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A fresh look at Operational Soil Compaction

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Abstract

The study aimed to quantify how much of a setting was adversely compacted during ground-based harvesting of an Orthic Pumice soil. Travel of harvesting machines was monitored using Global Positioning System (GPS) receivers fitted to the cabs. The resulting machine pass map was used to identify sites with 0, 1–3, 7–12 and 20–50 passes where physical properties of soil were measured. Two-thirds of the cutover was trafficked with 20% receiving more than 20 passes. Visual assessment classified the site as 87% disturbed, 6% showing deep disturbance (topsoil removal), and less than 0.2% rutted. One to three machine passes had no significant effect on soil physical properties. Although 20–50 passes led to a 60% decrease in the volume of air-filled pores, critical levels were not reached. Cone penetration resistance was >3 MPa below 34cm depth over 38% of the cutover and below 18 cm depth over 20% of the cutover.

Introduction

Nearly two decades ago, Greacen and Sands (1980) stated that although many forest managers were aware of soil compaction, the extent and degree of such compaction was not well documented. Researchers have since developed disturbance assessment methods based on either aerial photographs (Firth *et al.* 1984) or disturbance classification along transects (Murphy 1982, McMahon 1995a). The methods infer compaction where mineral soil is exposed or depressions from vehicle tracks are visible. Compacted areas over which litter or debris have been swept and areas where tracks are not visible are not detected, and compaction has been difficult to separate from soil disturbance. The proportion of a setting which has been trafficked has therefore been determined only indirectly.

The severity of compaction has been researched by measuring soil properties and tree growth. Trials have either compared areas with the same class of disturbance in operationally harvested forests, usually landings or skid trails and cut-over areas (Berg 1975, Hughes 1987), or plots subjected to controlled compaction by a known number of machine passes (Skinner *et al.* 1989, McQueen *et al.* 1996). Results from plot-based studies may be able to be related to disturbance within operational settings across a forest if the number of machine passes over each part of a setting could be determined. To do this requires a fresh look at field techniques for quantifying operational soil compaction.

Liro Limited have developed a technique for quantifying and analysing machine travel (McMahon 1997). The technique produces a geo-referenced machine pass map and pass statistics using Global Positioning System (GPS) technology, which allows investigation of operational soil compaction over entire settings. In this study we linked the GPS technique and measurements of soil physical properties to find out:

How much of a site was critically compacted due to the logging operation and where did this compaction occur?

The study site was within a strongly-dissected plateau in Kinleith Forest. Undisturbed Orthic Pumice soils, Taupo and Oruanui series, had 8-25 cm of black, humic gravelly to fine sandy loam topsoil over 10 to 55 cm of dark, reddish- to yellowish-brown gravelly to loamy fine sand subsoil. The underlying parent material of gravelly, coarse Taupo tephra sand was found at 14 to 57 cm depth.

Methods

Within five adjacent settings, approximately 20 ha of radiata pine was felled and extracted from May to July 1997. The logging operation comprised a 28 T Samsung excavator fitted with a 4 T Hultins 850 felling head (total 6.1 T/m^2 ground pressure, unloaded) (Fig. 1) and a 10.2 T Cat 518 wheeled skidder (6 T/m^2, unloaded). During the 5-week period, travel of the two machines was simultaneously measured using Trimble Pro XL GPS receivers fitted to the cab of each machine. Machine locations were recorded at 1-second intervals throughout each working day. This data was later processed to provide an expected error of less than 1.2 m (McMahon 1995b). The corrected data was then analysed using PassMap software to generate a machine pass map, at 0.5 m resolution, and pass statistics for the entire logged site. This map illustrated seven categories of machine traffic, ranging from zero to greater than 100 passes. At the completion of harvesting, disturbance across the site was visually assessed using the point transect technique of McMahon (1995a).

Figure 1 - Samsung excavator harvester fitted with Hultins head felling trees in Kinleith

One of the five settings was selected for detailed soil characterisation. Only disturbance within the 18.1 ha cutover area was characterised—the 2.1 ha of landings and road areas were excluded from the analysis. This allowed comparison of machine pass numbers with the site disturbance results. A pass map for the setting was redrawn, this time at a two-metre resolution. Pass categories were used rather than specific pass numbers to identify contiguous sampling sites at least 4 m by 4 m.

Twelve potential soil sampling sites in the 0, 1–3, 7–12 and 20–50 pass categorieswere identified on the pass map within a rolling, weakly dissected interfluve and located in the field with the aid of real-time GPS navigation. Disturbance at each sampling site was classified (McMahon, 1995a) to allow machine pass numbers to be related to surface disturbance features. Undisturbed sites were on the shoulder of the interfluve, where the depth to the underlying pumiceous parent-material would have been shallower prior to harvesting than at the broad crest of the interfluve, where logging traffic was concentrated.

Intact cores from the topsoil (0–80 mm) and upper subsoil (120–200 mm) were taken from eight sites in each pass category and analysed for macroporosity and air capacity (calculated from the volume of air-filled pores at 5 and 10 kPa tension respectively) and bulk density. Cone penetration resistance was measured at each site to a maximum of 500 mm depth. These measurements were chosen to show the extent of the two main effects of compaction. The volume (number) of large pores indicates the adequacy of oxygen-supply to roots, diffusion of toxic gases from the soil, and rapid drainage. Penetration resistance measures soil strength, which can mechanically impede root extension (Sands *et al.* 1979) and growth of mycelial strands (Skinner and Bowen 1974), and values greater than critical values indicate potential for reduced growth of the subsequent tree crop if there was no site amelioration before planting.

Results

Extent of disturbance

Sixty-six percent of the cutover area (11.9 ha) was trafficked by the harvester and/or skidder (Table 1), with 20 % (3.6 ha) having received more than 20 machine passes. The skidder travelled over a greater proportion of the cutover than did the harvester (54% versus 41% of the cutover area). Correspondingly, the proportion of heavily trafficked areas (20 or more passes) within the cutover was greater for the skidder than for the harvester (12 % versus 7% of the cutover area). There was no overlap of the heavily trafficked areas created by each machines— the harvester heavily trafficked areas near the edges of the site, while the skidder heavily trafficked primary and secondary trails close to the landing Despite 20% of the site receiving more than 20 passes, less than 0.2% of the site exhibited rutting. Consequently, channelisation of runoff was not expected. Untrafficked areas were located around the margins of the site and on steep faces where the trees were manually felled.

A visual assessment of disturbance found that 87% of observations (n = 1917) were classified as disturbed.

Table 1 - Proportion of the cutover area, excluding roads and landings, which was trafficked by harvesting machines. The total cutover area was 18.1 hectares.

Number of machine passes	Area affected (ha)	Proportion of site affected (%)
0	6.3	35
1-3	3.3	18
4-6	1.6	9
7-12	1.9	11
13-19	1.4	8
20-50	2.3	13
51-100	0.8	4
>100	0.4	2

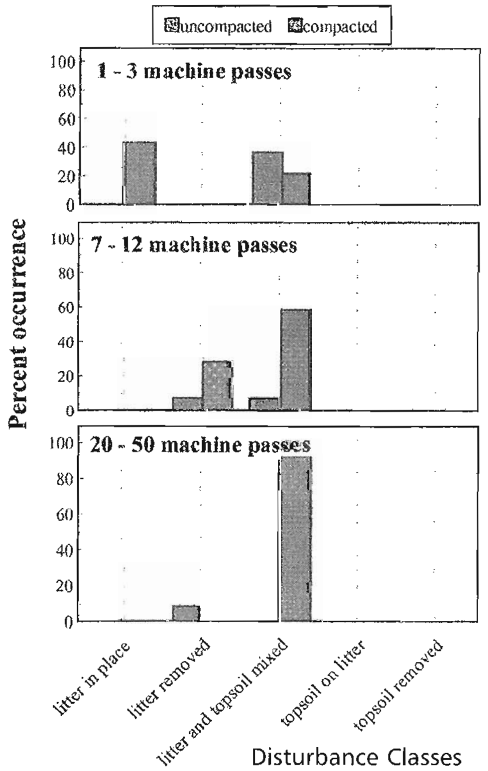
Only 6% of observations exhibited deep disturbance where the topsoil had been removed to expose the subsoil. Evidence of compaction was seen for 21% of the observations.

Severity of disturbance

The severity of soil disturbance was assessed in two ways: first by relating the site disturbance classification to machine pass category, and second by characterising changes in the physical status of topsoil and subsoil.

As the number of machine passes increased from 1–3, to 20–50 passes, the disturbance classification tended from litter in place, uncompacted to litter and topsoil mixed, compacted (Fig. 2). Primary and secondary skid trails subjected to 20–50 machine passes had only shallow disturbance, i.e., subsoil was not exposed.

Figure 2 - Surface disturbance classification for the three machine pass categories. The 20-50 pass category was classified as shallow disturbance (litter and topsoil mixed)



Soil cores revealed that although the total porosity of the topsoil decreased by only 10% after 20–50 passes, the volume of large pores was decreased by 60%, with a resultant increase in small pores (water-holding capacity of the topsoil increased by 50%) (Table 2).

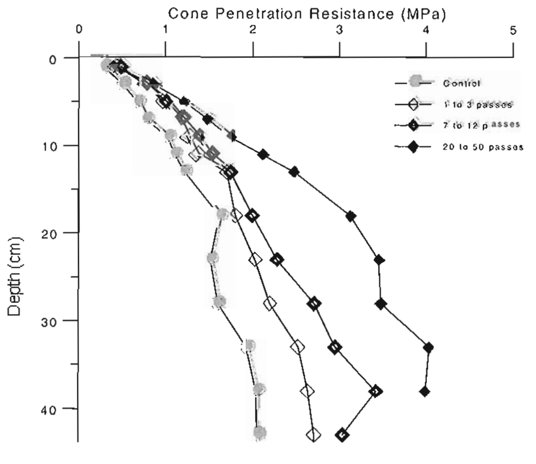
Table 2 - Mean porosity and bulk density values for topsoils and subsoils for four pass classes (n=8, different letters indicate significant differences at p<0.01).

Number of passes	None	1 to 3	7 to 12	20-50
Topsoil (0-80 mm)				
Total porosity (%)	71 a	72 a	68 ab	64 b
Air capacity (%)	40 a	32 ab	24 bc	17 c
Bulk density (T/m³)	0.68 a	0.65 a	0.75 ab	0.89 b
Subsoil (120-200mm)				
Total porosity (%)	71 a	68 a	66 ab	60 b
Air capacity (%)	38 a	32 ab	33 ab	25 b
Bulk density (T/m³)	0.68 a	0.76 a	0.81 ab	0.96 b

The upper subsoil was less affected, being cushioned by the overlying litter and topsoil and through the decreasing impact of compaction with increasing soil depth. Because this soil had such a large volume of air-filled pores in its undisturbed state, the compacted topsoils and subsoils still retained a favourable aeration status. The volumes of large, air-filled pores were above critical values for all pass categories measured, and root growth is, therefore, unlikely to be restricted by lack of oxygen.

Cone penetration resistance increased as the number of passes increased, with values considered to be limiting to root growth (>3 MPa) occurring below 18 cm in the 20–50 pass category and below 34 cm in the 7–12 pass category (Fig. 3). The depth to which penetration resistance could be measured was governed by the depth of a gravelly pumice layer which underlies the site. The depressed surface of the 20–50 pass category decreased the depth to this layer.

Figure 3 - Cone penetration resistance versus depth results for four pass categories. The depth of sampling was restricted by a layer of Taupo rephra with a coarse sand to gravel texture.



As the number of passes increased, the structure of the black topsoil changed from a loose friable nut and crumb to a blocky structure and topsoil thickness was reduced. After 51–100 passes, the upper subsoil was also visually affected, becoming blockier.

Discussion

Extent of operational compaction

Visual assessment of soil compaction can be difficult in operational settings. Surface expressions of compaction can be obscured by slash and toppled undergrowth. Also, the important impacts from a tree growth standpoint occur below the soil surface, out of view of an observer. These limitations mean that while visual disturbance assessment is likely to be a useful indicator of compaction extent, it is unable to discern differing levels of severity. This study provided us with the first opportunity to compare the extent of compaction defined by the disturbance assessment with machine travel information in operational settings.

Twenty-one percent of the classified disturbance within the cutover area was classified as compacted. These were sampling points that exhibited direct evidence of machine passage such as wheel ruts and tyre imprints. This result was similar to the proportion of the site having received 20 or more passes (Table 3). It may be coincidental that these results are similar. Given that this has been the first comparison of this type, it would be premature to believe that the disturbance assessment is providing an indication of more than 20 passes.

Table 3 - Comparison of disturbance assessment results with machine coverage measured by GPS technique.

	Proportion of total cutover area
Disturbance assessment method (classified as compacted)	21%
GPS method	
- 1 or more passes	66%
- 20 or more passes	20%

Bryan *et al.* (1985) related turn numbers (in and out journey of a skidder) to maximum disturbance depth for a small site in Mangatu Forest, finding that surface disturbance was correlated with turn number up to 10–20 passes and then essentially remained constant. A point transect method was used, finding 35% of the site visibly tracked. Firth *et al.* (1984) assessed the impact of ground-based harvesting on nine flat to undulating sites in New Zealand using a five-level site disturbance classification system that did not specifically identify compacted areas. On average, 54% of a site was undisturbed, 32% showing shallow disturbance (litter layer disturbed or topsoil exposed) and 14% showing deep disturbance (topsoil removed). Comparable figures for our study probably reflect the easy access across the site and resilient nature of the soil, with 80% of the site showing shallow disturbance and only 6% showing deep disturbance—9% of the area was covered with slash and therefore unclassifiable.

Severity of operational compaction

This study confirms that severity of compaction is positively correlated with machine pass numbers in this Orthic Pumice soil. Unusually, 1–3 machine passes caused no statistically significant change in the soil physical properties measured—significant changes were only evident after 7–12 passes, although the effects of 4–7 passes were not measured. Most damage to soils is usually expected in the first few passes. Critical soil porosity was not achieved within the range of sampling depths (0–200 mm) and machine pass categories (20–50 passes) studied. However, cone penetration resistance levels >3 MPA were reached below 34 cm in the 7–12 pass category (approximately 38% of the cutover) and below 18 cm in the 20–50 pass category (approximately 19% of the cutover). Resistance may be increased when compaction causes bridging of pumice fragments. Cone penetration resistance can be greatly affected by soil water content, so results should be viewed as applying only to soil conditions at the time of study.

Two other studies have measured the response of similar Orthic Pumice soils in Kinleith Forest to increasing levels of compaction or disturbance. McQueen *et al.* (1996) used an unladen 14.5 T, rubber-tyred skidder to provide three levels of machine passage on Taupo silt loam to sandy loam soils. The effects of compaction increased with increasing numbers of machine passes. Both 5 and 25 passes reduced the volume of large pores in the topsoil below levels considered critical for root growth—air capacity dropped from 31% to 6% v/v after 25 passes. This is a greater proportional decrease than that measured in our operational field trial (40% to 17% v/v after 20–50 passes), and the effect was exacerbated in McQueen's trial as the soil had a smaller volume of large pores before compaction, so could 'afford' to loose less of them. Proportional changes in total porosity (-10%) and bulk density (+27%) were similar in both trials. McQueen *et al.* (1996) report an increase in cone penetration resistance in compacted treatments, with 3 MPa exceeded in the 25-pass treatment at about 19 cm depth, and 22 cm depth in the 5-pass treatment. The shallower depth may reflect the impact of a natural barrier of pumice at about 30 cm depth.

The diminished impact of compaction measured in our operational study, compared to McQueen *et al.* (1996), probably reflects both the slightly coarser texture of Taupo fine sandy loam to sandy soils, and the possible lower compactive impact of operational harvesting associated with the protective cushion of slash over which the harvesting machines travel and incorporate slash and litter into the topsoil. In McQueen *et al.* (1996), slash was removed from the trial before compaction. Photographs of the site after compaction show that 25 passes had exposed the topsoil, but not the subsoil.

Hughes (1987) quantified changes in physical properties of a Taupo loamy sand after harvest with a 668 skidder—the same model as used by McQueen *et al.* (1996). Soil disturbance was classified in five levels according to Firth *et al.* (1984). Even in the most severely disturbed sites such as landings and main skid trails (level 4), the volume of large pores was non-limiting, though reduced by 46%. Cone penetration resistance was increased to >3 MPA within 35 cm of the soil surface on main skid trails where topsoil was exposed (level 3) compared to below 50 cm on undisturbed sites.

Orthic Pumice soils are among the most resistant soils to compaction and degradation in New Zealand. The topsoils have a high percentage of organic matter which cushions the soil, increases its elasticity and favours a very high volume of large pores in their undisturbed state. The porous, vesicular nature of pumice also provides a buffer against compaction. An exception is where a welded pumice layer that roots cannot penetrate is near the soil surface—in such soils degradation can occur if the depth of soil is reduced.

Conclusions

This has been the first compaction study in New Zealand to combine machine tracking with detailed soil characterisation. Using the newly developed GPS-based methodology, we have been able to investigate both the extent and severity of soil compaction across an operational area. The mechanised logging operation was shown to have trafficked 66% of the cutover area, with 19% of the area having been subjected to 20 or more passes. The landings and roads covered 10% of the entire site.

Results highlight the resilience of Orthic Pumice soil to compaction—after 20–50 machine passes the volume of large pores remained above critical limits, despite being reduced by as much as 60% compared with untrafficked areas. Damage to soil structure, most sensitively measured by the % of large pores (0 to -5 kPa and 0 to -10 kPa), was not significant after 1–3 machine passes. Cone penetration resistance was above 3 MPa below 34 cm depth over 38% of the cutover and below 18 cm depth over 19% of the cut over. These areas occurred primarily on the primary and secondary extraction tracks close to the landings. Without cultivation, will the soil recover while the newly-planted crop grows, or could compaction during the next harvest result in degradation to growth-limiting levels?

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