

Compaction and soil disturbances from logging in Southern Chile

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Summary — In an andesitic dystrochrept clay forest soil, the effect of a different number of passes of a rubber-tyred skidder on bulk density, total porosity and saturated hydraulic conductivity was studied. Soil samples were taken in undisturbed areas, and under skid trails with 1, 2, 3, 5 and 10 machine passes. Most compaction occurred after the initial few passes, but bulk density also increased significantly after more than 3 passes. Increases in bulk density were still important at the maximum sampling depth of 20 cm. Total porosity decreased for all treatments, associated with a reduction of macropores. The saturated hydraulic conductivity became significantly reduced after the first initial passes. The effect of compaction on tree growth needs to be further studied and quantified.

soil compaction / soil disturbances / ground-based logging / bulk density / saturated hydraulic conductivity

Résumé — **Compactage et perturbation du sol après une exploitation forestière au Chili méridional.** On a étudié l'influence du nombre de passages d'un débusqueur à pneus sur la densité apparente, la porosité totale et le coefficient de conductivité hydraulique d'un sol brun andésitique. Des échantillons de sol ont été prélevés dans des terrains non perturbés, et sous des chemins de débarquement ayant 1, 2, 3, 5 et 10 passages. Le compactage le plus important s'est produit après les premiers passages, mais la densité apparente a encore augmenté significativement après le troisième passage. La densité apparente a aussi augmenté jusqu'à 20 cm de profondeur. La porosité totale a été réduite dans tous les cas, associée à une réduction des macropores. Le coefficient de conductivité hydraulique a été significativement réduit après les premiers passages. L'effet du compactage du sol sur la croissance des arbres doit être étudié et quantifié.

compactage du sol / perturbation du sol / débusqueur à pneus / densité apparente / coefficient de conductivité hydraulique

INTRODUCTION

In Chile, forestry-related activities have increased substantially during the last 15 yr. This is partly due to the growth of the area under plantations at an average of 79 000 ha yr since 1973, reaching more than

1 240 000 ha in 1986 (Instituto Forestal, 1987). Increased mechanization and the use of heavy machinery in logging operations have caused severe disturbances to forest soils, and compaction effects have been widely reported within the country (Monrroy, 1981; Gayoso, 1982; Gayoso and Iroumé, 1984).

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According to Beekman (1987) compaction alters the soil's physical and mechanical properties and leads to a less favorable condition for plant growth, which in turn leads to a decline in site productivity (Ges-sel, 1981) and reduces the present net worth of future timber harvests (Routledge, 1987).

Compaction can extend to a considerable depth of the soil profile (Moehring, 1970) and the major compaction occurs during the first passes of machinery (Adams and Froehlich, 1981). Upon compaction, soil strength increases while total porosity, available water, air content, infiltration rate and saturated hydraulic conductivity decrease (Incerti *et al.*, 1987). As a consequence, tree growth can be reduced because of restrictions in root development, water supply and aeration (Corns, 1988; Vepraskas, 1988). In addition, surface runoff may increase and soil erosion be promoted (Sidle, 1980; Standish *et al.*, 1988).

The extension of soil disturbances can be reduced by designing skid trails prior to harvesting (Froehlich *et al.*, 1981). The intensity can be reduced by harvesting during the driest periods of the year, logging downhill where possible and selecting low ground pressure equipment (Wingate-Hill and Jakobsen, 1982). Sometimes damaged soils can be ameliorated by cultivation (Moehring, 1970).

Chilean foresters have become aware of soil alterations, but the degree and extent of the problem has not been widely quantified. The objective of this study was to assess compaction intensity and the effects on soil dry bulk density, total porosity and saturated hydraulic conductivity, following a clearcutting operation in southern Chile.

THE STUDY AREA

The study area is located approximately 39°44' S and 73°10' W, 15 km from the city of Valdivia in southern Chile. The site has a northern aspect with slopes varying between 5% and more than 60%, and elevations ranging from 110 to 220 m above sea level.

The area was covered with a 25-yr-old Monterey pine plantation clear-felled during the last winter. A rubber-tired skidder was used to transport uphill logs to landings.

The climate of the area is rainy-temperate with a Mediterranean influence (Fuenzalida, 1965). Annual rainfall in the city of Valdivia (9 m above sea level) ranges from 1 752 to more than 2 936 mm (Fuenzalida, 1965). The period between May and August concentrates 70% of the 2 340 mm long-term annual average rainfall (Reyes, 1981). Mean annual temperature is 12 °C with a maximum monthly mean of 16.9 °C in January, and a minimum of 7.6 °C in July. Predominant winds come from the north between April and September, and from the west between October and February.

The geological substratum corresponds to the "Piedra-Laja" formation, a coastal metamorphic complex formed mainly by micaceous schists with intercalations of quartz lenses (Illies, 1970).

Soils correspond to an andesitic dystrochrept forest type (Série Correltue) developed from pleistocene volcanic ash deposited on the coastal metamorphic complex (Gayoso and Iroumé, 1984). Apart from the high clay content (40–50%), they have a high porosity and high water

infiltration rate. Table I presents some of the soil's physical and chemical properties.

METHODS

Within the logging site, sampling plots were selected in undisturbed and disturbed areas. In this study, areas not used as trails or log landings were considered as undisturbed. In disturbed areas with a 10 and 20% slope, plots were chosen under skid trails with 1, 2, 3, 5 and 10 machine passes. In areas with a 10% slope, the logged volumes in each pass were 2 and 4 cubic meters (3 and 6 logs respectively), while in areas with a 20% slope the logged volume was 2 m³ (3 logs). The skidder used to log uphill whole trees was a rubber-tyred Caterpillar 518 with the following characteristics: weight: 10 250 kg; tyre sizes: 18.4 x 30", tyre pressure: 170 kPa.

In the top 5 cm of the soil profile of each plot, 9 undisturbed core samples of 100 cm³ were collected. In addition, 3 samples of 100 cm³ were taken from each of the following depths in the soil profile: 6 to 10, 11 to 15, and 16 to 20 cm. The soil samples were oven-dried at 105 °C

for 24 h to obtain dry bulk density and total porosity (Lee *et al*, 1983).

From the top 12 cm of the soil profile, 6 undisturbed core samples of 940 cm³ were also collected in each plot. The samples were saturated and the saturated hydraulic conductivity was measured using a constant head permeameter, according to Head (1982).

All intact core samples were collected using a double-cylinder hammer-driven core sampler, and all sample points were randomly selected. Traffic and sampling occurred during the wet period. Soil water content in undisturbed areas was 84% in surface (0–10 cm deep) and 66% in the 11–20 cm deep layer.

RESULTS AND DISCUSSION

In areas with a 10% slope, the differences between the results of soil alterations under trails where the skidder snig logged 2 and 4 m³, respectively, were statistically non significant, and are presented as belonging to the same data population.

Bulk density and total porosity

The results in figure 1 show that in areas with a 10% slope, the bulk density in the top 5 cm of the soil increased by 11% after 1 pass, 15% after 2 passes, 21% after 3 turns, 31% after 5 machine passes, and 45% under trails with 10 skid passes. Bulk density also increased in depth under the skid trails. For example, in areas with a 10% slope, the bulk density increased by 39% between 6 to 10 cm depth, by 34% between 11 to 15 cm, and by 32% between 16 to 20 cm, after 10 machine passes.

In areas with a 20% slope, the bulk density in the top 5 cm of the soil increased by 23% after 1 pass, 32% after 2 machine passes, 37% after 3 turns, 48% after 5 passes, and 60% under trails with 10 skid passes (fig 2). As occurred in areas with a

Table I. Selected top soil physical and chemical properties.

<i>Property</i>	<i>Value</i>
Bulk density (Mg·m ⁻³)	0.62
Particle density (Mg·m ⁻³)	2.50
Total porosity (%)	75
Porosity < 0.2 µm (%)	31
Sand (%)	30
Silt (%)	26
Clay (%)	44
Aggregate average size	
dry-sieved (mm)	1.7
wet-sieved (mm)	1.2
Plastic limit (%)	50
Liquid limit (%)	71
Cohesion (kPa)	71
Internal friction angle (°)	4
Total carbon (%)	7.45

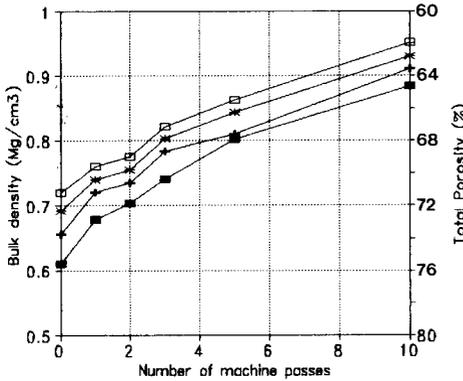


Fig 1. Effect of skid passes on soil bulk density (10% slope).

■ 0-5 cm; ▲ 6-10 cm; * 11-15 cm; □ 16-20 cm

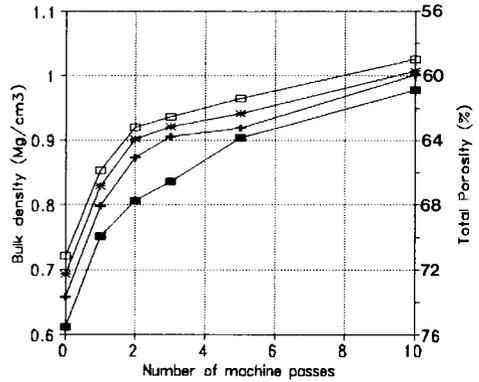


Fig 2. Effect of skid passes on soil bulk density (20% slope).

■ 0-5 cm; ▲ 6-10 cm; * 11-15 cm; □ 16-20 cm

10% slope, bulk density also increased in depth under the skid trails with a 20% slope. After 10 machine passes, the bulk density increased by 52% between 6 to 10 cm depth, 46% between 11 to 15 cm, and 43% between 16 to 20 cm.

These increases differ from those presented by Adams and Froehlich (1981) and Incerti *et al* (1987) but can be explained by different soil types and conditions, and logging equipment. Moehring and Rawls (1970) found that more severe compaction occurs from traffic on saturated than on dry soils.

In trails with a 20% slope, the increase in bulk density for all different numbers of machine passes and depths was significantly higher as compared with those observed in trails with a 10% slope. This may be a consequence of the difficulties that the skidder found when logging in steep terrains. Under these conditions the machine slipped continuously and remained for a longer period of time in a given place, puddling and dragging the soil.

From figures 1 and 2 it can be seen that most compaction occurred after the first few passes, although bulk density still increased significantly after more than 3 passes for all layers. This is slightly different from data presented by Froehlich (1978) and Adams and Froehlich (1981).

From data obtained in a clay loam soil in the Oregon coast range, Sidle and Drluca (1981) developed a regression equation to determine the impact of the number of passes and slope gradient on bulk density. These authors found that the slope did not significantly affect bulk density, but they concluded that it can be an important factor in the potential level of compaction.

This fact was proven in this study, and the best relationship between bulk density (*BD* in $Mg \cdot m^{-3}$) as dependent variable, and number of machine passes (*NP*) and slope gradient (*SG* in %) as independent variables, for all 4 depths, were :

$$(for\ 0 - 5\ cm)\ BD = 0.56 + 0.22 \log_{10}(NP) + 0.009 SG\ (r^2 = 0.977) \quad (1)$$

$$\text{(for 6 - 10 cm) } BD = 0.59 + 0.19 \log_{10}(NP) + 0.011 SG \quad (r^2 = 0.965) \quad (2)$$

$$\text{(for 11 - 15 cm) } BD = 0.62 + 0.18 \log_{10}(NP) + 0.011 SG \quad (r^2 = 0.969) \quad (3)$$

$$\text{(for 16 - 20 cm) } BD = 0.64 + 0.18 \log_{10}(NP) + 0.011 SG \quad (r^2 = 0.970) \quad (4)$$

The coefficients of determination for all equations were significant at the $\alpha = 0.01$ level and the standard errors of *BD* estimations were 0.016 for Eq 1, 0.019 for Eq 2, 0.017 for Eq 3 and 0.017 for Eq 4.

A value of $1.10 \text{ Mg}\cdot\text{m}^{-3}$ for bulk density on the top soil layer has been measured in the same area under logging roads and landings (Gayoso and Iroumé, 1984). Although it is hazardous to use Eq 1 to extrapolate beyond 10 passes, it is possible to estimate that such bulk density is reached after 50 or 100 machine passes, depending on the slope gradient.

Close to the studied area, growth losses of up to 30% in tree height have been reported associated with severe compaction and bulk densities of $1.07 \text{ Mg}\cdot\text{m}^{-3}$ (Gayoso, 1982). According to Sidle and Drlica (1981), bulk density in trails with 4 to 11 passes can be considered as intermediate compaction, and this level of compaction can affect site productivity. The limit of bulk density from which compaction can reduce non-capillary porosity and root development to critical levels for tree growth must be determined for each individual soil type.

As can be observed from these results, in all cases the major increases occurred in the top of the soil profile but they were still important at 16–20 cm, suggesting that compaction extended deeper. According to this observation, compaction could affect the top 30–40 cm of the soil where a greater part of the root system of Monterey pine is distributed (Murphy, 1982).

Bulk density can recover, especially in surface layers. Hatchell *et al* (1970) estimated by regressions that recovery to un-

disturbed conditions can be expected 18 yr after compaction. However, Went and Thomas (1981) reported that compaction was still severe after 32 yr. Severely compacted soils could be retored by ploughing, disking and subsoiling.

Due to the existence of the one-to-one correspondence between bulk density and percentage total porosity, total porosity decreased after a different number of machine passes associated with increases in bulk density (figs 1 and 2).

The decrease in total porosity for all treatments must be associated with a reduction of macropores. For this soil, Gayoso and Ellies (1984) determined that macropores (*ie* $> 50 \mu\text{m}$) decreased from 28.1 to 9.2%, that the percentage of intermediate porosity (*ie* 0.2 to $50 \mu\text{m}$) remained almost invariable, and that micropores (*ie* $< 0.2 \mu\text{m}$) increased from 30.5 to 40.4%, from undisturbed to severely compacted conditions.

According to Baver *et al* (1972), a reduction of macropores below 10% of soil volume at matric potentials below 100 cm water can be considered to be restrictive to root growth because of poor aeration and increase in soil strength. Jurgensen *et al* (1979) found that major productivity losses are associated with poor oxygen availability.

The decrease in total porosity is not a clear indication of restrictions to root and tree growth, and it is certainly not critical for Monterey pine establishment; at least in a soil such as the one studied that has 75% total porosity. The determination of pore size distribution is essential for future studies.

Saturated hydraulic conductivity

The results for the saturated hydraulic conductivity (*K*) of the top 12 cm of the soil are

presented in table II. According to Rogowsky (1972), Talsma and Hallam (1980) and Incerti *et al* (1987) it is possible to assume a log-normal distribution for the data of each individual treatment. The geometric mean can then be calculated because it equals the median value for a lognormal distribution, and the antilog of the standard deviation of the transformed data may be used as an index of variability.

Associated with an increase of bulk density and a decrease in total porosity, the saturated hydraulic conductivity varied for all treatments. In areas with a 10% slope, the geometric mean value for K decreased by 35% after 1 pass, 89% after 2 machine passes, 90% after 3 machine passes, 93% after 5 passes, and 99% under trails with 10 skid passes. In areas

with a 20% slope, K decreased by 90% after 1 pass, 94% after 2 machine passes, 97% after 3 passes, 98% after 5 passes, and 99% under trails with 10 skid passes.

In spite of the variations of 1–2 orders of magnitude of K , the higher values of antilog S were not much greater than 2, and for some of the individual treatments even smaller than 2. This value (2) for the index of variability has been tentatively suggested by Rogowsky (1972) as an upper limit for uniformity of hydraulic conductivity within soil series. The values obtained in this study for such an index suggest that K was relatively uniform.

According to Incerti *et al* (1987) the median and the range for each treatment can indicate the difference between treatments. In the skid trails with a 10 and 20%

Table II. Saturated hydraulic conductivity.

No of machine passes	Total porosity (%)	Slope gradient (%)	Saturated hydraulic conductivity ($m \cdot day^{-1}$)				Variability (antilog S)
			Mean	Geometric mean	Median	Range	
u(*)	74.8		3.737	2.078	3.586	0.13 – 8.55	4.04
	72.8	10	2.944	1.359	2.652	$7.77 \cdot 10^{-2}$ – 8.04	4.75
	70.5	20	0.330	0.218	0.302	$5.36 \cdot 10^{-2}$ – 0.80	2.75
2	72.4	10	0.335	0.230	0.246	$7.17 \cdot 10^{-2}$ – 0.95	2.14
	69.2	20	0.210	0.120	0.127	$2.73 \cdot 10^{-2}$ – 0.74	2.85
3	71.1	10	0.302	0.216	0.205	$6.82 \cdot 10^{-2}$ – 0.68	2.81
	68.0	20	0.067	0.054	0.055	$2.59 \cdot 10^{-2}$ – 0.16	1.88
5	64.4	10	0.171	0.140	0.113	$5.09 \cdot 10^{-2}$ – 0.37	1.86
	62.7	20	0.060	0.050	0.048	$2.59 \cdot 10^{-2}$ – 0.14	1.86
10	61.7	10	0.034	0.023	0.035	$4.32 \cdot 10^{-2}$ – 0.16	2.89
	56.9	20	0.035	0.018	0.017	$8.64 \cdot 10^{-3}$ – $5.96 \cdot 10^{-2}$	2.28

(*) u = undisturbed areas

slope, the median and also the mean, geometric mean and the range decreased with increases in the number of machine passes.

The decrease in hydraulic conductivity is related to a decrease in total porosity. The best relationship found between the geometric mean of K (in $\text{m}\cdot\text{day}^{-1}$) and total porosity (TP in %) obtained from the top 12 cm soil samples is :

$$\log_{10} K = -29.14 + 15.47 \log_{10} TP \quad (5)$$

$(r^2 = 0.760)$

The coefficient of determination of Eq 5 is significant at the $\alpha = 0.01$ level.

The saturated hydraulic conductivity decreased by 90% (*ie* from 2.078 to 0.216 $\text{m}\cdot\text{day}^{-1}$) with a decrease in total porosity of only 5% (*ie* from 75 to 71%). This last value of total porosity was achieved after 1 to 3 passes. A further decrease in K by 92% (*ie* from 0.216 to 0.018 $\text{m}\cdot\text{day}^{-1}$) was associated with an additional decrease in total porosity of 20% (*ie* from 71 to 57%). This may be a consequence of a strong reduction of macropores during the first levels of compaction (after 1 to 3 machine passes). After the initial passes, the reduction of total porosity may be caused by a decrease of pores of all sizes, which results in a slower reduction of K .

Although saturated hydraulic conductivity is not the only factor that determines surface runoff, in a first approach it can be said that runoff will occur when the rainfall rate exceeds K . From rainfall data for the studied area, rainfall events with a recurrence interval of 20 yr can be estimated at 0.15 $\text{m}\cdot\text{d}^{-1}$, and the soil is able to allow the infiltration of such events in areas with less than 2 to 5 skid passes. Because hydraulic conductivity determined *in situ* can be an order of magnitude smaller than results measured from core samples (Topp and Binns, 1976), runoff may occur more often than predicted.

As occurs with bulk density, the saturated hydraulic conductivity can also recover. Perry (1964) estimated that approximately 40 yr are required to recover the initial infiltration capacity. Considering that the usual rotation period for Monterey pine plantations in Chile is about 25 yr, the recovery of K could be restricted.

The decrease in saturated hydraulic conductivity should result in increased runoff, which could promote erosion and nutrient losses while reducing soil water availability. These effects are now being evaluated in experimental sampling plots.

CONCLUSION

The results show that logging operations at the studied site have a significant impact on the soil's physical properties. Increases in bulk density and decreases in total porosity and saturated hydraulic conductivity were detected. Most compaction occurred after the first few machine passes, although bulk density increased significantly after more than 3 passes. Increases were still important at 20 cm depth suggesting that compaction could affect the top 40 cm of the soil, where a greater part of the root system of Monterey pine is located. Further work in this area should at least consider the top 40 cm of the soil profile and determine critical values of bulk density above which tree growth can be affected. In addition, the effect of high organic matter content on soil compaction resistance under humid conditions must be quantified.

The observed decrease in total porosity must mainly be associated with a reduction in macroporosity, shown by the decrease of hydraulic conductivity. This suggests that poor oxygen availability can be the primary limiting factor to tree growth. Pore size distribution analysis is essential for future studies.

Saturated hydraulic conductivity was found to be markedly reduced with relatively low decreases in total porosity, resulting in an increased potential for runoff, erosion and nutrient losses, which can further affect site productivity.

In Chile, large areas of man-made forests are intensely managed. Increasing mechanization and the use of heavy machinery in forest operations suggests the need to quantify the extension and intensity of soil compaction, and the effect on tree growth. The natural rate of recovery and the effect of some cultivation practices must also be analyzed.

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