HARVESTING TRAFFIC AND RIPPING AFFECT GROWTH OF *PINUS RADIATA*

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ABSTRACT

Growth of *Pinus radiata* D. Don was examined after a harvesting and tillage trial at Taringatura in the South Island of New Zealand; in that experiment forest soils had been subjected to various intensities of traffic by a range of harvesting machinery, followed by ripping of the soil. Harvesting traffic disturbed but did not compact the soil. Soil penetration resistance was markedly decreased by ripping but not significantly affected by traffic intensity. Ripping increased and traffic reduced the stem volume of *P. radiata*.

Most notably, there was an interaction between ripping and traffic: stem volume increased with the number of passes of harvesting machines on ripped soils but decreased with the number of passes on non-ripped soils. This was explained by traffic reducing the competitive weeds in the ripped treatments.

Keywords: soil compaction; soil disturbance; weed control; soil penetration resistance; soil bulk density.

INTRODUCTION

Harvesting machines can both compact (increase the bulk density) and disturb (displace and mix) forest soils. The extent to which soils are compacted and/or

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disturbed depends on the characteristics of the machines and how they are used, the soil type, and the soil water content. Soil compaction may improve plant growth when it increases the water retention and hydraulic conductivity of loosely packed soils, but it may reduce plant growth on more tightly packed soils by increasing soil penetration resistance and/or reducing soil air-filled porosity. Soil disturbance can adversely affect subsequent plant growth if it removes nutrient-rich topsoil, exposes subsoil, or removes litter. Depending on circumstances, soil disturbance may have greater adverse effects on plant growth than soil compaction. The effect of heavy machinery on soil compaction and disturbance has been reviewed by Hadas (1994) and that of soil compaction on the growth of trees has been reviewed by Kozlowski (1999).

Ripping can be used as a remedial treatment to counteract the negative effects of compacted soils by reducing soil bulk density which reduces soil penetration resistance, thereby enhancing root growth. Ripping can also increase the proportion of air-filled pores relative to water-filled pores; this may enhance root growth if soil aeration is a problem, but can also reduce root growth (through reduced water retention) if aeration is not a problem. The optimal bulk density for plant growth will be a balance between soil penetration resistance, soil water retention, and soil air-filled porosity.

This study was part of the Taringatura harvesting and tillage trial, an experiment in the South Island of New Zealand in which forest soils were subjected to various intensities of traffic by a range of harvesting machinery followed by ripping of the soil (Wood *et al.* 2006). This aim of this study was to examine the effect of these treatments on the growth of *Pinus radiata* subsequently planted on the site.

MATERIALS AND METHODS

The establishment of the traffic and ripping trial in the Taringatura Forest has been reported in full by Wood *et al.* (2006). In summary, the trial was located on a relatively flat, south-sloping site, approximately 50 km north of Invercargill in New Zealand's South Island. The mean annual rainfall was 1000 mm, and the soil was a stony silt loam classified as a Humic Dystrudept according to the International Soil Classification. The experiments were established during the routine harvesting of a plantation of *P. radiata* that had been planted at a spacing of approximately 3 × 3 m in 1972. Duplicate experiments were established — Trial 1 in November 2001 and Trial 2 in June 2002. The initial objective was to replicate the experiment under dry and wet conditions as usually the soil in November would be expected to be relatively dry and in February relatively wet. However, the soils were wet in both months. There were three types of fully laden harvesting machines (Timberjack 1710 forwarder, John Deere 648G-II skidder, and Cat 525 skidder) each of which made one, three, 10, and 30 passes, east–west, over plots 10 × 25 m. An area in each plot was left undisturbed as a control. There were two replicates per treatment and consequently there should have been 48 plots in total (2 trials × 3 machines × 4 passes × 2 replicates). However, operational difficulties in some of the 30 pass treatments reduced the plots to 45. In July 2002, one-half of each experimental plot was ripped to a depth of 50 cm at 2 m spacing, five rip lines in total running north–south, using a Komatsu 220LC tracked excavator with a boom fitted with a winged ripping tine.

One-year-old bare-rooted GF17 *P. radiata* seedlings were then planted (July 2002) at a spacing of 2 × 2 m at the intersection of the machine tracks and the rip lines. Consequently, each experimental plot (Fig. 1) contained four subplots representing four treatments: (a) ripping + traffic; (b) ripping; (c) traffic; (d) control (no traffic and no ripping). There were 10 trees in each sub-plot and the ripped and non-ripped sections of the plots were separated by a buffer comprising a single line of trees running north–south through the centre of the plot. Weeds were initially controlled by spot sprays of terbuthylazine (19 kg/ha) and hexazinone (260 kg/ha) applied prior to planting.

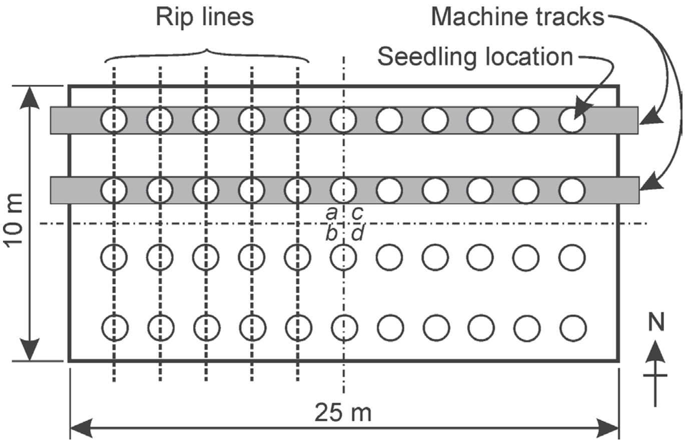

FIG. 1–The layout of an experimental plot. There were four subplots: (a) ripping + traffic; (b) ripping; (c) traffic; (d) control. Each sub-plot contained 10 trees.

The height, diameter at ground level (mean of east–west and north–south), form (number of leaders, straightness, toppling), visual health (graded 1–5 from poor to good), and a visual estimate of weed abundance in each subplot (from 0 no weeds to 3 full cover) were measured in April 2005. Stem volume (v) was calculated from basal stem diameter (d) and stem height (h) using the equation $v = \pi d^2 h/12$. The results demonstrated the desirability of more detailed information about root distribution and weed abundance. It was not practical to take these measurements over the whole experiment because of time and logistical constraints. Consequently, in June 2005, the forwarder 10-pass experimental plots (both replicates, Trial 2 only) were sampled in more detail for the quantity of weeds and the distribution of *P. radiata* roots >1 mm diameter. It was not possible to distinguish between weed and tree roots <1 mm diameter within the time and equipment constraints of this study. The three trees closest to the mean height in each treatment (sub plot, Fig. 1) were selected. Weeds were harvested above ground level from an area defined by a square of 1 × 1 m where the tree was in the centre of the square. The dry weights (70°C for 72 hours) of the weeds were recorded. Soil samples were collected around the selected trees in 80-mm long × 50-mm external diameter stainless steel tubes (1 mm wall thickness) at depths of 1–9, 11–19, and 46–54 cm at a distance of 50 cm from the tree in each cardinal direction (north, east, south, and west). The soil samples were wet sieved and the clean *P. radiata* roots >1 mm diameter were collected, oven dried (70°C for 48 hours), and weighed. The results were analysed using discriminate analysis and analysis of variance. Unless stated otherwise, significant differences in analysis of variance are $p>0.05$.

RESULTS

The results refer to either the extensive experiment (all treatments, both replicates, both trials) or the intensive experiment (forwarder, 10 pass, both replicates, Trial 2 only). The treatment combination for the intensive experiment was chosen because it represented the treatment with the highest number of passes where there was a complete data set available (no missing plots). Time and logistical constraints confined the intensive experiment to one machine-type only.

The Extensive Experiment

Wood *et al.* (2004, 2006) reported that traffic did not significantly increase soil bulk density but disturbed the soil through rutting, lateral displacement, and soil heave. Traffic did not significantly alter penetration resistance but ripping caused significant and substantial decreases in soil penetration resistance (Fig. 2).

There were no significant differences in tree form or tree health, and there were no significant effects of season or machine type on any variables. Significant effects ($p<0.05$) are summarised in Table 1 — the 30-pass treatments were disregarded because of missing values. The effects of traffic and ripping were highly significant except for the effect of traffic on stem height (Table 1). Stem volume of *P. radiata* increased on plots with traffic and particularly ripping, and there was an inverse relationship between the abundance of weeds and stem volume (Fig. 3). The passes × ripping interaction was significant (Fig. 4). Stem volume decreased with number of passes when the soil was not ripped but increased with number of passes when the soil was ripped.

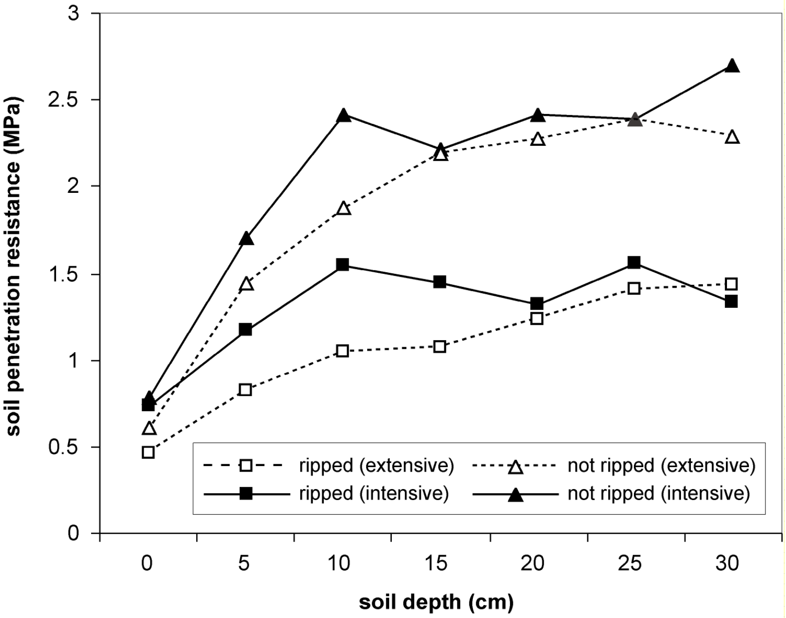

FIG. 2–The relationship between soil penetration resistance and soil depth for the extensive experiment and the intensive (forwarder, 10 pass) experiment. Penetration resistance was measured using a recording portable unit with a detachable conical tip of 30° point angle and basal diameter of 12.8 mm.

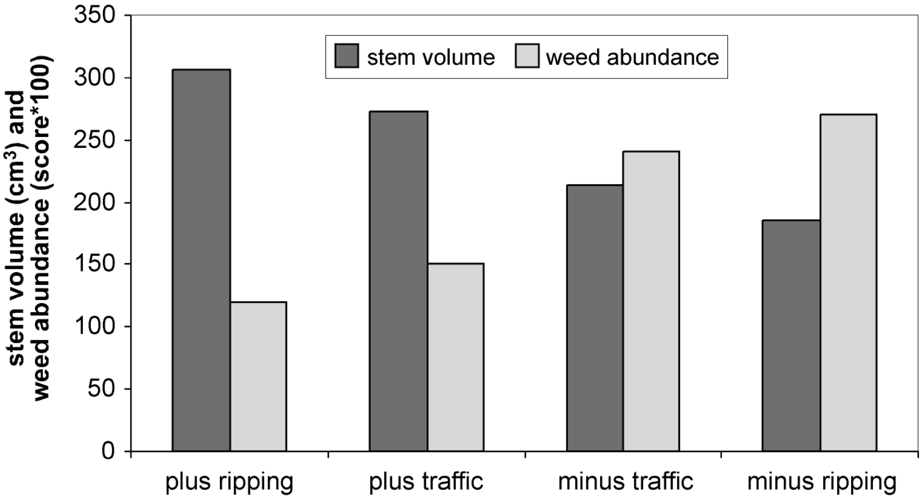

FIG. 3–The effect of ripping and harvesting traffic on the stem volume of *Pinus radiata* and the abundance of weeds in the extensive experiment. The abundance of weeds was measured on a visually assessed scale of 0 (no weeds) to 3 (full cover). These values have been multiplied by 100 in this diagram.

stem volume (cm3)

TABLE 1–Probabilities for effects of treatments on tree parameters and weed abundance ($p > F$) from analysis of variance (ns = not significant at $p = 0.05$) for the extensive experiment.

	Stem height	Stem diameter	Stem volume	Weed abundance
traffic	ns	<0.0001	0.0002	<0.0001
ripping	0.0038	<0.0001	<0.0001	<0.0001
number of passes	0.0392	ns	ns	ns
passes x ripping	ns	0.0102	0.0100	ns

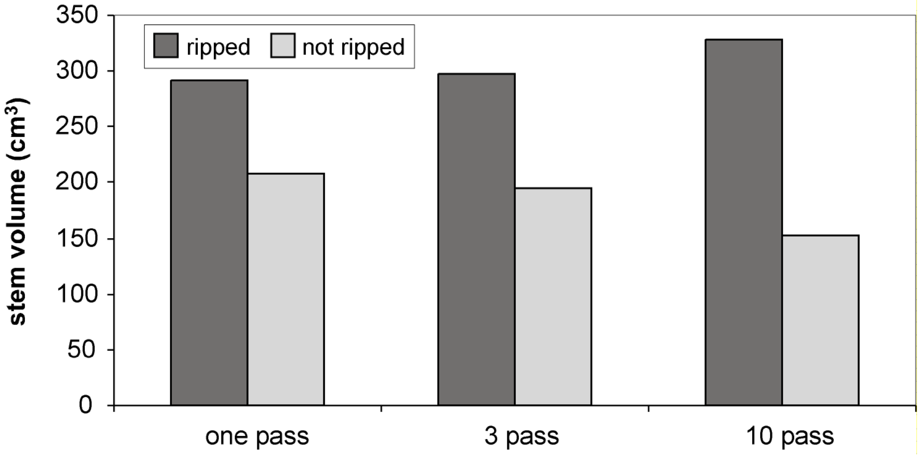

FIG. 4–The effect of ripping and the number of passes by harvesting machines on the stem volume of *P. radiata* in the extensive experiment.

The Intensive Experiment

The nature of this somewhat unanticipated passes × ripping interaction, and the possible involvement of weeds, were examined in greater detail in the forwarder 10-pass plots (both replicates, Trial 2 only). Ripping also decreased soil penetration resistance in the intensive experiment (Fig. 2). Multiple analysis of variance showed that traffic, ripping, and the traffic × ripping interaction were all significant at $p<0.01$ for stem height, diameter, and volume, and for ripping at $p<0.05$ for the weight of weeds. The relationship between tree stem volume and the weight of the surrounding weeds is given in Fig. 5. The control and the traffic alone treatment were not significantly different in stem volume and in weight of weeds. The ripped treatments had greater stem volume and less weed weight than the non-ripped treatments, and the combined ripped + traffic treatment had the most stem volume and least weeds of all.

There were no significant effects of ripping, traffic, or cardinal direction or any interactions on the density of roots (<1 mm) of *P. radiata*. There was a strong

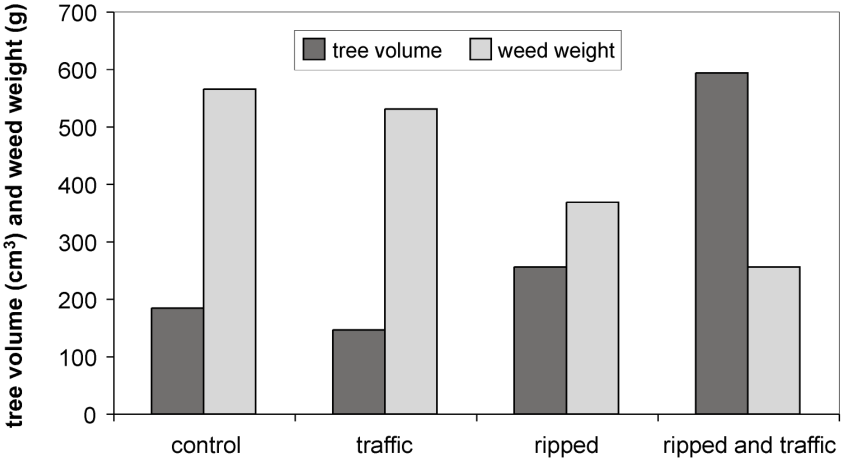

FIG. 5–The stem volume of *P. radiata* and the above-ground dry weight of the surrounding weeds for the forwarder 10 pass treatments (the intensive experiment). The stem volume is the mean of three trees and the weed weight is the mean per tree of the above-ground dry weight of the weeds harvested from a 1-m quadrat around each of the same three trees.

($p<0.0001$) effect of soil depth and a weak ($p<0.1$) ripping × soil depth interaction (Fig. 6). Ripping promoted the development of roots at depth (particularly at 46–54 cm soil depth) at the expense of roots in the surface (1–9 cm) layer.

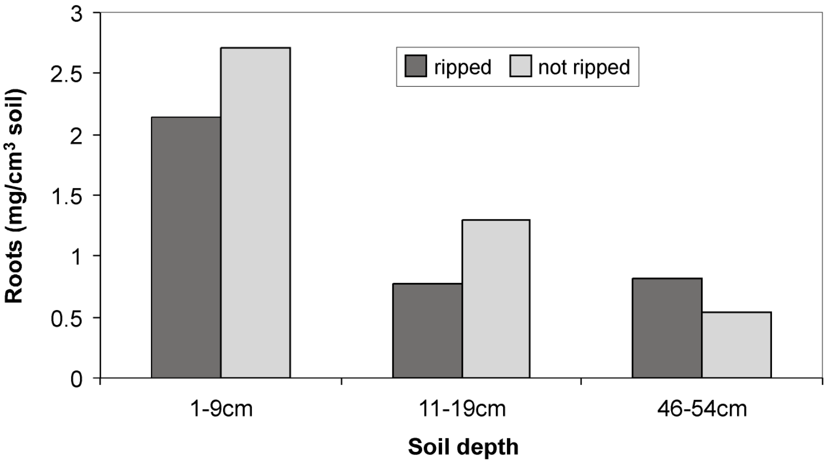

FIG. 6–The weight of roots (mg/cm³ soil) in ripped and non-ripped treatments as a function of soil depth in the intensive experiment.

DISCUSSION

Harvesting *P. radiata* plantations may disturb and compact soils (Lacey & Ryan 2000), increase soil penetration resistance (Sands *et al.* 1979; Lacey & Ryan 2000), and reduce soil air-filled porosity (Simcock *et al.* 2006). Corresponding decreases in productivity of *P. radiata* in the following rotation may (Murphy *et al*. 2004) or may not (Lacey & Ryan 2000) result. Fleming *et al.* (2006) also showed, in a comprehensive trial involving a range of climates, soil types, and tree species across North America, that soil compaction can reduce, have little effect on, or increase subsequent tree growth.

In our study, harvesting machinery did not compact the soil (Wood *et al.* 2004). The original intention was that the Taringatura trial should be replicated in two distinct seasons, wet and dry. However, both seasons were wet. The gravimetric soil water contents in the surface 20 cm of soil were 46% in Trial 1 and 50% in Trial 2, indeed so wet that in both trials the soil water contents were well in excess of the optimum for compaction (30–37% depending on soil depth, as determined by the Proctor compaction test). The high soil water content lowered shear strength and this reduced the bearing capacity offered to tyres and tracks, so favouring soil displacement rather than soil compaction. This is explained in greater detail by Wood *et al.* (2006) and is the reason why the harvesting machines did not significantly compact the soil (increase the soil bulk density) in the Taringatura trial. Seixas & McDonald (1997) also found, in a harvesting trial in North Carolina, that harvesting machinery did not compact the soil and for the same reasons as suggested in our study. It is not surprising, therefore, that no significant differences in soil penetration resistance from traffic were reported in either the extensive or intensive experiments (Wood *et al.* 2006). It is also possible that the soil was already compacted to some unknown extent by the silvicultural operations in establishing the first rotation in 1972.

There were some unanticipated results in the extensive trial. The first was that, averaged over all treatments, traffic flow increased stem volume growth of *P. radiata* (Fig. 3). The second, and the most intriguing, was the interaction between the number of passes of harvesting machinery and ripping in their effect on tree growth: increased traffic *without* ripping reduced stem volume growth, whereas increased traffic *with* ripping increased growth (Fig. 4). The third was the possibility that weed abundance was at least as important as, and possibly more important than soil properties in explaining the effects of the treatments on stem volume growth. The intensive experiment was undertaken to try to explain these results.

In the intensive experiment harvesting traffic (without ripping) had no significant effect on the growth of *P. radiata* or on the amount of weed competition (Fig. 5). Traffic did not significantly increase soil bulk density or soil penetration resistance and therefore this result was not surprising. There was good evidence that the control treatment was already at a bulk density sub-optimal for tree growth, and it was possible that the soil had been compacted to some degree by historical machine operations on the site prior to the establishment of the trial. However, even if the soil was undisturbed it could still be at a bulk density sub-optimal for root growth. Indeed this probably holds true for many undisturbed soils. Soil penetration resistance increases with increasing soil bulk density and decreasing soil water content. The concept has been reported of a critical value of soil penetration resistance (e.g., 3 MPa for *P. radiata* by Sands *et al.* (1979) and Mason & Cullen (1986)) above which root growth is negligible. Sometimes this has been interpreted by managers as root growth being uniformly satisfactory below the critical limit and suddenly unsatisfactory above the limit (see (a) in Fig. 7) but this does not make biological sense. Root growth is reduced exponentially as soil penetration resistance increases (Greacen & Sands 1980) and a typical relationship for *P. radiata* on soils similar to those in this study (Zou *et al.* 2001) is indicated as (b) in Fig. 7. It follows that root growth can be adversely affected by increases in soil penetration resistance over most of the range from low to the so-called critical value. At lower values of soil penetration resistance the soil may be so loosely packed that low soil water content and conductivity will limit root growth. The soil penetration resistance for the control treatments was therefore sub-optimal for root growth (Fig. 7) and improved by ripping (Fig. 2).

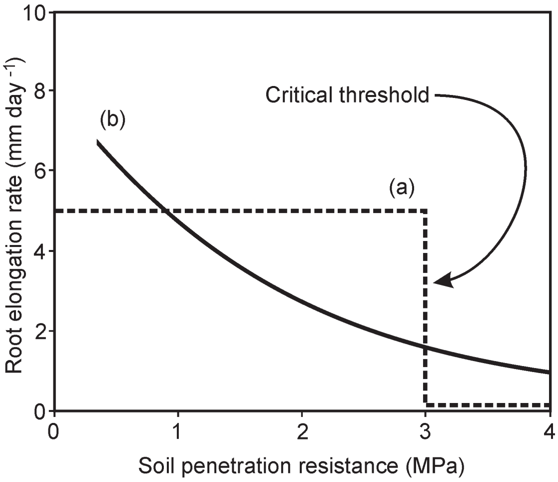

FIG. 7–The relationship between soil penetration resistance and the rate of elongation of roots of *P. radiata*. (a) is a line which assumes a threshold value for soil penetration resistance of 3 MPa below which root growth is uniformly satisfactory and above which root growth is negligible. (b) is the actual experimentally derived relationship from Zou *et al.* (2001).

Ripping (with and without traffic) markedly improved the growth rate of *P. radiata* in the extensive experiment (Fig. 3). This was due, in part, to the decrease in soil penetration resistance (Fig. 2). However, this was not the whole story because it did not explain the interaction of ripping with traffic. This interaction in the extensive experiment (Fig. 4) can probably be explained by ripping increasing soil penetration resistance in combination with better weed control arising from both passage of traffic and ripping. Increasing the number of passes of harvesting machinery reduced stem volume in the absence of ripping (Fig. 4). This was not due to increasing levels of soil compaction (since there were none) but could have been a result of increasing levels of soil disturbance. However, increasing the number of passes of harvesting machinery increased stem volume in the presence of ripping (Fig. 4). Two things were happening together here to more than counteract the negative effects of soil disturbance. The first of these was the marked decrease in soil penetration resistance effected by the ripping. The second was the weed control caused by the passage of the ripper and by each pass of the harvesting machinery. Consequently, the best treatment of all was the ripping treatment with the highest number of passes of harvesting machinery (Fig. 4).

The interaction between ripping and traffic was also evident in the intensive experiment (Fig. 5) for the same reasons as in the extensive experiment and with better data. Weed abundance in the extensive experiment was assessed visually and so a more detailed quantitative study of weeds was made in the intensive experiment. In the intensive experiment, ripping had a marked beneficial effect on tree growth and more so with than without harvesting traffic. Most weeds were in the control and traffic treatments, fewer weeds were in the ripped minus traffic, and least in the ripped + traffic. This is consistent with the argument that ripping improved the growth of *P. radiata* by reducing soil penetration resistance but that tree growth was also improved by both ripping and harvest traffic reducing the amount of weeds. Ripping and traffic in combination was the best treatment because of its superior weed control. Murphy & Firth (2004) also reported that weed growth in *P. radiata* plantations was suppressed by soil disturbance.

There were no significant primary treatment effects on root distribution in the intensive experiment. The root weight data were confined to pine roots >1 mm diameter because it was not possible, within the time and equipment constraints, to distinguish between weed and pine roots below this diameter. Consequently, care is needed in interpretation because it is possible that the abundance of pine roots <1 mm in diameter responded differently from those above 1 mm to treatment. Even so, the results support the principle of a dynamic equilibrium between above and below ground (Brouwer 1983) where assimilate would be preferentially directed towards capturing rate limiting resources. There were significant changes in stem volume with treatment but not in the amount of roots. For example, the stem volume of the ripped + traffic treatment was more than three times that of the control and had half the weight of surrounding weeds, but there was no significant difference in the amount of roots. This suggests that the *P. radiata* with fewer competing weeds had less difficulty in capturing adequate water and nutrients than the *P. radiata* with more competing weeds, and therefore could afford to invest a greater proportion of assimilate above ground. It does not follow that improving the soil conditions for root growth (better nutrient and water relations, decreasing soil penetration resistance) will increase root growth at the expense of top growth. Indeed, it is more likely to be the opposite.

There was a strong ($p<0.0001$) effect of soil depth and a weak ($p< 0.01$) ripping × soil depth interaction (Fig. 7). Other studies have shown there is greater abundance of *P. radiata* roots on than off the rip line (Mason & Cullen 1986). This is consistent with roots preferentially penetrating zones in the soil of lesser soil penetration resistance (Nambiar & Sands 1992). This study did not show an overall increased abundance of roots in the rip line but rather showed that ripping changed root distribution with depth, there being more roots at depth and fewer in the surface than in the non-ripped soil. This also can be explained in terms of a dynamic equilibrium. The herbaceous weeds in this study had roots confined to near the surface. Ripping reduced the amount of weeds and therefore the necessity for the pine to allocate more assimilate to the roots near the surface to effectively compete with the weeds. Under these circumstances it makes sense that the pine should change its pattern of allocation towards growing roots at depth because the ripping has made it easier to do so.

CONCLUSION

There were no significant changes in bulk density caused by traffic but in this study the bulk density of soil in the control plots was still high enough for ripping to decrease soil penetration resistance and probably enhance tree growth. The best growth of *P. radiata* was in the traffic + ripping treatment and a major reason for this was the more effective weed control than in any other treatment. This was by default rather than design. Indeed, the most convincing results in this study had nothing to do with harvesting traffic or with ripping. This study confirmed the importance of early weed control in the establishment of *P. radiata* and showed that the basic weed control was sub-optimal on this site.

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