *in situ* manual sampling (Trial 1) and Shelby testing (Trial 2).

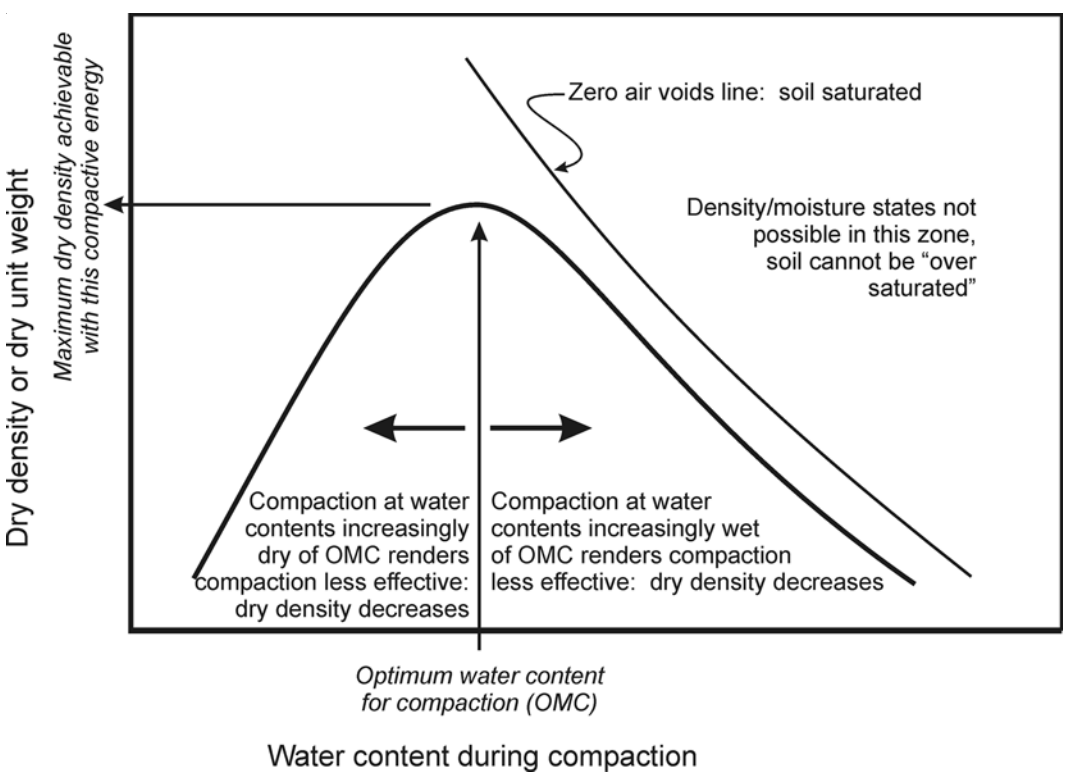

Figure 12. The Proctor moisture -- density curve.

in, with considerably greater disturbance observed in the wet season.

It was observed that while the soil was remoulded and moved a large amount by machine traffic, it was not densified. While the lack of densification would be beneficial to the growth of the next rotation, large amounts of soil displacement could lead to puddling and running of surface water, which in turn could lead to significant erosion. Besides loosening the soil, ripping was seen to leave the soil in a smoother state, reducing the chances of erosion.

ACKNOWLEDGEMENTS

The authors wish to express sincere appreciation for the financial support and enthusiastic backing provided by Rayonier Ltd. A field-based project of this size, scope, and duration is simply not possible without a willing and forward-thinking industry partner. University of Canterbury funding for Dr. Wood's Postdoctoral Fellowship at Canterbury is gratefully acknowledged.

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