New Zealand Forest Site Management Cooperative

Trial FR345: Effect of compaction, site preparation and fertilisation on foliar nutrition and tree growth of radiata pine at age 8 years

By
Author(s): Jianming Xue[1], Peter Clinton[1], Robyn Simcock[2], Mark Kimberley[1] and Doug Graham[1]

[1]Ensis/Scion, [2]Landcare Research

Date: June 2006

Confidential to participants of the NZ Forest Site Management Cooperative

The opinions provided in the Report have been prepared for the Client and its specified purposes. Accordingly, any person other than the Client, uses the information in this report entirely at its own risk. The Report has been provided in good faith and on the basis that every endeavour has been made to be accurate and not misleading and to exercise reasonable care, skill and judgment in providing such opinions.

Neither Ensis nor its parent organisations, CSIRO and Scion, or any of its employees, contractors, agents or other persons acting on its behalf or under its control accept any responsibility or liability in respect of any opinion provided in this Report by Ensis.

ABSTRACT

This trial was established at a second-rotation site on an imperfectly drained clay loam located in the North Island, New Zealand to investigate the effects of compaction, site preparation and fertilization on soil physical and chemical properties, foliar nutrition and tree growth. The experiment consisted of 12 treatments in a factorial design of 2 compaction levels (compaction, no compaction) by 2 site preparation levels (ripping, no ripping) by 3 fertiliser levels (N, N+P, None). Each treatment had 4 replications giving a total of 48 plots, which were arranged in a randomised block design. Foliar nutrition and tree growth response of radiata pine to the treatments were studied for the second 4 years of growth (i.e. between ages 4 and 8 years).

In contrast to the results from the first 4 years of growth, compaction had no significant effect on foliar nutrient concentrations and tree growth during the second 4 years. This is probably because the much larger root systems of the trees from age 4 years have exploited favourable (aerated) soils adjacent to compacted strips, in combination with the trees increasing the volume of air-filled pores by lowering the water table (a combination of interception and evapotranspiration), although neither factor has been quantified. Similarly, site preparation also had no significant effect on foliar nutrition and tree growth from at ages 4 to 8 years. Fertilising, especially the N+P fertiliser treatment, continued to improve nutrient uptake and tree growth until at least age 8 years. This suggests that fertilising may have been an effective practice to improve the tree growth on an imperfectly drained clay loam soil.

However, since survival of seedlings is important, especially where planting densities are low, ripping or spot mounding of soils with low macropore volume is considered as an effective management tool, whether low macropore volume is an inherent soil property or induced by compaction. Where low macropore volume is exacerbated by a high water table, cultivation must drain the soil (e.g., careful ripping), or raise the soil surface (e.g., spot mounding).

We recommend quantification of the drop in water table height from 1997 to 2007 to quantify the effect of a newly-closed tree canopy on mitigation of soil compaction.

TABLE OF CONTENTS

INTRODUCTION

Ground-based harvesting of plantation forests can result in soil compaction and disturbance, leading to reduced soil quality and loss of production of subsequent tree crops (Bockheim *et al.* 1975; Rab 2004). Compaction often causes a reduction in soil porosity and increased soil bulk density (Gent *et al.* 1983). In northern New Zealand, highly weathered, clay-rich Ultisols are used for production forestry. However, since these soils have low iron oxide content and shallow topsoils over low-permeability subsoils, they are vulnerable to loss of soil quality during harvest operations (Hewitt 1998). They are particularly vulnerable to loss of macropore volume. They also have relatively low total P content (<40 mg/kg), but severe P limitations in the soil have been remedied in the 1970s and 1980s with aerial applications of P fertiliser when foliar concentrations of P reached a limiting value (Ballard 1978; Hunter and Graham 1982).

The trial AK917 at Maramarua Forest, which imposed different levels of disturbance on an imperfectly drained Ultisol, demonstrated major loss in radiata pine productivity after 4 years arising from loss of litter, loss of topsoil, and compaction following harvest of the previous rotation (Skinner *et al.* 1989). In an extreme disturbance treatment (topsoil removed and compaction of the entire plot with a bulldozer), tree volume was reduced by 45 to 54% because of poorer N and P nutrition and unfavourable soil physical conditions. Due to the limitation of the trial design, three major issues as described by Skinner *et al* (2002) were associated with extrapolating the results of AK917 to a field setting

Therefore, another trial (FR345) was established in an imperfectly drained Ultisol (clay soil) at Riverhead Forest in 1997, using a randomised block design with three factors to investigate the effects of compaction, site preparation (rip and disk) and fertiliser on soil physical and chemical properties, tree growth and nutrition of radiata pine in order to help forest managers maximise forest productivity. There were 5 specific objectives detailed as follows:

1. To determine if increasing harvesting disturbance and soil compaction results in decreasing tree growth.
2. To quantify tree growth improvement after ripping both minimally compacted and moderately compacted soils.
3. To measure the effect on tree growth of combining ripping with additions of N and P fertiliser and understand how the effects may change over time.
4. To confirm that nitrogen needs to be supplied to trees growing on Ultic clay soils which have been adequately fertilised with N and P in the previous section.
5. To determine if growth of trees in moderately compacted soils is limited by lack of oxygen in winter (wet soil) and by increased soil resistance to root extension in summer (dry soil). These compaction effects reduced P availability (reduced exploitable soil volume) and N availability (greater denitrification and leaching).

The first 4-year results (1998-2001) have been reported by Skinner *et al* (2002) and Simcock *et al* (2006). The main findings were: 1) Compaction reduced survival of *P. radiata* at planting and during the first year of growth due to an increased oxygen deficit, caused by a reduction in macropore volume, and a shallower depth to the perched water table; 2) Site preparation improved both survival of the seedlings and growth over 4 years; 3) There was an initial growth response to N, but fertiliser did not increase survival of the seedlings; 4) At year 4, both site preparation and N+P treatments gave about 10% extra growth, suggesting N+P may have been as effective as site preparation for improved growth of the trees that survived the first two years.

This update report covers the results of tree growth and foliar nutrition of radiata pine over the second 4 years (i.e. 2002-2005).

MATERIALS AND METHODS

Site description

The FR345 trial was located in a compartment 18/3 in Riverhead Forest, 80–120 m above sea level and 20 km north of Auckland, New Zealand. The mean annual rainfall is 1430 mm (distributed evenly through the year) and the mean annual temperature is 13.7 ^{o}C. The soil is a Mottled Yellow Ultic Soil (Hewitt 1998) (shown as Whangaripo clay loam series in old soil maps) formed in highly weathered metamorphosed sandstones and claystones. The cation exchange capacity (CEC) of the topsoil (0–10 cm) is 15 cmol/kg, and the base saturation is 20–30% in the topsoil and <10% in the subsoil. The clay content is about 40% in the topsoil and 70% in the subsoil; the clay minerals are mainly smectite with some kandite (J.S. Whitton, pers. comm.). The first rotation of planted forest did not yield a commercial crop because of severe P limitation. The second rotation was planted in 1969 after cutting and burning the first crop. The second crop was thinned to 407 stems/ha at age 11 years. Superphosphate fertiliser was applied in 1969 at a rate of 17 kg P/ha, in 1974 at 125 kg P /ha, and in 1977 at 125 kg P /ha. In 1995, foliage contained 1.27% N and 0.15% P. The estimated total standing volume was 652 m^3/ha.

The trees were clear-cut in July to October 1996 and removed using a cable-hauler that generally lifted the trees, without vehicles travelling over the site, thus causing minimal soil disturbance. Disturbance over the nine-hectare site was characterised using the visual scoring system of McMahon (1995) along transects 50 m apart. Hauler harvesting caused a typical gradient of fingers of disturbance increasing in intensity towards the skid landing. This primary disturbance, together with site aspect, was taken into account by blocking the trial area into high, medium, low-medium, and low disturbance blocks, based on visual scoring of 130 to 160 points in each 40 by 40 m plot along four transects 10 m apart (Simcock and Dando 1996; Simcock *et al*. 1997).

Trial design, treatments and establishment

The trial consisted of four replicates (i.e. blocks) of 12 treatments (i.e. plots) in a randomised block design (48 plots in total). Each plot was 40 by 40 m with a central core for measurements of 20 by 20 m. The 10-m buffer strip in each plot was required to prevent the treatment effects extending to the cores of adjacent plots during the experimental period. A factorial design of 2 × 2 × 3 was used to examine compaction (no compaction, compacted), site preparation (no ripping, ripped) and fertilising (no fertiliser, N fertiliser, N and P fertilisers), which gave a total of 12 treatments (Skinner *et al*. 2002; Simcock *et al*. 2006).

(1) Compaction treatment: 2 levels – 1) no compaction; 2) An unloaded rubber-tyred C6E Tree farmer skidder (tire width 55 cm, gap between tires 110 cm) was used to compact 40% to 50% of the entire plot area in 4-m-wide rows along the contour, i.e. the compaction was in rows to simulate a ground-based harvesting pattern; half the rows within the plot were not compacted. The degree and area of compaction were within the range associated with operational impacts (Simcock *et al*. 2000). GPS recording of ground-based harvesting on similar soils and topography under moist soil conditions showed that about 2/3 of an operational area is often trafficked, and in these soils 1 to 3 passes reduced topsoil macropore volume (measured from water release at -10 kPa) to <10% v/v, a level marginal for seedling establishment (Simcock *et*

al. 2000). Two passes were used here in November 1996.

(2) Site preparation treatment: 2 levels – 1) no ripping; 2) The plots were ripped to a depth of 0.6 to 0.7 m with a single-winged tine followed by four disks in February 1997 when soils were at their driest to maximise shattering of soil; all six rows of the central core were ripped and disked, together with the buffer zone.

(3) Fertiliser treatment: 3 levels – 1) no fertiliser; 2) N fertiliser- 50 kg N/ha as urea was broadcast across the plots by hand in October 1997 after planting; 3) N and P fertilisers- 50 kg N/ha as urea plus 50 kg P/ha as Sechura phosphate rock (reactive phosphate rock - RPR) were broadcast across the plots by hand in October 1997 after planting. An additional 50 kg N/ha as urea was applied in October 1998 for both fertiliser treatments.

The trial was established with GF 28 radiata pine seedlings in winter (July) 1997 at 1250 stems per ha. The herbicide Velpar (4 kg hexazinone /ha) was applied in late 1998 to control weed growth, followed by a combination of hexazinone and terbuthylazine in 2001.

Growth measurement and foliage sampling

The height and root collar diameter (RCD) of all seedlings were measured after planting, and in June of 1998 and 1999. In winter (July-Aug.) 2001, 2003 and 2005 (at ages 4, 6 and 8), tree height and diameter at breast height (DBH) were measured for every tree in the central 20 by 20 m core of each plot; double leaders were treated as individual stems, and included in the measurements. Mean DBH, mean top height (MTH) and total stem volume were calculated for each plot. In Autumn (Feb.-Mar.) 1999, 2000, 2001, 2002, 2005 (at ages 2, 3, 4, 5, 8), foliar samples (1-year-old fully expanded non-flush needles) were taken from 10 trees in each plot to determine foliar nutrient concentrations of N, P, K, Ca, Mg, B, Zn and Cu.

Statistical analysis

Growth data were analysed using factorial ANOVA for the effects of compaction (no compaction, compacted), site preparation (no ripping, ripped), fertilising (no fertiliser, N fertiliser, N and P fertilisers), and their interactions. Stocking was included as a covariate in these analyses. Variables analysed were Mean DBH (cm), MTH (m) and Total Stem Volume (m^3/ha) at ages 4, 6 and 8.

Foliage nutrient concentrations were also analysed using factorial ANOVA for the effects of compaction (no compaction, compacted), site preparation (no ripping, ripped), fertilising (no fertiliser, N fertiliser, N and P fertilisers), and their interactions. Analyses were performed for N, P, K, Mg, B for years 1999, 2000, 2001, 2002, 2005 (at ages 2, 3, 4, 5, 8). The foliar K and B data were not presented due to no treatment effect in any individual year.

RESULTS AND DISCUSSIONS

Effect of treatments on foliar nutrient concentrations

<u>Compaction and site preparation</u>

Compaction and site preparation had no significant effects on foliar N, P and Mg concentrations at ages 5 and 8 years (Table 1). For foliar Mg concentration, a significant interaction between compaction and site-preparation was only found at age 8 years (Table 1). This interaction indicates that ripping had a positive effect on foliar Mg concentration under no compaction while it had a negative effect after compaction (Fig. 1). However, differences in foliar Mg concentration between these treatments at age 8 were similar to the increase in foliar Mg between years 4 and 8. Foliar Mg has significantly increased over time in all treatments, indicating Mg is unlikely to be contributing to differences in tree health or growth at age 8 years.

Table 1. *P* values for main effects and interactions on foliar N, P and Mg concentrations of radiata pine at Riverhead Forest.

	At age 5 years (2002)			At age 8 years (2005)		
	N (%)	P (%)	Mg (%)	N (%)	P (%)	Mg (%)
Block	0.995	0.177	0.127	0.018	0.750	0.309
Compaction	0.580	0.237	0.131	0.454	0.535	0.135
Site-prep [b]	0.429	0.113	0.126	0.707	0.257	0.965
Compact*prep	0.531	0.469	0.105	0.370	0.179	**0.010**
Fertiliser	0.522	**0.002**	**0.035**	0.227	0.584	**0.004**
Prep*fertiliser	0.953	0.928	0.996	0.264	0.433	**0.005**
Compact*fertiliser	0.944	0.327	0.319	0.720	0.382	0.219
Compact*prep*fertiliser	0.592	0.758	0.916	0.355	0.987	0.531

[a.] TSV- Total stem volume [b.] Site-prep - Site preparation

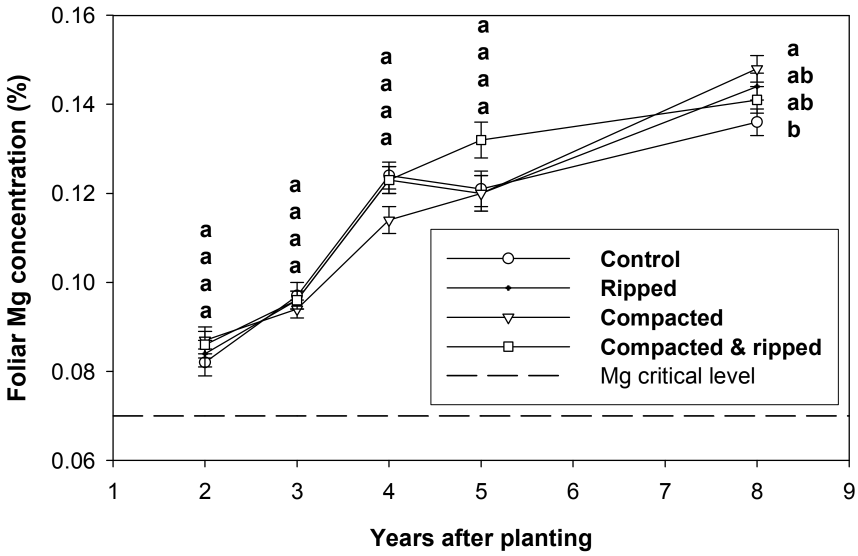

Fig. 1. Interactive effect of compaction and site preparation on foliar Mg concentration. 1) Control – no compaction, no ripping; 2) Ripped – no compaction but ripped; 3) compacted – compacted with no ripping; 4) Compacted & ripped – compacted and ripped. Mean values are presented and different letters within a column indicate significant differences at $P < 0.05$.

<u>Fertilisation</u>

Fertiliser treatments had significant effects on foliar N concentration at age 4 years (Fig. 2), P concentration at ages 3, 4 and 5 years (Fig. 3) and Mg concentration at ages 5 and 8 years, respectively (Table 1, Fig. 4).

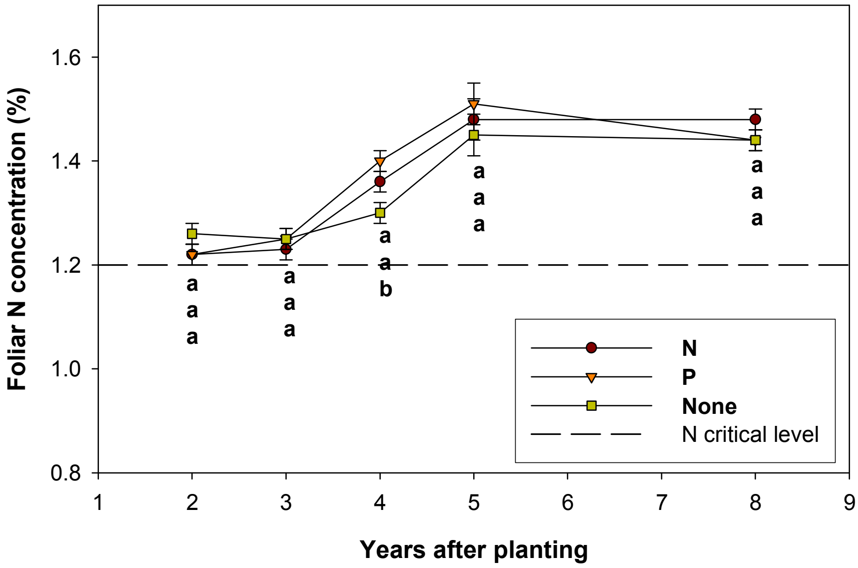

Fig. 2. Effect of fertiliser treatments on foliar N concentration. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha; 3) None – no fertiliser. Mean values are presented and different letters within a column indicate significant differences at $P < 0.05$.

The foliar N concentration was significantly greater in N and N+P treatments than the unfertilised treatment only at age 4 years. Generally, the foliar N concentrations for all the 3 fertiliser treatments were marginal (Will, 1985) during the 8 years after planting, and showed a small, but significant increase from age 4 years (Fig. 2).

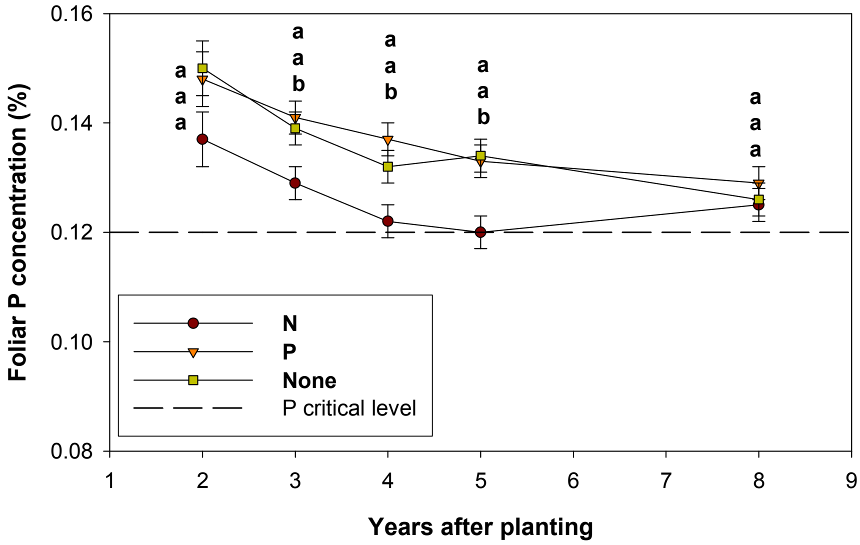

Fig. 3. Effect of fertiliser treatments on foliar P concentration. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha no compaction but ripped; 3) None – no fertiliser. Mean values are presented and different letters within a column indicate significant differences at $P < 0.05$.

The foliar P concentration was significantly lower in the N treatment than the other treatments at ages 3, 4 and 5 years (Fig. 3). This was due to the growth dilution of the N treatment (Fig. 6). In spite of a larger growth increase, the foliar P concentration in the N+P treatment was similar to the level in the unfertilised treatment due to the addition of P fertiliser. Generally, the foliar P concentrations for all the 3 fertiliser treatments were marginal (Will, 1985) during the 8 years after planting, and gradually decreased with increasing age (Fig. 3)

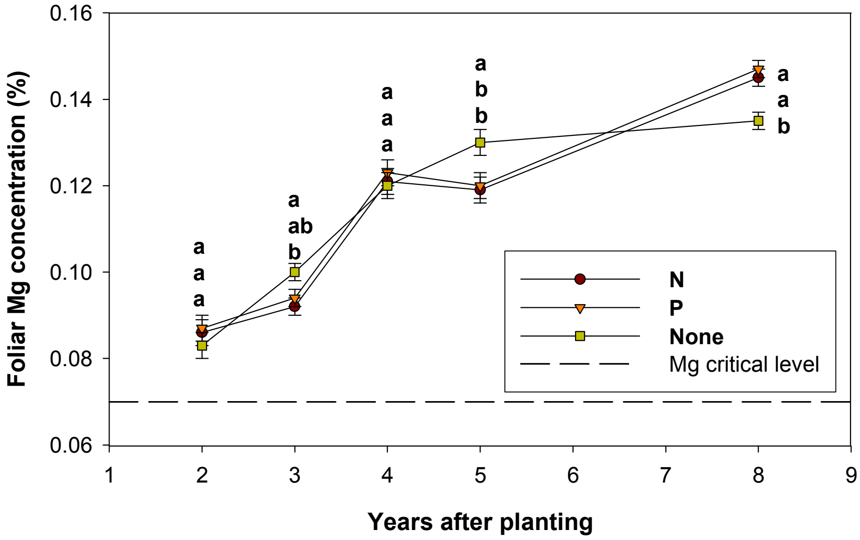

Fig. 4. Effect of fertiliser treatments on foliar Mg concentration. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha no compaction but ripped; 3) None – no fertiliser. Mean values are presented and different letters within a column indicate significant differences at $P < 0.05$.

The foliar Mg concentrations for all the 3 fertiliser treatments were marginal at ages 2 and 3 years and increased to satisfactory levels (Will, 1985) thereafter (Fig. 4). This change could be related to the increased uptake of Mg from soil by larger root systems in older trees. Significantly lower Mg concentrations in the N and N+P treatments at ages 3 and 5 years were generally due to the growth dilution when compared to the unfertilised treatment.

Effect of treatments on tree growth

At age 8 years, fertilising was the only treatment that generally increased tree DBH and volume significantly (Table 2). There was a significant interaction between compaction and site preparation on MTH at age 6 years and a weak interaction ($P = 0.08$) at age 8 years. There was no significant difference between the blocks, indicating no impact from the disturbance that was assessed in 1996 following harvest.

Table 2. *P* values for main effects and interactions on the tree growth of radiata pine at Riverhead Forest.

	At age 6 years			At age 8 years		
	DBH (cm)	MTH (m)	TSV [a] (m^3/ha)	DBH (cm)	MTH (m)	TSV [a] (m^3/ha)
Block	0.120	0.450	0.552	0.053	0.144	0.156
Compaction	0.769	0.509	0.894	0.810	0.912	0.659
Site-prep [b]	0.790	0.433	0.652	0.929	0.899	0.841
Compact*prep	0.137	**0.048**	0.209	0.101	0.083	0.207
Fertiliser	**0.0008**	0.267	**0.014**	**0.0004**	0.156	**0.007**
Prep*fertiliser	0.497	0.765	0.977	0.178	0.257	0.909
Compact*fertiliser	0.846	0.123	0.811	0.790	0.186	0.840
Compact*prep*fertiliser	0.431	0.777	0.574	0.434	0.641	0.629

[a.] TSV- Total stem volume [b.] Site-prep - Site preparation

Compaction and site preparation

Compaction had no significant effect on radiata pine tree growth measured at ages 4, 6 and 8 years (Table 2). This differed from the early effect of compaction on tree survival and growth at age 1 year (Simcock *et al*. 2006). This change is probably due to the much larger root systems of the trees at age 4 years and thereafter. Root systems preferentially develop in and into aerated soil – the greatest volume of aerated soils were in uncompacted strips which lay approx 2 m from each seedling planted into compacted zones. At an individual tree scale, the survival of trees planted in compacted soil was lower than in the control plots. However, excavation near several trees showed that roots of some 1-year-old and 2-year-old seedlings grew out of hostile compacted zones into favourable areas, e.g., a 1-year old seedling had a 1-m-long root extending into a patch of decomposing fern stump, where root growth proliferated (Simcock *et al*. 2006).

Site preparation (i.e. ripping) had significant effects on tree survival and growth during the first 4 years of rotation (Skinner *et a*l. 2002; Simcock *et al*. 2006). However, the growth advantage with site preparation appeared to decrease over time. In ripped plots, the trees were 14% taller than those in plots with no ripping at age 1 year and 9% taller at age 4 years. But this positive effect of site preparation on tree growth disappeared after that time (Table 2). This agreed with the findings of Miller *et al*. (1996) who showed tillage improved survival and early height growth. Site preparation of both disturbed and undisturbed soils increased macropore volume and increased the depth to the water table in areas where water-filled channels could drain away from the rip-zone, and/or where disking had raised the soil surface up to 10 cm. The overall effect of site preparation was to give the surviving roots access to a greater volume of aerated soil, allowing increased tree growth over the first 4 years.

A small but significant interaction was found between compaction and site preparation on mean top height (MTH) at age 6 years (Table 2). Ripping improved tree MTH without compaction but had no effect on it with compaction (Fig. 5). No significant interactions were found between compaction and site preparation on DBH and total stem volume during the period of ages 4 to 8 years (data not shown).

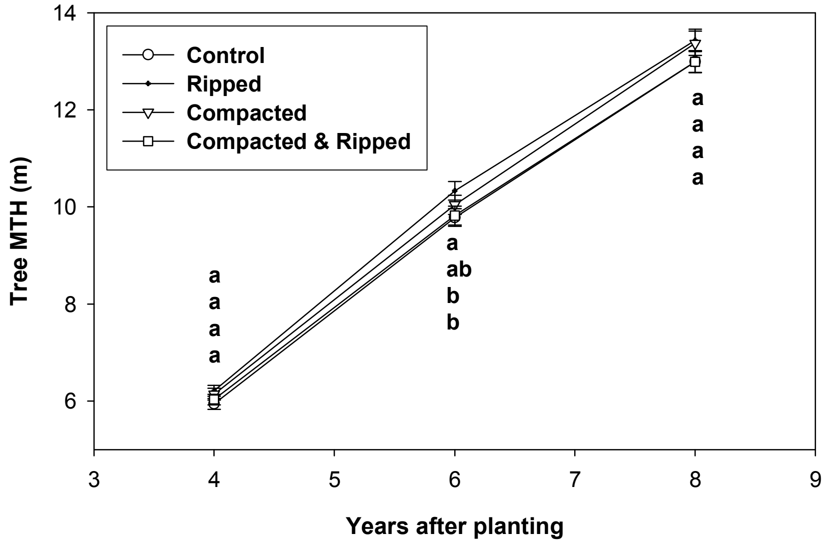

Fig. 5. Interactive effect of compaction and site preparation on mean top height (MTH). 1) Control – no compaction, no ripping; 2) Ripped – no compaction but ripped; 3) compacted – compacted with no ripping; 4) Compacted & ripped – compacted and ripped. Mean values are presented and different letters within a column indicate significant differences at $P < 0.05$.

Fertilisation

Fertiliser treatment had significant effects (P < 0.01) on tree DBH and total stem volume (Table 2). Generally, both N and N+P fertiliser treatments increased tree DBH (Fig. 6). However, only the N+P fertiliser treatment significantly increased total stem volume (Fig. 7). Fertiliser treatment had no significantly effect on MTH (Fig. 8). Overall, the improved tree growth at the fertilised treatments was related to the increased uptake of N and/or P, which, however, was not reflected in the foliar N and P concentrations due to the growth dilution.

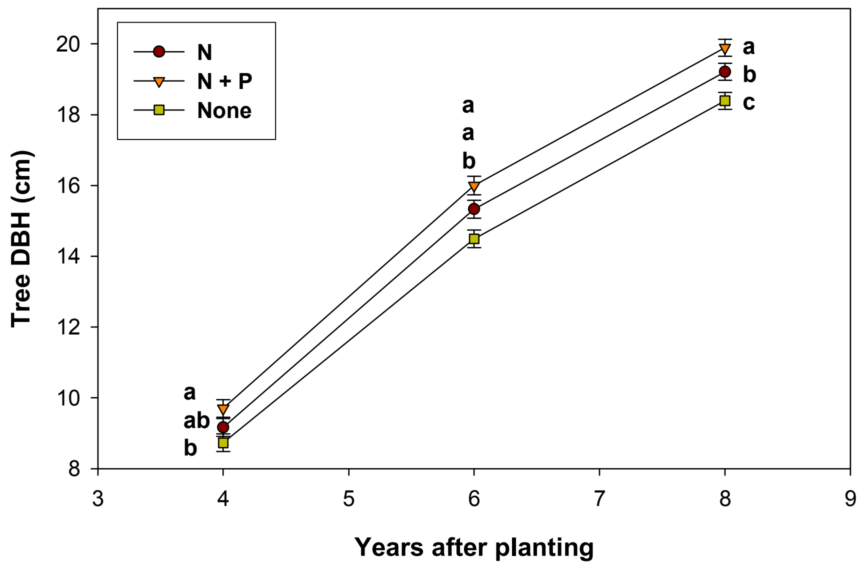

Fig. 6. Effect of fertiliser treatments on tree DBH. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha no compaction but ripped; 3) None – no fertiliser. Mean values are presented and different letters within a column indicate significant differences at P < 0.05.

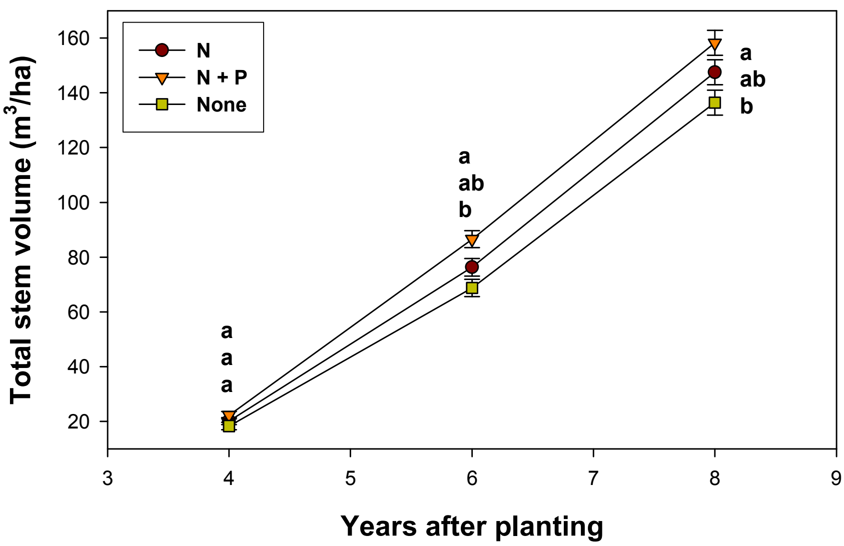

Fig. 7. Effect of fertiliser treatments on total stem volume. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha no compaction but ripped; 3) None – no fertiliser. Mean values are presented and different letters within a column indicate significant differences at P < 0.05.

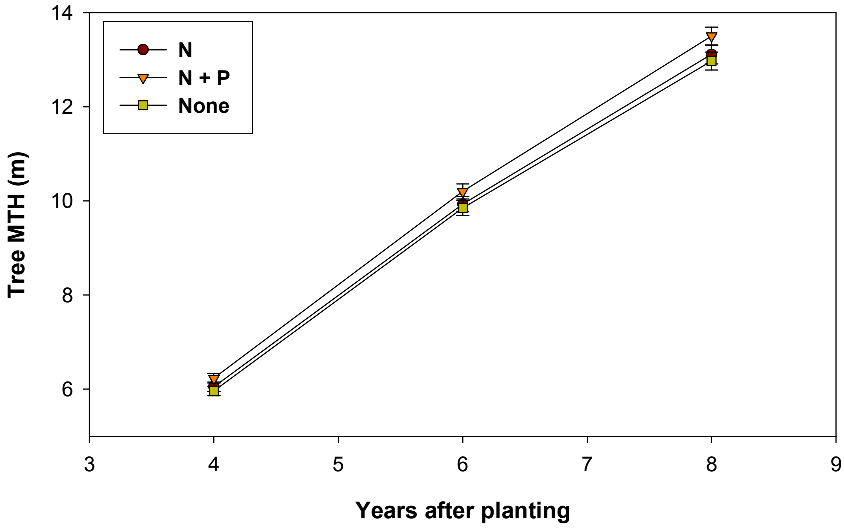

Fig. 8. Effect of fertiliser treatments on tree MTH. 1) N – 100 kg N/ha; 2) N + P – 100 kg N/ha plus 50 kg P/ha no compaction but ripped; 3) None – no fertiliser. Mean values are presented and error bars represent 1 SE.

CONCLUSIONS

- Compaction had no significant effect on foliar nutrition and tree growth during the period of ages 4 to 8 years. However, this trial showed that compaction reduced survival of radiata pine seedlings at planting and during the first year of growth, which was as a result of reduced macropore volume, a shallower depth to the perched water table, and increased oxygen deficit.

- Site preparation (i.e. ripping) also had no significant effect on foliar nutrition and tree growth during the period of ages 4 to 8 years. However, the first 4-year results from this trial demonstrated that site preparation improved the survival and growth of the seedlings during the early stages after treatment, by increasing the depth to the perched water table, and increasing topsoil macropore volume. Since survival of seedlings is important, especially where planting densities are low, ripping of soils with low macropore volume should be considered as a management tool.

- Fertilising continued to improve the foliar nutrition and tree growth over 8 years after planting. Due to the marginal levels of both N and P in the needles of radiata pine at this trial, N+P fertiliser treatment resulted in a greater increment in tree growth when compared to the N fertiliser only.

- In contrast to the first 4 years of results, there were no significant interactions between site preparation and fertiliser treatment for the foliar N and P concentrations and tree growth.

RECOMMENDATIONS

Management of trees on imperfectly drained Ultic soils

- Cultivate soils if required seedling survival is >85% to increase air-filled pore volume.

Air-filled volume is increased by raising the soil surface (where water table is high) and loosening the soil (especially where it is compacted).

- Seedlings compensate for poor physical and chemical site conditions until canopy closure as they increase root density and are able to exploit areas of favourable soils

- An alternative strategy to 'blanket' cultivation may be to plant seedlings at higher densities (allowing for survival as low as 65%) and only treating large, or linear, compacted areas.

Trial management

- Increase rate of P fertiliser application in N + P treatment?

- Monitor water table heights in 2007/2008 to quantify the reduction in water table height from 1997 and 1998; this reduction in water table height maybe a major factor in continued recovery of growth rates in compacted and control plots.

- Remeasure trees in 2009 to follow impact of full roots and tree canopy occupancy

ACKNOWLEDGMENTS

We would like to acknowledge the contributions of Carter Holt Harvey Forests Limited and the New Zealand Forest Site Management Cooperative for the field assistance and financial support.

REFERENCES

Ballard, R. 1978. Effect of first rotation phosphorus applications on fertiliser requirements of second rotation radiata pine. N.Z. J. For. Sci. **8**: 135–145.

Bockheim, J.G., Ballard, T.M., Willington, R.P. 1975. Soil disturbance associated with logging in southwest British Columbia. Can. J. For. Res. **5** 285–290.

Gent, J.A., Ballard, Jr., R., Hassan, A.E. 1983. Impact of harvesting and site-preparation on physical properties of Lower Coastal Plain forest soils. Soil Sci. Soc. Am. J. **47**: 595–598.

Hewitt, A.E. 1998. New Zealand Soil Classification. Landcare Research Science Series No. 1. Manaaki Whenua Press, Lincoln, Canterbury, New Zealand. 133 p.

Hunter, I.R., Graham, J.D. 1982. Growth response of phosphorus-deficient *Pinus radiata* to various rates of superphosphate fertilizer. NZ J. For. Sci. **12**: 49–61.

McMahon, S. 1995. Survey method for assessing site disturbance. Logging Industry Research Organisation project report 54. Rotorua. 16 p.

Miller, R.E., Scott, W., Hazard, J.W. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Can. J. For. Res. **26**: 225–235.

Rab, M.A., 2004. Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. For. Ecol. Manage. **191**: 329–340.

Simcock, R., Dando, J. 1996. Riverhead Compaction and Amelioration Trial research plan and pre-harvest site assessment. Landcare Research Report. Landcare Research. Palmerston North.

Simcock, R., McMahon, S., Dando, J., Ross, C. 1997. Riverhead compaction and amelioration trial: Report on the 1996/97 year. Landcare Research Report. Landcare Research. Palmerston North.

Simcock, R., Skinner, M., Dando, J., Ross, C., McMahon, S. 2000. Soil compaction during harvesting of *P. radiata* on an Ultic Soil: severity and impact on establishment of the next-rotation seedlings. *In* Soil 2000: New Horizons for a new century. Australian and New Zealand Second Joint Soil Societies Conference Volume 2. Oral papers.3–8 December 2000, Lincoln University. *Edited by* J.A. Adams and A.K. Metherell. pp. 269–270.

Simcock, R.C., Parfitt, R.L., Skinner, M.F., Dando, J., Graham, J.D. 2006 The effects of soil compaction and fertilizer application on the establishment and growth of *Pinus radiata* (D.Don). Can. J. For. Res. **36**: 1077-1086.

Skinner, M.F., Murphy, G., Robertson, E.D., Firth, J. 1989. Deleterious effects of soil disturbance on soil properties and subsequent early growth of second rotation *Pinus radiata*. Proceedings IEA/BE Workshop, Seattle, WA, August 1988. IEA/BE A3, Report 8.

Skinner, M.F., Simcock, R.C., Kimberley, M., Graham, J.D. 2002 NZFRI TRIAL AK345: Compaction and amelioration of tree growth and foliar nutrition at age 4 in an imperfectly-drained clay soil. Report No 121, Feb. 2002, Forest Research.