INTERSPECIFIC COMPETITION BETWEEN *PINUS RADIATA* AND SOME COMMON WEED SPECIES—FIRST-YEAR RESULTS

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ABSTRACT

A trial designed to quantify the reduction in *Pinus radiata* D.Don seedling growth caused by competition from a range of important weed species was established at Rotorua, a moist North Island site, and at Rangiora, a South Island site with low summer rainfall. At both sites, *P. radiata* seedlings were grown on their own and with either herbaceous broadleaves (a volunteer mixture of species from which grasses were excluded), *Cytisus scoparius* L. (broom), or *Ulex europaeus* L. (gorse). Trees were also grown with *Buddleja davidii* Franchet (buddleia), *Holcus lanatus* L. (Yorkshire fog) plus *Lolium multiflorum* L. (Italian ryegrass), and *Cortaderia selloana* (Schult) Asch. et Graeb. (pampas) at Rotorua and with *Agrostis capillaris* L. (browntop) at Rangiora. Resource (nutrient and water) levels were varied by factorial ± irrigation and fertiliser treatments. At Rotorua, *P. radiata* stem volume after 10 months was greatest in weed-free, gorse, broom, and Yorkshire fog plots and least in herbaceous broadleaf and buddleia plots, with pampas intermediate. At this time, there was no strong evidence of interspecific competition for water or nutrients. At Rangiora, trees growing with grass and herbaceous broadleaves were substantially reduced in stem volume compared to trees in the weed-free, broom, and gorse plots. There was essentially no difference in growth with the latter three treatments.

Keywords: competition; weeds; water; nutrients; *Pinus radiata*.

INTRODUCTION

Many studies have demonstrated that *Pinus radiata* growth and survival are reduced by the presence of other plant species (Baker *et al.* 1988; Balneaves 1982,1987; Balneaves & Christie 1988; Balneaves & Henley 1992; Balneaves & McCord 1990; Brunsden 1980; Cellier & Stephens 1980; Mason 1992; Nambiar & Zed 1980; Ray *et al.* 1989; Sands & Nambiar 1984; Smethurst & Nambiar 1989; Squire 1977; Turvey *et al.* 1983; Turvey & Cameron 1986; West 1984). Large growth benefits after removal of competing vegetation are apparent over a wide range of site types and with many different competitor species. Because of this, intensive vegetation management practices, with heavy emphasis on herbicide use, are typical in the establishment of *P. radiata* plantations in New Zealand.

This large body of information illustrates the size of short-term crop growth gains after weed control. However, there is relatively little information on the actual mechanisms of the interaction between the crop and associated plants. This understanding is critical for the development of models of crop growth that include weed competition effects and that can be applied to different site types with a range of competitor species. Increased tree growth as a result of competition removal can usually be explained in terms of improved moisture and nutritional conditions or reduced competition for light. These factors enhance physiological processes such as leaf area development, carbon assimilation, diffusive conductance, and water-use-efficiency (Boomsma & Hunter 1990). With the increasing cost of weed control and the pressure against the use of herbicides, it is essential that competition removal operations are applied only to the degree required to give optimal gains, and are targeted against the most damaging species in terms of the impact on crop growth. These objectives can be achieved only by understanding the nature of the interaction between the crop and the competitors, and how this varies over different sites and climates. To this end, a study was designed to investigate the effect on tree growth of some of the prominent New Zealand forest weed species. First-year results are presented from two trials on contrasting site types where treatments included manipulation of site resources (water and nutrients).

METHODS

Sites

Two trial sites were selected, one adjacent to the NZ FRI Rotorua nursery (38°S 176°E) and one at Rangiora nursery (43°S 172°E). Rotorua has a mean annual rainfall of 1491 mm, a mean annual temperature of 12.7°C, and an annual average raised pan evaporation of 1186 mm (NZMS 1980). By contrast, Rangiora is much drier with a mean annual rainfall of 702 mm, a mean annual temperature of 11.4°C, and an annual average raised pan evaporation of 1329 mm (based on Christchurch airport data) (NZMS 1980). There is a deep, moderately fertile, pumice soil at Rotorua (yellow-brown Ngakuru loam), which is well drained and has a high moisture-holding capacity. The soil at Rangiora nursery consists of a heavy Wakanui silt loam with high nutritional status but low organic content. The site is prone to drought during the period from late spring till late autumn, but during winter and early spring, the soil is often very wet.

Experimental Design

At each location, a complete factorial set of treatments was laid out in a split plot design. There were three treatment factors—weed type, fertiliser, and irrigation. At Rotorua, there were seven levels of weed type (Table 1) and at Rangiora there were four. At each location there were two levels of fertiliser (nil; fertiliser applied) and irrigation (nil; water applied). The experimental blocks were split into halves, one half being irrigated. Within each irrigation treatment block, fertiliser and weed type treatment combinations were completely randomised. At Rangiora there were four replicates installed in 1990. At Rotorua, three replications were installed at one per year from 1990 to 1992. The advantages of replication through time are that effects of different climatic conditions on the competitive interaction can be observed, there is some protection against atypical conditions in the year of installation, and limited manpower and financial resources can be spread over a greater time.

TABLE 1–Weed type treatments at Rotorua and Rangiora

Rotorua	Rangiora
1. Gorse (*Ulex europaeus* L.)	1. Gorse
2. Broom (*Cytisus scoparius* L.)	2. Broom
3. Buddleia (*Buddleja davidii* Franchet)	3. Browntop (*Agrostis capillaris* L.)
4. Pampas (*Cortaderia selloana* (Schult) Asch. et Graeb.)	4. Herbaceous broadleaves (volunteer species)
5. Yorkshire fog (*Holcus lanatus* L.) plus Italian ryegrass (*Lolium multiflorum* L.	5. Weed-free
6. Herbaceous broadleaves (volunteer species)	
7. Weed-free	

The disadvantage is the length of time before the results can be properly analysed based on statistical replication, with the "first year's" growth reported in this study being gathered over a 3-year period. The trial site at Rangiora and the first two of the replicates at Rotorua were previously under grass; the third, however, had been under mature *P. radiata* clearfelled during the previous year.

Installation

To eliminate existing vegetation, predominantly a mixture of herbaceous broadleaves and grasses, the sites were prepared using a combination of mechanical cultivation and herbicide applications. Seedlings (GF17, 1/0) were lifted from the respective nurseries adjacent to the sites and planted in July 1990 (also in August 1991 and 1992 at Rotorua) using conventional techniques. To improve stock uniformity, seedlings were graded according to root collar diameter and height. Tree seedling spacing was 1 × 1 m, giving 25 trees per plot (5 × 5 m). At Rotorua, gorse, broom, buddleia, and pampas were planted as seedlings (germinated during or shortly after the winter of tree planting) at 0.5 × 0.5 m spacing in the October following tree planting. At the same time as this planting, Yorkshire fog and Italian ryegrass seeds were scattered by hand, and herbaceous broadleaves were allowed to emerge and grow. At Rangiora, broom, gorse, and browntop were established by scattering seed on to the plots, the broom and gorse in the autumn prior to tree planting, and the grass the following spring. After tree planting, herbaceous broadleaves were allowed to emerge and grow in the appropriate plots.

Unwanted weeds were periodically killed with a combination of hoeing, hand weeding, and spot applications of glyphosate; haloxyfop was used to remove grasses from the herbaceous broadleaf plots and clopyralid to remove broadleaves from the grass plots.

Irrigation and Fertiliser

The goal of irrigation and fertiliser application was to ensure that moisture and nutrients were non-limiting on these respective treatments. At Rotorua, an automatic overhead-irrigation system was installed and the trial was irrigated every night with an amount of water greater than the calculated maximum evaporation. In total, this amounted to approximately 1000–1100 mm/year in excess of annual rainfall. At Rangiora, overhead-sprinkler irrigation was limited to once per week during the late-spring and summer months. Although it was realised that this may have been an inadequate moisture supply to achieve the goal of the treatment, it was all that could be achieved with limited resources and manpower. There was no record of the absolute quantity of water applied. To try to achieve a non-limiting nutrient supply, an intensive fertiliser regime was designed (P.Knight, pers. comm.). Although the Rotorua site is less fertile than Rangiora, the same regime was applied to each site (Table 2). All fertilisers were broadcast over the plots so that the nutrients were reasonably accessible to the trees and the weeds.

TABLE 2–Fertiliser regime applied at both Rotorua and Rangiora

Timing	Treatment	Rate (kg/ha)
Pre-plant	15% potassic Magphos (0-8-8-6(S)-20(Ca)-5(Mg))	750
Pre-plant	IBDU (Isobutylidenediurea) (32%N)	500
Pre-plant	FTE 36 (trace elements)	20
At planting	Nitrophoska yellow (15-7-5-4(S)-2.4(Mg))	100
Summer (annually)	Nitrophoska blue (12-5-14-1.2(Mg)+TE)	120
Autumn (annually)	Nitrophoska blue (12-5-14-1.2(Mg)+TE)	120
Spring (year 2 on)	Nitrophoska yellow (15-7-5-4(S)-2.4(Mg))	100

Measurements

Using nine trees in the centre of each plot, root collar diameter and tree seedling height were measured at the time of planting and repeated at monthly intervals at Rotorua for the first two replications and every 2 or 3 months with replication three. With tall weeds (broom, buddleia, pampas, gorse), the height of eight sample plants per plot and the percentage ground cover were also recorded at regular intervals. Two 900 cm^2 (square) samples of above-ground vegetation were taken at approximately 3-month intervals from each grass and herbaceous broadleaf plot, and oven-dry weights were recorded. Sample areas were selected randomly from the plot borders with the proviso that they were not taken from an area that had obviously been harvested previously. Plant moisture stress (using a pressure bomb), stomatal conductance, and photosynthesis (using a LiCor 6200 photosynthesis system) were measured on several days during dry periods in mid-late summer. Physiological measurements were restricted to plots with fertiliser because of the large number of treatments. A Stephenson screen was installed adjacent to the trial area. Rainfall, temperature (wet and dry bulb), and incoming solar radiation were continuously recorded.

At Rangiora, measurements were limited to crop height and root-collar diameters, weed height, and percentage ground cover, taken 10 months after planting. At Rangiora, temperature and humidity were measured using a recording thermohygrograph and maximum and minimum thermometers, and rainfall was measured with a simple rain-gauge.

Data Analyses

Tree and weed growth and physiological data were all analysed using analysis of variance, after a natural logarithm transformation to stabilise the variance where appropriate. Initial tree size (height and diameter) was tested as a covariate in the analysis of crop growth but was found to be not significant. Regression analysis was used to quantify monthly tree stem volume growth for the first two replications (replication three having less frequent measurements). A fourth-order polynomial model was fitted, with dummy variables used to represent replication, irrigation, and fertiliser treatments.

RESULTS

Rotorua Trial

Meteorological conditions

Total rainfall at Rotorua for the first 10 months after planting each replication was 919, 1074, and 1120 mm for the periods commencing August 1990, 1991, and 1992, respectively. Similarly, average temperatures were 13.7°, 12.3°, and 12.2°C, respectively. Over the first 4 months, rainfall was slightly higher and temperatures were cooler for replication 3 (499, 562, and 586 mm, and 11.2°, 10.5°, and 9.9°C for replications 1, 2, and 3, respectively).

Tree growth

Tree stem volume (calculated as root collar diameter^2 × height × $\pi/4$) was significantly influenced by replication ($p = 0.01$), weed type ($p = 0.0002$), and fertiliser application ($p < 0.0001$) (Fig. 1), but there was no effect of irrigation and there were no significant interactions among any of the experimental factors. Tree stem volume was similar in replications 1 and 2, but on the third replication, planted in 1992, volume was reduced by about 29%. Nevertheless, growth trends over the various treatments were consistent across all replications.

Although trees in the weed-free treatment had the greatest mean stem volume, this was not significantly different from trees growing with gorse, broom, or the grass mixture. Trees growing with pampas, buddleia, or herbaceous broadleaves had significantly lower stem volumes, by up to 36%. There were small but statistically significant differences in *P. radiata* height growth resulting from the replication, weed type, and fertiliser treatments ($p = 0.0006$, $p = 0.028$, $p < 0.0001$, respectively) (Fig. 2). However, tree volume is a much more sensitive measure of the effect of competition on overall crop growth (Fig. 3). Tree stem volume is calculated from measurements of diameter and height. Given the small changes in *P. radiata* height, the effect of treatments on tree volume is largely attributable to changes in stem diameter.

The fourth-order polynomial regression models of monthly tree stem volume growth provided a good fit with the data and gave coefficients of determination (r^2) of at least 0.97. Growth trends predicted by these regression models are illustrated in Fig. 4 for trees in plots with fertiliser and irrigation, growing with all weed species except gorse or broom. Growth of trees in gorse plots was almost identical to the weed-free treatment and data from the broom treatment were unreliable because of disease problems, as explained below. From the slopes of the curves (Fig. 4) it is apparent that the stem volume growth rate of trees was affected earliest by herbaceous broadleaves, with the growth curve distinctly diverging from that of the control by 5 months after planting. Effects of pampas and buddleia on stem volume growth rates began to show at about 7 months. By age 10 months, the growth rate of trees in pampas or buddleia was slowing relative to those growing with herbaceous broadleaves.

Weed growth

Crop volume growth losses commenced earliest with trees growing with herbaceous broadleaves, the most important competitor over the first 10 months (Fig. 4). The Yorkshire fog plus Italian ryegrass treatment proved to be a much less effective competitor over the same period. There was a wide variety of species in the herbaceous broadleaf plots, the most

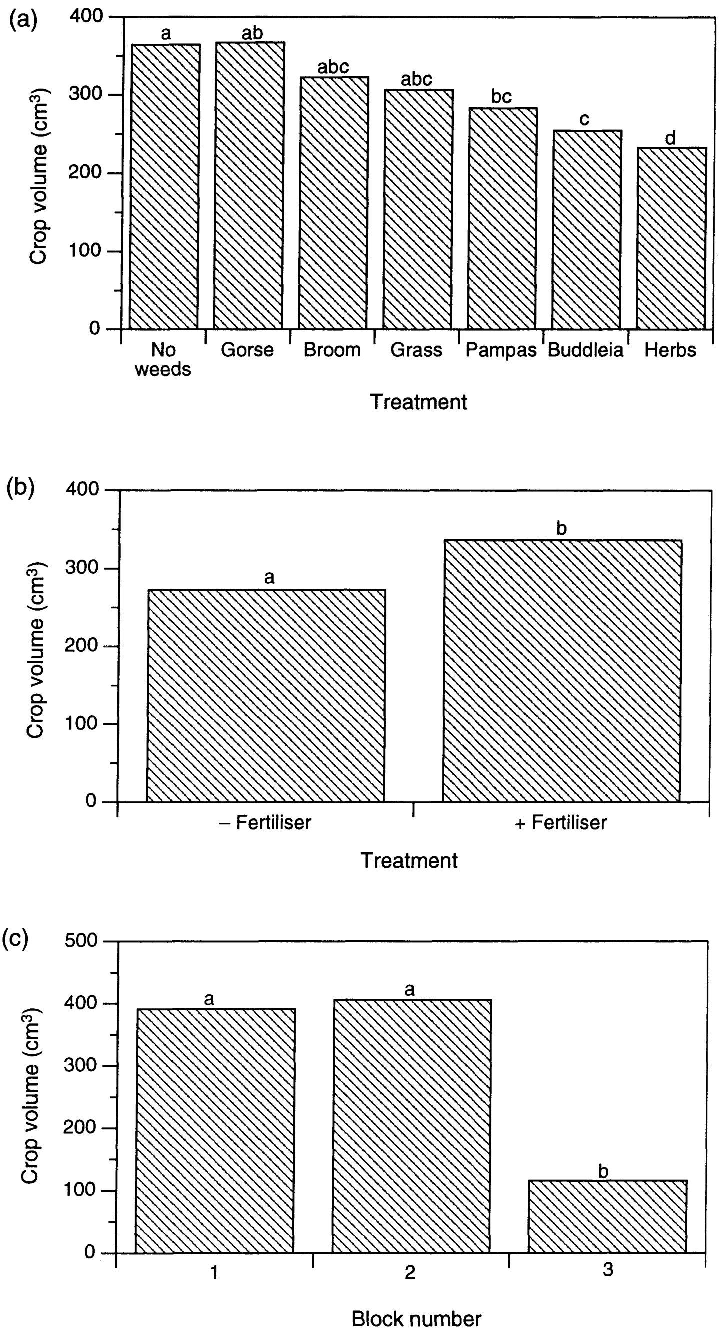

FIG. 1–Effect on *P. radiata* volume, 10 months after planting, of (a) weed competition, (b) fertiliser application, and (c) block number (replicated through time). Bars topped by the same letter are not significantly different at the 5% level according to Fisher's Protected LSD test.

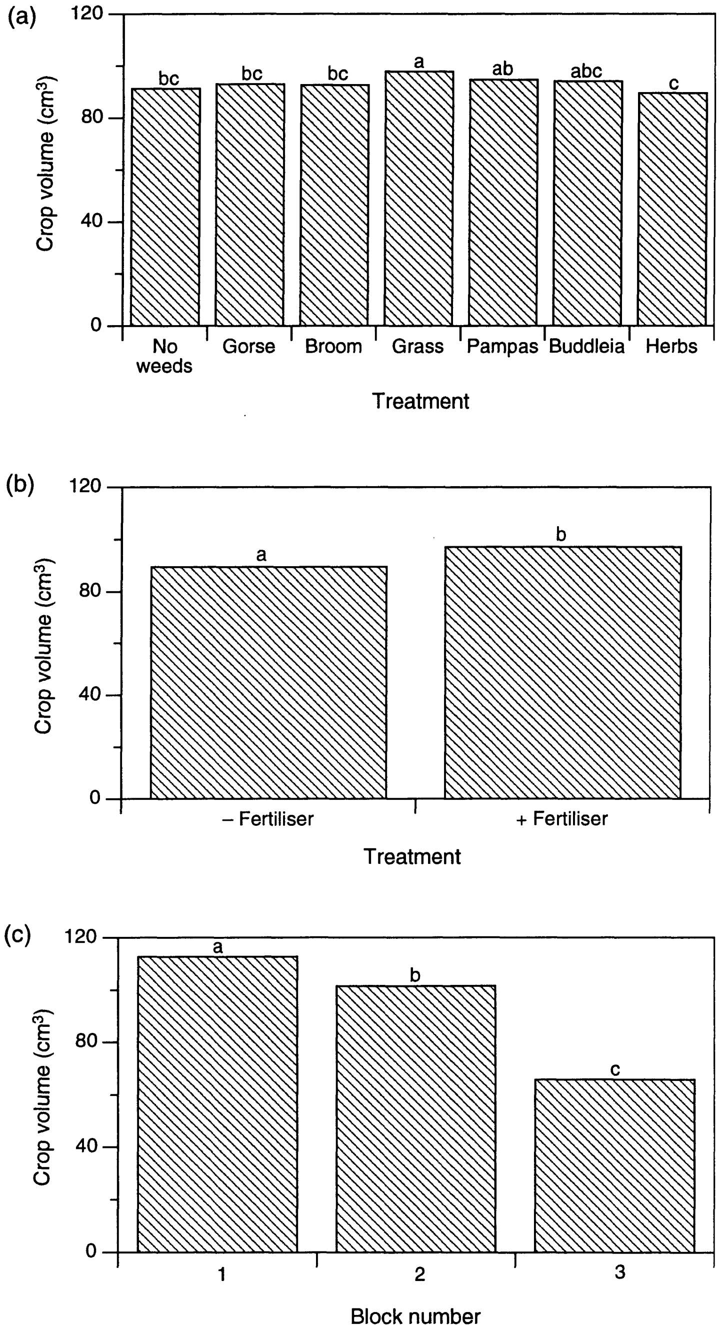

FIG 2–Effect on *P. radiata* height, 10 months after planting, of (a) weed competition, (b) fertiliser application, and (c) block number (replicated through time). Bars topped by the same letter are not significantly different at the 5% level according to Fisher's Protected LSD test.

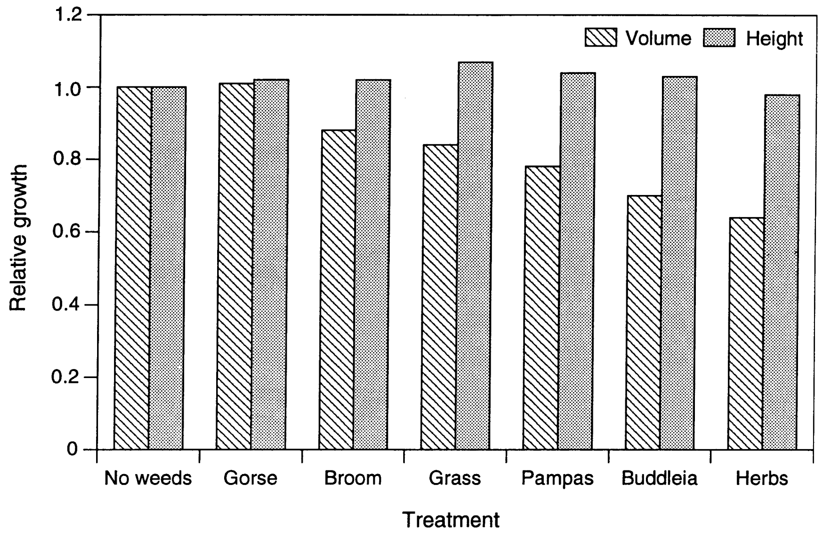

FIG 3–Volume and height growth of *P. radiata* 10 months after planting growing under various competition treatments, expressed relative to growth on the weed-free controls.

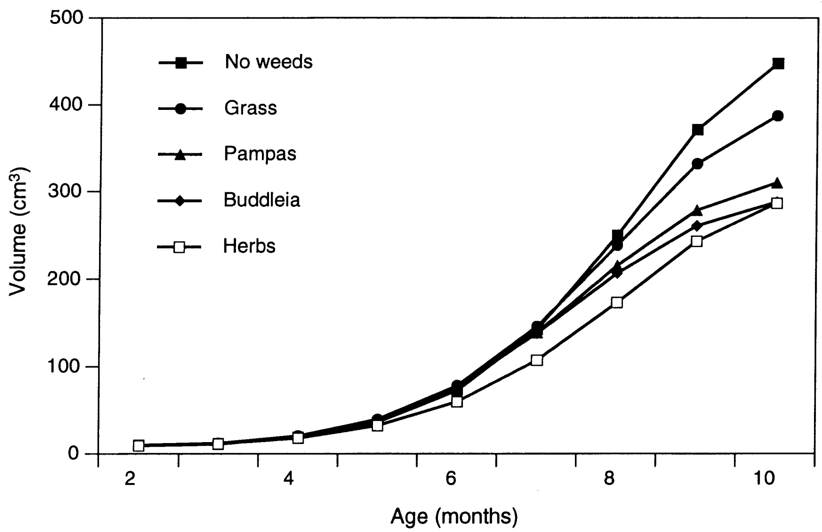

FIG 4–Predicted *P. radiata* stem volume growth trends under various types of competition.

prolific being a variety of docks (*Rumex* spp.) but especially sorrel (*Rumex acetosella* L.), plantains (*Plantago spp.*), catsear (*Hypochaeris radicata* L.), willow weed (*Polygonum persicaria* L.), yarrow (*Achillea millefolium* L.), and lotus (*Lotus uliginosis* Schk.). Initial establishment of the grass mixture appeared to be slower, and after 5 months above-ground dry matter averaged 2095 kg/ha on the herbaceous broadleaf plots compared to 1303 kg/ha on the grass treatment. However, growth of both weed types was considerably enhanced by fertiliser application (above-ground dry matter averaged 2777 kg/ha over both weed types and with fertiliser *v.* 622 kg/ha without fertiliser).

Nine months after planting, there was no significant difference in dry matter production between the grass mixture and herbaceous broadleaves, although the fertiliser effect was still significant ($p = 0.016$) (above-ground dry matter with fertiliser 5368 kg/ha *v.* 4002 kg/ha without).

The fastest-growing competitors in terms of height growth were pampas and buddleia. These species began to overtop *P. radiata* about 7–8 months after crop planting. From this time onwards, crop growth with these treatments was substantially reduced. Broom growth over this same period was slower than the pampas and buddleia, and was undoubtedly affected by infection with the pathogen *Pleiochaeta setosa* (Kirchn.) Hughes, which caused significant mortality in replications 2 and 3. If the broom in all replications had not been sprayed with fungicide (chlorothalonil plus benomyl), it is doubtful whether many plants would have survived. Because of this, the intensity of competition from broom was probably a lot lower than might otherwise have been expected. Overall weed height growth was increased by fertiliser application but, as with the crop growth, was much reduced on replication 3 compared to replications 1 and 2. Once again, there were no significant interactions.

The negligible effect of gorse on *P. radiata* was almost certainly due to its slow growth. At the end of the first year, gorse height was still well below that of the *P. radiata* and percentage ground cover was relatively low. At this same time, all of the other competition treatments has achieved more-or-less complete ground cover.

Mechanisms of competition

There were no significant differences among treatments in plant moisture stress, stomatal conductance, or photosynthetic rates. Even though measurements were taken during dry periods in mid-late summer, moisture stress was never particularly severe. The average pre-dawn water potential over all treatments and years was –392 kPa, with an average midday to mid-afternoon value of –1216 kPa.

The growth enhancement observed after fertiliser application showed that nutrient supply was limiting growth on this site. The growth benefit from fertiliser application was consistent across all competition treatments (no statistically significant interaction) which implies that interspecific competition for nutrients was probably not an overriding factor during this period. Analysis of foliar nutrient concentrations, when available, will be used to further test this hypothesis.

Rangiora Trial

Tree growth

The contrasting characteristics of the Rangiora site compared to Rotorua nursery resulted in more extreme competitive effects over the first year. Tree volume and height growth 10 months after planting were significantly influenced by weed type ($p < 0.0001$ in both instances) (Fig. 5 and 6) but not by the irrigation or fertiliser treatments. There was no

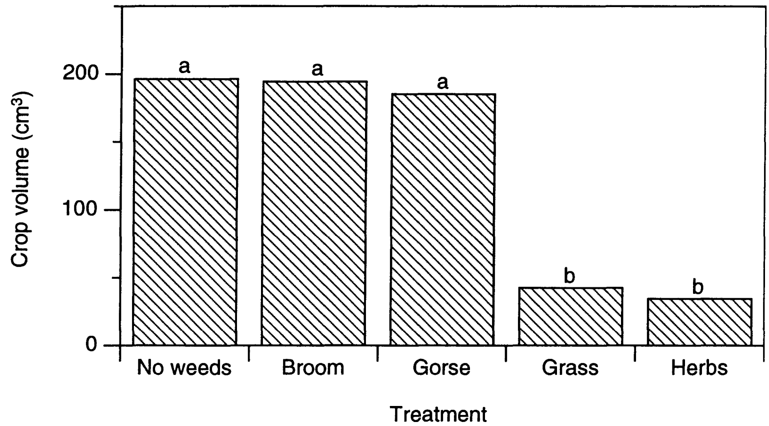

FIG 5–Effect on *P. radiata* volume, 10 months after planting, of weed competition treatments at Rangiora. Bars topped by the same letter are not significantly different at the 5% level according to Fisher's Protected LSD test.

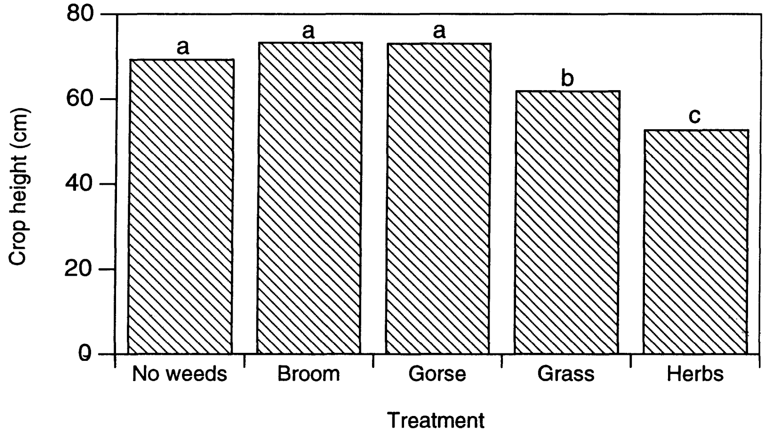

FIG 6–Effect on *P. radiata* height, 10 months after planting, of weed competition treatments at Rangiora. Bars in a graph with the same letter are not significantly different at the 5% level according to Fisher's Protected LSD test.

significant difference in crop volume for the weed-free, broom, or gorse plots, but there was a large, and approximately equal, reduction in volume for the grass and herbaceous broadleaf plots. Pine height growth was also reduced by the presence of grass, and even more so by herbaceous broadleaves, but these differences were small compared to volume effects. In terms of volume growth, there were significant interactions between competition treatments and both the irrigation and fertiliser treatments. For *P. radiata* seedlings grown on their own or in association with gorse, there was an apparent inhibitory effect from irrigation. Given the low-intensity irrigation regime at this site, it is not known why irrigation should result in growth reductions.

Although there was an apparent growth benefit from fertiliser application for trees growing with gorse, a comparison with the competition-free treatment reveals that this benefit was more a result of the treatment without fertiliser having lower than average growth than a true growth stimulation from the added nutrients.

Weed growth

The estimated percentage ground cover of competing vegetation was used as an index of competition. Observations indicated that browntop and herbaceous broadleaf species rapidly attained 100% ground cover. Predominant broadleaves were *Rumex* spp., sorrel, and catsear. The growth of broom and gorse was slower and more patchy, and by April 1991 the average ground cover for both of these species was approximately 40%.

Mechanisms of competition

Because the Rangiora study was not intensively monitored or maintained there is little information on which to base inferences as to likely mechanisms of competition. Surprisingly, there was no significant main effect of irrigation even though summer water limitations in this part of New Zealand are well known (Clinton & Mead 1990). The most likely explanation is that irrigation once per week during the summer months was insufficient to overcome the moisture limitations. Unfortunately, there were no measurements of moisture stress over the first year to test this hypothesis. The fact that there was no effect of fertiliser and no interaction between competition treatment and fertiliser, suggests that nutrients were non-limiting on this site. This is not a surprising result given the relatively high soil fertility.

As with the Rotorua trial, there was a short period, prior to summer die-back, when the herbaceous species overtopped the *P. radiata* seedlings. However, the broom plants were only approaching the height of the pines at the end of the first year, and gorse growth was even slower, so that competition for light was not a factor with these two species.

DISCUSSION

Although herbaceous broadleaves had the largest effect on *P. radiata* stem volume after 10 months, growth trends at Rotorua (Fig. 4) indicated that the fast-growing tall species, namely buddleia and pampas, were having an increasingly severe effect on tree growth. From an examination of weed and tree height growth data (not presented) it appeared that when the height of the competitor species was approximately the same as or greater than that of the pines, crop growth rates were rapidly reduced. Gorse at Rotorua, and both gorse and broom at Rangiora, grew relatively slowly and, probably because of this, had a minimal effect on crop growth. Broom growth at Rotorua was variable because of disease problems.

It was notable that growth of both trees and weeds at Rotorua was much reduced on replication 3 compared to 1 and 2. One possible explanation is that nutrient levels were lower in replication 3. This area was atypical in that a stand of mature *P. radiata* growing on it had been clearfelled in the year prior to establishment of the replication. The possibility that this reduced growth may have resulted from lower fertility will be examined by nutrient analysis of soil samples that were taken prior to establishment of each replication. However, given the amount of nutrients added on the plots with fertiliser and the soil type, it seems unlikely that the growth differences were nutrient related. If the reduced growth on replication 3 was not related to water or nutrient supply, it was possibly a result of environmental variables such as temperature. Small differences over a long period could have significantly influenced growth. This will be examined in subsequent analyses using meteorological data collected on-site.

It is known that stem diameter growth of seedling *P. radiata* is very sensitive to competitor-induced water stress (Nambiar 1984; Sands & Nambiar 1984). In areas such as the central North Island of New Zealand, where there is high, evenly distributed, annual rainfall and the pumice soil has a high storage capacity, it might be expected that soil water deficits should not limit *P. radiata* growth in a typical year (Whitehead & Kelliher 1991). It has been hypothesised that even in this situation soil water deficits may develop near the soil surface, resulting in stress to newly planted *P. radiata* seedlings with roots restricted to the upper soil layers (Richardson in press), but evidence from this trial does not support the hypothesis. Irrigation had no significant effect on tree or weed growth, and there was no significant interaction between irrigation and competition treatment. This implies that water was not a growth-limiting factor on this site, and measurements of plant water-stress and stomatal conductance supported this. Low soil-water availability and high leaf-to-air vapour pressure differences during the summer months make water a growth-limiting factor to tree growth in the Canterbury environment (Balneaves 1982; Clinton & Mead 1990). It has been shown that on dry sites in South Australia, even 5–10% weed cover can reduce *P. radiata* growth through water-stress (Nambiar & Zed 1980). Given these results it is perhaps not surprising that low levels of irrigation had such a moderate effect on crop growth, which varied depending on weed type, in the climatically similar Canterbury environment.

The development of water-stress in pines can be influenced by the competitor species. This is probably a result of variable water usage patterns due to the species' growth habits, physiological characteristics, and type and depth of their rooting systems (Flinn *et al.* 1979; Jackson *et al.* 1983; Nambiar & Zed 1980; Sands & Nambiar 1984). However, at Rangiora, where competition for water was probably the critical factor, there was no significant difference in crop volume on either the grass or herbaceous broadleaf treatment, although height growth was reduced more by herbaceous broadleaves than grass. By contrast, at Rotorua there was a considerable difference in pine volume growth with the herbaceous broadleaf and grass treatments. The greater effect of the herbaceous broadleaves may be related to their faster rate of establishment. The different effect on crop growth of the grass species at Rotorua and Rangiora also may have been related to the rate of establishment or some inherent difference between the species.

It is well known that interspecific competition can limit the ability of the crop to respond to otherwise favourable treatments, such as fertiliser application (Flinn *et al.* 1979; Flinn & Aeberli 1982; Squire *et al.* 1979; Waring 1972; West 1984; Woods 1976). In these trials, the objective was to supply the treated plots with excess nutrients so that competition for nutrients was not a factor. It appears that this goal was achieved because, although both the trees and weeds responded positively to added nutrients on the less-fertile Rotorua site, there was no interaction between competition treatment and fertiliser.

If it is assumed that the weed effect on tree growth was not due to restriction of water or nutrient supply by the weeds, the most probable mechanism leading to crop growth reduction was competition for light, although other mechanisms such as competition for CO_2 or allelopathy cannot be ruled out. Competition for light was likely the dominant factor for tall, fast-growing species such as buddleia and pampas. As soon as these competitors reached approximately the same height as the pine seedlings, crop growth rates began to decline rapidly. It is, however, less certain whether the large growth reduction from the herbaceous broadleaf and, to a lesser extent, the grass treatments, can be explained entirely in terms of competition for light. During the time of peak growth (early summer), these competitors approached and sometimes exceeded the height of the crop. Thus, there was undoubtedly competition for light for a small part of the first year. However, the rapid and severe reduction in crop growth throughout the first year of the herbaceous broadleaf treatment also hints that other mechanisms may have been involved. One possibility is that the development of *P. radiata* roots was directly inhibited by interactions with roots of the herbaceous broadleaf and possibly grass species, such as by the production of allelochemicals (Putnam & Tang 1986).

The mechanism of competition can have important management implications. In general, herbaceous weed control takes the form of spot or strip herbicide treatments centred on the crop tree. If the crop/weed interaction was entirely above-ground, the required spot diameter could be estimated based on the maximum height growth of the herbaceous species relative to tree height. As tree height exceeded the maximum height of the competitors, the spot diameter could be reduced or maintained no longer. However, with root mediated competition for water or nutrients, it is likely that spot diameter would have to be increased over time to give the growing tree free access to water and nutrients. To maximise growth this control would have to be maintained until either the tree roots could reach resources that were unavailable to roots of herbaceous species, possibly deeper in the soil profile, or the crop canopy excluded the herbaceous species through competition for light. Similarly, where tall species compete with *P. radiata* primarily for light, it should be a relatively simple matter to develop indices of competition from which to predict the effects on crop growth for a given level of weed abundance (Morris & Forslund 1991). Such competition indices and competition models would provide an objective method for making decisions on whether weed control is economical.

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