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Impacts of Forest Harvesting Related Soil Disturbance on End-of-Rotation Wood Quality and Quantity in a New Zealand Radiata Pine Forest

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The long-term effect of soil disturbance (litter removal, topsoil removal and compaction) from forest harvesting on wood quality and quantity of second-rotation *Pinus radiata* growing on a clay loam soil, was assessed at the end the rotation, 26 years after planting. Relative to Control plots, average tree and stand total volume at rotation end was not significantly affected by litter removal and nil or light compaction, but was significantly reduced by 28% by litter and topsoil removal and moderate subsoil compaction, and further reduced by 38% by heavy compaction. Wood density at breast height in the inner rings of trees in the most disturbed treatments was elevated by up to 30 kg m^{-3}. This occurred because these treatments were more N deficient as reflected by foliar N levels during the first 11 years of growth relative to the Control. However, no treatment differences in wood density were evident in outer rings, and by rotation age overall mean density did not differ significantly between treatments. Neither acoustic velocity of standing trees, nor acoustic velocity of logs, was significantly affected by soil disturbance, indicating that stiffness of lumber cut from trees in the trial was likely to be similar for all treatments. Economic impacts of soil disturbance and compaction on this soil type will therefore result largely from the considerable negative impacts on final tree size, with little or no compensation from improved wood properties.

Keywords harvesting, *Pinus radiata*, tree growth, wood density, stiffness, litter removal, compaction, nitrogen deficiency

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1 Introduction

Radiata pine (*Pinus radiata* D.Don) is one of the most widely grown exotic timber species in the world, covering 3.7 million ha with large areas of plantation forest in Chile, New Zealand, Australia, Spain, and South Africa. Silvicultural management regimes for radiata pine differ between and within countries. In New Zealand, rotation lengths are typically between 25 and 35 years and may include both pre-commercial and commercial thinnings.

Ground-based logging equipment such as felling machines, mechanical processors, forwarders, skidders and crawler tractors are used in the commercial thinning or clearfelling of forests in many parts of the world, including the plantation forests of New Zealand. This equipment may travel over two-thirds or more of a site (McMahon et al. 1999, Lacey and Ryan 2000). It may cause soil disturbance by displacing or mixing litter and soil, and/or compacting the soil. Removal of litter and soil alters the amount and availability of nutrients. Compaction and removal of topsoil can alter root volume by increasing resistance to root growth or reducing the ability of the soil to supply oxygen and water to plant roots. Not all soil disturbance on a harvesting site is the same. Murphy (1984) noted from a survey of 19 harvesting operations in New Zealand that "deep" disturbance covered from 5 to 25% of the harvest area and was affected by such factors as slope, type of harvesting equipment and harvest planning.

Many trials and a number of worldwide literature reviews have shown that soil disturbance and compaction resulting from harvesting often increase seedling mortality and reduce tree growth (Murphy 1982, Grey and Jacobs 1987, Skinner et al. 1989, Minore and Weatherley 1990, Wronski and Murphy 1994). However, the effects of compaction on tree growth can vary with soil texture. Analysis of 26 long-term site productivity trials by Powers et al. (2005) demonstrated that soil disturbance resulted in forest productivity declines on compacted clay soils, but increases on sands. The effects of soil disturbance can also vary with tree species; pine species have been shown to be less sensitive than spruce species (Wästerlund 1985, Kranabetter et al. 2006). Modification of the soil as a result of harvesting is of particular importance where fast growing species or multiple entry thinnings are utilized. The negative effects of soil compaction, where they do occur, may last for decades unless remedial action is taken.

Stewart et al. (1988) developed a model for evaluating the economic impacts of soil compaction. Cost-benefit analyses of various ground-based harvesting practices, such as the use of designated skidtrails, could be estimated using their model. In their analyses, a drop in volume equated directly to the same percentage drop in value. Murphy et al. (2004) showed, however, that economic impacts were likely to be greater than volume impacts since stem size, and hence log-product distributions, were also negatively impacted.

In recent years, mills and markets have begun to include internal wood properties, in addition to log dimensions, to specify the logs they require. Consideration is now being given to such wood properties as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews 2002, So et al. 2002, Young 2002). Wood properties, such as density, are affected by genotype (Cown and Ball 2001), by silviculture (e.g., thinning (Cown and McConchie 1981) or stocking (Beets et al. 2007)) and by environmental factors. A number of studies have demonstrated a strong trend for radiata pine wood density to increase with increasing mean air temperature (Harris 1965, Cown et al. 1991). It has also been shown that wood density decreases in response to increased nitrogen (N) supply, e.g., by the addition of fertiliser (Cown and McConchie 1981, Beets 1997, Beets et al. 2001) or biosolids (Wang et al. 2006). A correlation between wood density and N supply as reflected in foliar N concentration (Beets 1997, Beets et al. 2001) or soil Carbon/N ratio (Beets et al. 2007) has been demonstrated. A model that predicts breast height wood density from age, stocking density, mean air temperature, and soil C/N ratio is provided by Beets et al. (2007). Although the effects of the forest environment on wood stiffness have been less studied than wood density in radiata pine, there is a good association between these two properties in mature trees suggesting that similar environmental factors may be implicated in both. There is certainly evidence that N supply can affect wood stiffness; application of biosolids to a radiata pine plantation caused a reduction in wood stiffness (Wang et al. 2006). In summary, since harvesting related soil disturbance can affect tree nutrient status and water availability it can potentially also influence wood quality, growth and, by implication, the economic potential of a site.

In 1982 the New Zealand Forest Research Institute established a trial 1) to investigate the short-term and long-term impacts of soil disturbance on soil properties and second-rotation radiata pine (*Pinus radiata* D.Don) tree growth and 2) to assess the long term effects on tree economic potential. This paper reports on the impacts on tree growth and wood quality at rotation-end, 26 years after establishment.

2 Materials and Methods

2.1 Site

Descriptions of the site, site preparation, and trial establishment and management have been given in earlier papers by Skinner et al. (1989) and Murphy et al. (1997, 2004). The information is repeated here for completeness.

The trial is located in Maramarua Forest, New Zealand, on rolling terrain with Ultic soils (NZ soil classification, Hewitt 1993) or Typic Hapludults (US classification). Ultic soils are common on old landscapes in the northern third of the North Island. Soils at the trial site are developed from highly weathered greywacke and dominated by kaolinitic and halloysitic clays. Shallow clay-loam topsoil overlies mottled, slowly-permeable subsoil. The soils are acidic with low native chemical fertility, particularly phosphorus (P); however P levels at the trial site reflect fertilisation of both the first rotation plantation and 110 kg P ha^{-1} applied during the first year of the trial. The climate at Maramarua Forest is mild and humid, with a mean annual rainfall of 1280 mm, mean annual temperature of 13.7 °C, and small soil moisture deficits may occur from November to February on average. The growing season for radiata pine in this part of New Zealand is 12 months per year. Mature stands of fertilised radiata pine in Maramarua Forest generally have a standing volume of 700 to 800 m^3 per ha and are harvested after 25 to 29 years.

2.2 Site Preparation

The pre-study stand was harvested with a cable logging system. The trial was located on a gently sloping portion (0 to 10% slopes) of the harvest unit which had received minimal soil impacts from the cable logging operation. Blocking of areas was also undertaken to ensure minimal differences in initial site conditions for each treatment replication. The trial design is detailed in Skinner et al. (1989).

Treatments were selected to match the minimal through to severe impact ratings of the visual classification system used by Murphy (1982) to classify soil disturbance after harvesting forests. Five treatments were replicated five times in a randomised complete block design. Each treatment was applied evenly across the whole surface of the 30 × 20 m plot. Soil and litter removed from the 0.06 ha plots was windrowed into a 10 m buffer strip between adjacent plots. Measurements at age 15 years showed that growth of trees adjacent to windrows was not significantly different from trees in the central core of each plot; indicating that edge trees were not exploiting the more favourable conditions in the windrows. The treatments in descending order of soil disturbance were:

1) Topsoil removed with a small bulldozer and subsoil heavily compacted with eight passes of a loader (TR-HC). The topsoil was about 10 cm deep. This treatment is equivalent to Disturbance Class (DC) 4 under the visual classification system described by Murphy (1982) and is usually associated with landings or with skid trails that have had much traffic over them.
2) Topsoil removed with a small bulldozer and subsoil moderately compacted with two passes of a loader (TR-MC). This treatment is equivalent to DC3 under the visual classification system and is usually associated with skid trails that have had a medium amount of traffic over them.
3) Forest litter removed by a small bulldozer; light compaction (LR-LC).
   This treatment is equivalent to DC2 under the visual

classification system and is usually associated with skid trails that have had a small amount of traffic over them.

4) Forest litter removed by hand; no soil compaction (LR-NC). There is no equivalent disturbance class under the visual classification system. This treatment was included to see what impact forest litter removal had on growth but it also simulates removal of the litter layer by a log dragged over the ground.
5) Control. This treatment is equivalent to DC0 under the visual classification system and is associated with undisturbed areas.

The visual disturbance classification system includes a DC1 category, where the harvesting machine has driven over a piece of ground, maybe only one or two times, but did not break through the litter layer. No equivalent treatment was included in this trial.

Two small, steel-tracked bulldozers were used to remove the litter layer and topsoil; a Bristol Taurus dozer (45 HP; mass unknown) and an Allis Chalmers HD6 (75 HP; ~5700 kg). The rubber-tyred front end loader used to compact the subsoil was a Hough 65 Payloader (~9300 kg).

The weed pampas grass (*Cortaderia selloana*) can be a problem during the establishment of radiata pine in Maramarua Forest. Before planting, the whole site was sprayed with hexazinone (5 kg ha^{-1}). New pampas growth was removed annually to age 10 by spot spraying with 2% glyphosate (0.7% active ingredient). Since age 10, pampas plants have been removed manually.

2.3 Second Rotation Establishment and Management

Radiata pine seedlings (1/0 stock) which had been hand-lifted and root trimmed were planted at a rate of approximately 90 per plot (3 × 2 m spacing; 1700 stems ha^{-1}). After planting, 170 g of super phosphate was applied by hand around each seedling. Diammonium phosphate (250 g/tree) was applied one year later by the same method.

Canopy closure was noted in Control plots at age four. To prevent unequal crown competition due to treatment, all plots were thinned to approximately 600 stems ha^{-1} at age four. Small and atypical trees were selected for removal. Atypical trees were defined as those present in microsites that were not representative of the treatment, e.g., where topsoil had not been completely removed around the stumps of first-rotation trees.

At age four all residual trees were pruned, half of the green crown being removed regardless of tree height. At age five a second pruning was carried out to the same prescription. A second thinning at age six resulted in a nominal final crop stocking of 250 stems ha^{-1} (treatment means ranged between 244 and 251 stems ha^{-1}). The trial was clearfelled at age 26.

2.4 Soil Properties and Foliar Concentrations

In the summer following trial establishment, soil compaction was assessed using a “Bush” Recording Penetrometer with 9 readings taken diagonally across each plot. This instrument measured resistance to penetration (in kg cm^{-2}) in ~3cm steps down to a total depth of about 40 cm.

Soil total C and N at 0–10 cm depth were measured in soil samples collected from 4 of the 5 blocks of the trial at age 16 years, and bulked and analysed by plot. Foliar N and P were analysed in needles collected in late summer from second order branches in the upper sun-lit portion of the crown at age 7 and 11 years, supplementing data collected annually from 1–4 years by Skinner et al. (1989). Soil and foliage samples were analysed following Nicholson (1984).

2.5 Growth Assessments

The heights of all trees were measured annually from age one to age six and again at ages 11, 15, 21 and 26. Heights were measured immediately before and after each thinning if a thinning occurred in a given year. Diameter at breast height measurements were made from age four at the same time as tree height measurements. These data were used to determine individual tree volume from a volume table (No. T009; Dunlop 1995). Results up to age 11 are reported in Skinner et al. (1989) and Murphy et al. (1997).

The age 21 and age 26 measurements were taken on a 0.03 ha per plot “central core” of trees to minimise the possibility of any edge effects between the treatments and the buffer strips between plots. The plot size was collapsed to a central core even though earlier measurements indicated that edge effects were not evident at age 15 years. After mortality, two thinnings and a reduction in plot size to a central core, the median number of trees per plot assessed at rotation end was nine; ranging from five to eleven. The average density of residual trees was 334, 300, 286, 266 and 240 stems ha^{-1} for the TR-HC, TR-MC, LR-LC, LR-NC and Control treatments respectively. The overall average stand density for all plots was 285 stems ha^{-1}.

2.6 Wood Quality Assessments

Wood quality was assessed using three methods.

Basic density was assessed based on cores taken at breast height from five randomly selected trees per plot. Cores were separated into three 5-ring segments, for rings 1 to 15 from pith, and a final segment from ring 16 to the outer ring. Basic resin-extracted wood density was then obtained for each sample using the maximum moisture content method described by Smith (1954). A breast-height area-weighted mean density was also calculated for each tree.

Wood modulus of elasticity, also known as stiffness, is one of the most important mechanical properties and is the most frequently used indicator of the ability of wood to resist bending and support loads. Dynamic stiffness is a function of density and acoustic velocity (Wang et al. 2007a). A significant body of research has built up in recent years evaluating the relationships between acoustic velocity and forest product yields (Wang et al. 2007b). Relationships tend to be stronger between log acoustic velocities than standing tree acoustic velocities. Stiffness of standing trees was assessed based on the average of two time-of-flight acoustic velocity measurements taken on opposite sides of each tree using a Director ST300 (Fiber-Gen, Christchurch, New Zealand). All treatments were sampled, however only one-third of the plots were sampled. All trees within each sampled plot were measured. Because of small sample sizes, plot data were combined for each treatment yielding 8 to 19 standing tree acoustic measurements per treatment and a total of 69 measurements.

Stiffness of felled stems and logs from all plots was assessed using a Director HM200 (Fiber-Gen, Christchurch, New Zealand); a resonance-based acoustic velocity tool. Prior to felling, trees were numbered and colour-banded according to treatment. After felling, the plot and tree number was painted on the cut-face of each tree. The trees were then extracted to a landing for processing into logs and for taking acoustic measurements. Despite the precautions taken to paint numbers on the stems, by the time the stems were extracted to the landing only 116 of the 215 stems were clearly identifiable. The following numbers of felled stems were assessed; 21 in Control plots, 24 in LR-NC plots, 30 in LR-LC plots, 22 in TR-MC plots, and 18 in TR-HC plots. Acoustic velocities were also taken of the first (109 in total) and second (94 in total) logs cut from each stem. For practical reasons some logs could not be assessed.

2.7 Analyses

Analyses of variance (ANOVA) and analyses of covariance (ANOCOVA) were used to test for treatment differences using the SAS (Version 9) procedure PROC MIXED. Analyses were either performed on plot means, or when individual tree data was analysed, using the plot-level variance as the error term to test for treatment differences. Comparisons between individual pairs of treatments were performed using the Least Significant Difference (LSD) test. The following variables were analysed:

- Soil C and N concentrations and C/(N-0.014) ratio
- Foliar N and P concentrations
- Basal Area (BA, m^2 ha^{-1})
- Mean Top Height (MTH, m)
- Tree Volume (m^3, estimated from height and DBH for each tree using the volume function appropriate for this forest)
- Stand Volume (m^3 ha^{-1}, estimated from tree volumes summed for each plot)
- Breast height basic wood density (kg m^{-3})
- Standing tree acoustic velocity (km s^{-1})
- Felled stem and log acoustic velocities (km s^{-1} from the felled stem, and the first and second log for each tree)

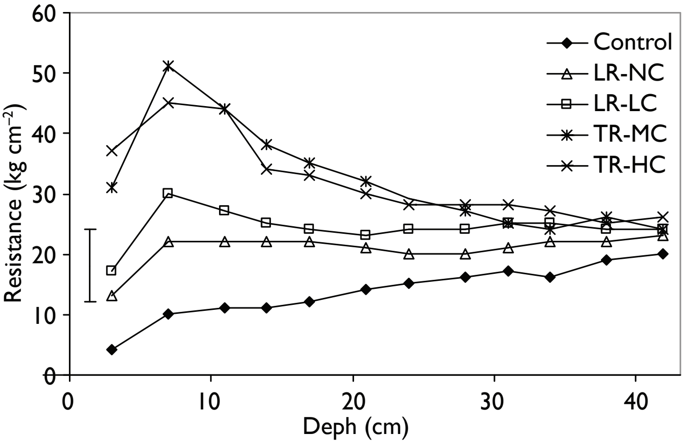

Fig. 1. Soil resistance to penetration assessed in the summer following trial installation (November, 1982). Bar shows LSD for 0–5 cm depth; treatment differences greater than the LSD are statistically significant (α = 0.05).

As there was a slight variation in stocking density between plots, the growth variables (BA, MTH, Tree Volume and Stand Volume) were analysed using ANOCOVA using stocking density in each plot as a covariate. The reported means for these variables are adjusted to a common stocking across all treatments.

For the wood property variables (basic density and acoustic velocity), a simple 1-way ANOVA was performed on plot means to compare treatments. In addition, because tree diameter was weakly negatively correlated with both wood properties within each treatment (pooled with-treatment correlation was r=–0.31 for mean density and r=–0.41 for stem velocity), these variables were also analysed using ANOCOVA using DBH as a covariate. These analyses established whether there were treatment differences in wood properties for trees of a common DBH.

3 Results

3.1 Soil Properties and Foliar Concentrations

Soil resistance measurements taken in the summer following trial establishment showed a highly significant increase in soil resistance with site disturbance, with elevated resistance in the most disturbed treatments extended down about 30 cm into the soil (Fig. 1).

At mid-rotation, the concentrations of C and N in the upper 10 cm of soil were significantly reduced by the removal of topsoil (TR-MC and TR-HC) compared to treatments where topsoil was retained (Control, LR-NC, and LR-LC) (Table 1). However, the soil C/N ratio did not differ greatly between treatments.

Foliage concentrations taken at ages 7 and 11 years showed significant reductions in foliar N in the most disturbed treatments (Table 2) with the concentration of foliar N indicative of N deficiency, especially in the most disturbed treatments. Foliar P also showed a slight reduction in the most disturbed treatments, but even in the most disturbed treatment was slightly above the level used to indicate deficiency.

3.2 Full Rotation Impacts of Soil Disturbance on Productivity

Mean top height, basal area and volume at age 26 were not significantly affected by removal of the litter layer at the time of planting (Table 3). On treatments where the topsoil had been removed and the subsoil compacted, the effect on some tree size parameters was clearly apparent, however. Although tree height was not greatly affected,

Table 1. Treatment means of %C, %N, and adjusted C/N ratio in top 10 cm soil at age 16 yrs assessed using 4 of the 5 blocks in the trial. F-ratio (4 & 15 d.f.) and p-value of the test for treatment differences is also given. Within a column, treatments followed by the same letter do not differ significantly (LSD test, α = 0.05).

Treatment	C (%)	N (%)	C/(N-0.014)
TR-HC	1.37 a	0.090 a	18.1 a
TR-MC	1.38 a	0.085 a	19.5 ab
LR-LC	3.71 b	0.208 b	19.2 a
LR-NC	3.18 b	0.179 b	19.4 ab
Control	3.47 b	0.173 b	21.8 b
F-ratio (p-value)	29.06 (<.0001)	18.45 (<.0001)	2.74 (0.068)

Table 2. Treatment means foliar concentrations of N and P at ages 7 and 11 years. F-ratio (4 & 20 d.f.) and p-value of the test for treatment differences is also given. Within a column, treatments followed by the same letter do not differ significantly (LSD test, α = 0.05).

Treatment	N (%)		P (%)	
	7 yrs	11 yrs	7 yrs	11 yrs
TR-HC	1.11 a	1.01 a	0.114 a	0.103 a
TR-MC	1.16 ab	1.09 ab	0.125 ab	0.115 ab
LR-LC	1.19 abc	1.28 d	0.124 ab	0.113 ab
LR-NC	1.27 c	1.15 bc	0.142 b	0.123 b
Control	1.24 bc	1.27 cd	0.128 ab	0.119 b
F-ratio (p-value)	3.36 (0.029)	7.94 (0.0005)	1.94 (0.14)	2.55 (0.071)

Table 3. Key measured and calculated growth productivity variables at age 26. F-ratio (4 & 19 d.f.) and p-value of the test for treatment differences is also given. Within a column, treatments followed by the same letter do not differ significantly (LSD test, α = 0.05).

Treatment	Basal area (m^2 ha^{-1})	Mean top height (m)	Tree volume (m^3 per tree)	Stand volume (m^3 ha^{-1})
TR-HC	43.7 a	37.1 a	1.91 a	529 a
TR-MC	51.6 b	37.3 ab	2.21 b	629 b
LR-LC	65.2 c	38.9 c	2.83 c	808 c
LR-NC	68.1 c	38.8 bc	3.00 c	839 c
Control	69.3 c	38.1 abc	3.08 c	835 c
F-ratio (p-value)	21.05 (<.0001)	2.72 (0.059)	29.57 (<.0001)	20.35 (<.0001)

basal area was reduced by 25% in the TR-MC plots and by 37% in the TR-HC plots. Volume per tree was reduced by 28% in the TR-MC plots, and by 38% in the TR-HC plots. The degree of compaction did not have a significant effect on tree volume in the plots where litter had been removed (none versus light compaction) but degree of compaction caused a significant reduction in both basal area and volume in the plots where the topsoil had been removed (medium versus heavy compaction).

3.3 Long-term Growth Trends to Age 26

Treatment differences were generally more marked early in the rotation than at harvest age. At young ages, there were clear treatment differences in mean top height but these became less significant over time (Fig. 2). At age 11 the mean heights of LR-LC, TR-MC and TR-HC trees were significantly different from the Control (Murphy et al. 1997). By age 21 only the TR-MC and TR-HC treatments had mean heights that were significantly lower than the Control. By the end of the rotation, at age 26, there were no

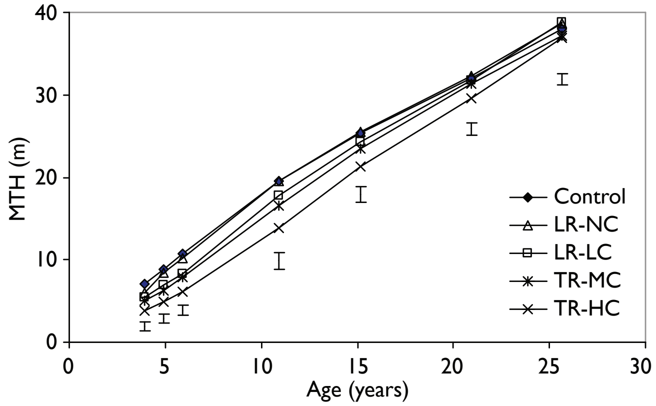

Fig. 2. Mean top height of soil disturbance treatments from age 4 to age 26. Bars show LSDs at each age; treatment differences greater than the LSD are statistically significant (α = 0.05).

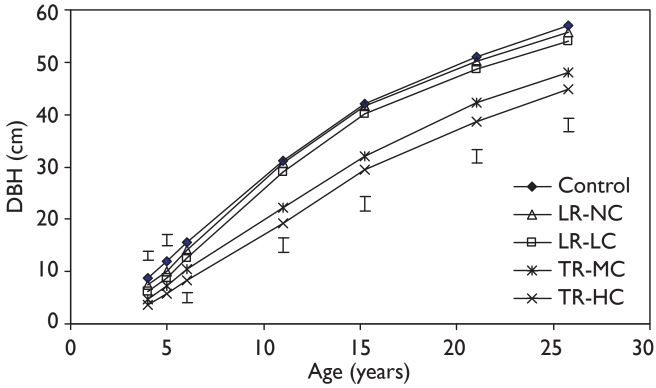

Fig. 3. Quadratic mean diameters of soil disturbance treatments from age 4 to age 26. Bars show LSDs at each age; treatment differences greater than the LSD are statistically significant (α = 0.05).

significant differences between treatment mean tree heights. There was also more treatment differentiation in mean diameter early than later in the rotation, although trees in the two most extreme disturbance treatments remained much smaller in diameter at harvest (Fig. 3).

The relative differences between the Control and the soil disturbance treatments on volume per tree decreased with time although the absolute differences tended to increase. Absolute differences are provided below in parentheses, m^3 per tree, as additional information to the relative differences. At age 4 the difference between the LR-NC treatment and the Control was 29% (0.01 m^3). This difference decreased to 18% (0.01 m^3) by age 6 (post-thinning) and to 1% (0.01 m^3) by age 11. The difference at age 26 was 0% (0.01 m^3) and not significant. Relative differences for the LR-LC treatment dropped from 50% (0.01 m^3) at age 4 to 4% (0.13 m^3) at age 26; the age 26 difference being not significant. Relative differences dropped from 71% (0.02 m^3) to 25% (0.74 m^3) for the TR-MC treatment for ages 4 and 26 years respectively. Relative differences dropped from 76% (0.02 m^3) to 33% (0.98 m^3) for the TR-HC treatment for ages 4 and 26 years respectively.

Table 4. Treatment means of breast height area-weighted mean basic wood density at age 26 years. Treatment means in the same column with the same letter are not significantly different (LSD test, α = 0.05). Simple means and means adjusted to a common DBH are shown. F-ratio (4 & 20 d.f.) and p-value of the test for treatment differences is also given.

Treatment	Mean Weighted Density ($kg\ m^{-3}$)	Mean Weighted Density corrected to a common DBH ($kg\ m^{-3}$)
TR-HC	428 a	412 a
TR-MC	438 a	433 a
LR-LC	420 a	423 a
LR-NC	421 a	429 a
Control	421 a	431 a
F-ratio (p-value)	1.34 (0.29)	1.46 (0.25)

Table 5. Treatment means of breast height resin-extracted wood density parameters at age 26 years in 5-ring groups (starting from pith). Treatment means in the same column with the same letter are not significantly different (LSD test, α = 0.05). F-ratio (4 & 20 d.f.) and p-value of the test for treatment differences is also given.

Treatment	Rings 1–5 ($kg\ m^{-3}$)	Rings 6–10 ($kg\ m^{-3}$)	Rings 11–15 ($kg\ m^{-3}$)	Rings 16+ ($kg\ m^{-3}$)
TR-HC	387 a	411 ab	435 ab	445 a
TR-MC	378 ab	427 a	440 a	459 a
LR-LC	360 b	399 b	416 b	455 a
LR-NC	361 b	406 ab	425 ab	446 a
Control	356 b	407 ab	421 ab	450 a
F-ratio (p-value)	2.98 (0.044)	2.21 (0.10)	2.24 (0.10)	0.50 (0.73)

3.4 Impacts of Soil Disturbance on Wood Quality

3.4.1 Wood Density

At age 26 years there were no significant differences between treatment means for breast height area-weighted mean basic wood density (Table 4). However, splitting the data into ring groups indicated some treatment differences in the inner rings. In rings 1–5, there was a significant trend of wood density increasing with site disturbance, with HR-HC being 31 $kg\ m^{-3}$ or 9% higher in wood density than the Control (Table 5). Treatment differences in wood density beyond ring 5 were less clear and entirely absent beyond ring 15.

Attempting to relate wood properties to soil C/N ratios in this trial were unfruitful as soil C/N ratios differed hardly at all between treatments (Table 1). If anything, there was a slight decrease in C/N ratio with increasing soil disturbance, the reverse of what might have been expected. Therefore, the model of Beets et al. (2007) which predicts wood density from temperature, stocking density, and soil C/N ratio, was unable to predict the treatment differences observed at this site, although it produced good estimates for those treatments where topsoil was retained (Fig. 4). However, there was a significant treatment-level negative correlation between wood density and foliar N for ring group 1–5, and a smaller but still significant correlation for rings 11–15 (Fig. 5), with ring group 6–10 not being significant.

3.4.2 Acoustic Velocities of Standing Trees, Felled Stems and Logs

At age 26 acoustic velocities were not affected by soil disturbance treatments. The overall test for treatment differences indicated no significant treatment effects for the standing tree acoustic velocity measurements (Table 6), nor for the felled stem acoustic velocities, the 1st log acoustic velocities, and the 2nd log acoustic velocities

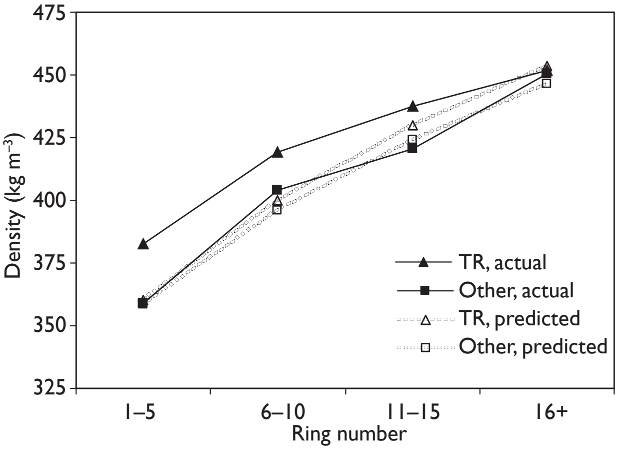

Fig. 4. Resin extracted mean basic wood density by ring group for topsoil removed treatments (TR, Actual), and other treatments (Other, Actual) compared with those predicted (TR, Predicted and Other, Predicted) using the model of Beets et al. (2007).

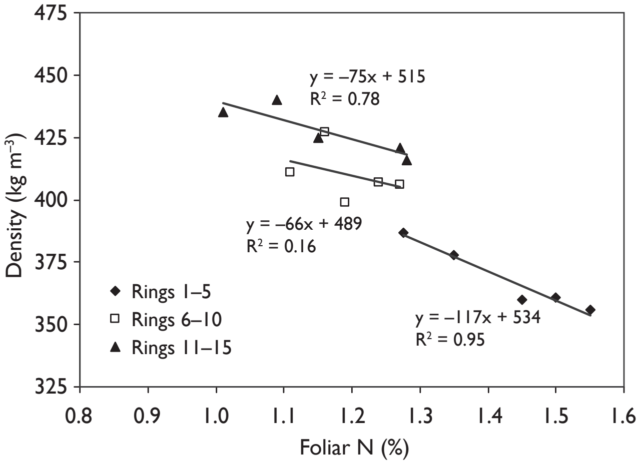

Fig. 5. Resin-extracted basic density at breast height by ring group shown in relation to foliar N based on treatment means, where foliar N averaged over ages 1–4 was used for ring group 1–5, foliar N averaged over ages 7 and 11 was used for ring group 6–10, and foliar N at age 11 was used for ring group 11–15.

(Tables 7). The LSD test indicated that trees in the LR-LC plots had significantly lower stiffness than those in the TR-MC plots, but this difference was eliminated once tree size was taken into account (Table 8). There were no significant correlations between wood stiffness measurements and foliage concentrations, although if anything, velocity tended to decrease with increasing foliar N.

Table 6. Simple treatment means of acoustic velocity parameters for standing trees at age 26 years. F-ratio (4 & 3 d.f.) and p-value of the test for treatment differences is also given.

Treatment	Number of trees measured	Standing Tree Velocity (km s^{-1})
TR-HC	15	4.34 a
TR-MC	8	4.57 a
LR-LC	10	4.59 a
LR-NC	18	4.40 a
Control	19	4.46 a
F-ratio (p-value)		0.61 (0.69)

Table 8. Treatment means of acoustic velocity parameters for felled stems and logs at age 26 years corrected to a common DBH.

Treatment1	Whole stem (km s^{-1})	1st log (km s^{-1})	2nd log (km s^{-1})
TR-HC	2.98 a	3.08 a	3.06 ab
TR-MC	3.08 a	3.15 a	3.20 ab
LR-LC	2.97 a	3.09 a	3.06 a
LR-NC	3.01 a	3.21 a	3.21 b
Control	3.00 a	3.12 a	3.15 ab
F-ratio (p-value)	0.94 (0.46)	0.93 (0.47)	1.91 (0.16)

[1] Treatment means in the same column with the same letter are not significantly different (LSD test) at the $p < 0.05$ level. F-ratio (4 & 18 d.f.) and p-value of the test for treatment differences is also given.

4 Discussion and Conclusions

Tree growth reductions due to treatment were most evident during the first five years of this trial Skinner et al. (1989). Growth losses were attributed to degraded soil physical conditions and to soil fertility. Skinner et al. (1989) noted that “losses in productivity during the first 4 years resulted from combinations of nutrient loss through topsoil removal, changes in soil resistance, and less favourable soil temperature regimes owing to the absence of the forest litter”.

By mid-rotation (age 15), tree volume on the litter removed plots had recovered following canopy closure and development of a new litter layer which probably created a favourable microclimate (modifying soil temperature) that would have helped protect the surface soil from drying out and thereby prevented the increase in soil resistance to penetration observed during the first few years in summer when the litter layer was still absent (Skinner et al. 1989). In addition, recycling of nutrients through the litter layer would be expected to reduce nutrient uptake requirements from the mineral soil. Powers et al. (2005) noted that long term site productivity trials in North America showed no effect after 10 years of surface organic matter removal for 25 of the 26 sites assessed. It should be noted that their assessment included understory biomass as well as tree biomass.

Table 7. Simple treatment means of acoustic velocity parameters for felled stems and logs at age 26 years.

Treatment1	Whole stem (km s^{-1})	1st log (km s^{-1})	2nd log (km s^{-1})
TR-HC	3.06 ab	3.18 ab	3.20 ab
TR-MC	3.14 a	3.22 a	3.28 a
LR-LC	2.95 b	3.05 b	3.02 b
LR-NC	3.05 ab	3.16 ab	3.15 ab
Control	2.96 ab	3.06 ab	3.08 ab
F-ratio (p-value)	1.67 (0.20)	1.74 (0.18)	2.56 (0.08)

[1] Treatment means in the same column with the same letter are not significantly different (LSD test) at the $p < 0.05$ level. F-ratio (4 & 18 d.f.) and p-value of the test for treatment differences is also given.

Mid-rotation nutrient equilibria work suggested that the sites with limited disturbance would return to “normal” by about age 30+ (Zabowski et al. 1996); with a gradual narrowing of the gap between treatments. Their work indicated, however, that it was unlikely that the severely disturbed sites would recover by harvest time.

Three quarters of the way through the rotation (age 21), height, diameter and volume per tree continued to be affected on the plots where the topsoil had been removed and the subsoil compacted. The degree of subsoil compaction (high versus medium) affected diameter, height and tree volume growth on sites where the topsoil had been removed (Murphy et al. 2004).

An assessment of forecast log product yields indicated that impacts of soil disturbance on stand economic potential were greater on a percentage basis than the impacts on volume growth (Murphy et al. 2004). The losses in economic potential were projected to be up to NZ$ 42 000 ha^{-1} (64%) or NZ$ 140 per tree at the projected harvest age (age 28) on the severely disturbed sites (TR-HC); it should be noted that usually only a small proportion of harvest units are severely disturbed. Losses in economic potential were due to reductions in tree size and total volume per hectare, a decrease in high-value pruned log yields, and an increase in low-value pulp log yields.

By the end of the rotation (age 26), only the treatments where the topsoil had been removed and the subsoil compacted continued to have a significant affect on some tree productivity variables; tree and stand volume were significantly reduced by topsoil removal and moderate compaction, with heavy compaction causing a further significant reduction by up to 38%, but tree height was not significantly affected by any treatment. These substantial differences in tree size still evident at the end of the rotation must be due in large part to the direct effects of soil compaction and the consequent reduction in soil porosity and increase in resistance. The growth difference between the moderately and heavily compacted treatments which persisted to the end of the rotation is clear evidence of this.

As noted in the introduction, since harvesting related soil disturbance can affect nutrient status and water availability it could potentially affect wood quality and the economic potential of the site. While soil C/N ratio and air temperature jointly provided realistic predictions of breast height density by ring group in treatments with top soil retained, density of rings less than 16 years of age was not well predicted by the model when topsoil had been removed (Fig. 5). Clearly, the wood density model of Beets et al. (2007) should only be applied in situations where topsoil has been retained, because the decrease in the C/N ratio with depth found in undisturbed soil (Skinner et al. 1989) is not equivalent to a decrease expected in undisturbed topsoil with increasing site nitrogen fertility.

Foliar N chemistry provides an indication of the nutritional status of a stand, and data analysis has shown that differences in foliar N between treatments affected wood density during the first 15 years of the rotation. By the end of the rotation, however, soil disturbance had no significant impact on wood quality, as measured in terms of outerwood density or tree or log acoustic velocities, and strongly suggests that initial treatment differences in foliar N probably disappeared later on in the rotation. No foliage chemistry data were acquired at age 26 to confirm this suggestion, however, three independent studies (Beets 1997, Beets et al. 2001, and the current study – see Fig. 6) have shown that wood density is negatively correlated with foliar N. It seems likely that the root systems of trees in the topsoil-removed treatments eventually penetrated through the compacted soil horizons, or by some other means exploited nitrogen outside the plot margin. It is possible that nitrogen deficiency would have persisted to the end of the rotation if the topsoil had been removed over large areas rather than in smaller plots as in this trial, although this would be unlikely to occur operationally using conventional harvesting methods based on sound harvest planning.

In contrast to the minor effects of soil disturbance on wood density which were mostly confined to the inner rings, and the absence on any significant effect on wood stiffness, tree growth effects were considerable and remained strongly evident at the end of the rotation. Economic impacts should therefore result largely from growth impacts on final tree size, with little or no compensation from improved wood properties.

As noted by Murphy et al. (2004), there are limitations associated with this trial. *First*, the work has been carried out on one soil type and may not be applicable to other soil types. *Second*, since weeds were controlled throughout the duration of this trial, the differences found between the undisturbed control and the heavily disturbed areas may be greater than would be found in practice. Murphy and Firth (2004) found in operational trials that weed growth was influenced by soil disturbance with the greatest weed growth and, therefore, competition for tree growth, occurring on undisturbed areas and the least on heavily disturbed areas. *Third*, differences between the undisturbed control and the heavily disturbed areas may be less than would be found in practice since the treatments were established on relatively large (600 m^2), rectangular blocks, which do not truly reflect the irregular mosaic of disturbance classes found in New Zealand after a harvesting operation, and each treatment received similar management practices. In the same operational trials referred to above, Murphy and Firth (2004) found that soil disturbance also influenced the early management of trees. Trees planted on heavily disturbed areas were less likely to be selected for low pruning and more likely to be selected for pre-commercial thinning. *Fourth*, although a) the treatments were established on large rectangular blocks with a buffer zone, b) the plot size was reduced to include only an inner core of trees, and c) a mid-rotation check on tree data indicated that there was no difference between the core trees and the outer plot trees, by the end of the trial it is possible that treatments were affected by neighbouring plots.

Despite these limitations the Maramarua soil disturbance trial does provide an improved understanding of the consequences of soil disturbance on economic return of radiata pine. The authors are unaware of any studies that have followed the impacts of soil disturbance on tree growth and wood quality from seedling establishment through to final harvest.

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