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MATURATION STATUS AND GENETIC IMPROVEMENT EFFECTS ON GROWTH, FORM, AND WOOD PROPERTIES OF PINUS RADIATA CUTTINGS UP TO AGE 12 YEARS

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ABSTRACT

A field trial was initiated in 1986 to evaluate nursery methods for producing aged cuttings of varying physiological age (PA) from stool-beds. Seedlings and cuttings taken from 5-year-old *Pinus radiata* D.Don seedlings grown in the field were included as controls. Three seedlots of different genetic improvement levels from unimproved bulk seed (GF3) to control-pollinated seed from a seed orchard (GF21) were used to study differences in growth rate, tree form, and wood properties (density and acoustic velocity) between cuttings of five different physiological ages up to 5 years and seedlings, and any interaction between physiological age and levels of genetic improvement.

Results showed no persistent long-term height growth differences, and by 4 years of age, any height differences were no longer significant. GF16 and GF21 plants had significantly larger diameters than GF3 plants at both 4 and 11 years of age. Also, seedlings (PA0), and cuttings from 1-year-old seedlings (PA1), had significantly larger diameters than PA5 cuttings from field-grown trees; the cuttings of other physiological ages were intermediate at both 4 and 11 years of age. Physiologically older cuttings had better butt log straightness and freedom from malformation than seedlings and PA1 cuttings. There was no effect of seedlot or physiological age on wood density, up to a physiological age of 5 years. However, acoustic velocity at breast height (as an indicator of stiffness) increased significantly and consistently with increasing physiological age.

Previous research has shown that cuttings with a physiological age of 1 to 3 years will perform as well as or better than seedlings on both farm and forestry sites, with an optimum physiological age of about 3 years, when there will be improved stem form without any early loss of growth rate. This trial on a fertile ex-farm site has confirmed these trends and also shown improvement in breast-height acoustic velocity of around 6.4% from PA3 cuttings and more than 11% from PA5 field cuttings, compared with seedlings.

Keywords: maturation; physiological age; cuttings; genetic improvement; growth; wood density; acoustic velocity; *Pinus radiata.*

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INTRODUCTION

Trials of cuttings of different physiological ages or maturation status from trees up to 7 years from seed were planted in the 1970s and 1980s in the North Island, New Zealand. The results demonstrated that there were some advantages and disadvantages associated with increasing physiological age (Menzies, Klomp & Holden 1991). While there was no consistent effect on height growth, cuttings from trees aged 4 years onwards had significantly slower initial diameter growth. However, cuttings from 3-year-old and older trees had less stem and leader malformation and a higher proportion of defect-free trees than seedlings of similar genetic quality. This led to a recommendation that physiological age should be kept to 3 years or less if diameter growth losses were to be avoided (Menzies, Klomp & Holden 1991). However, until 1984 the genetic quality of the planting stock in these trials was only up to GF14 (Vincent 1987). The introduction of control-pollinated seedlots in the 1980s allowed levels of genetic improvement above GF20, and it has been hypothesised that the advantages of improved form from increasing physiological age might disappear with higher levels of genetic improvement.

Conventional nursery stool-bed management in New Zealand nurseries involves hedging the stool-beds annually at a height of 10–30 cm, increasing that height each year for up to 4 years (Dibley & Faulds 1991; Faulds & Dibley 1989; Menzies *et al.* 1985). During this time, new improved seedlots usually become available, and so stool-beds are replaced on a rotational basis. If stool-beds are maintained at a low height, the physiological age of cutting material collected from them stabilises at an age of 2–3 years. If older cutting material is required, it has been collected from field plantations (Arnold & Gleed 1985; Menzies *et al.* 1985). However, field-collected cuttings are expensive, because of the distance from the nursery to the collection site, and the time taken to walk between trees for cutting collection. It would be an advantage if physiologically older cuttings could be produced from nursery stool-beds.

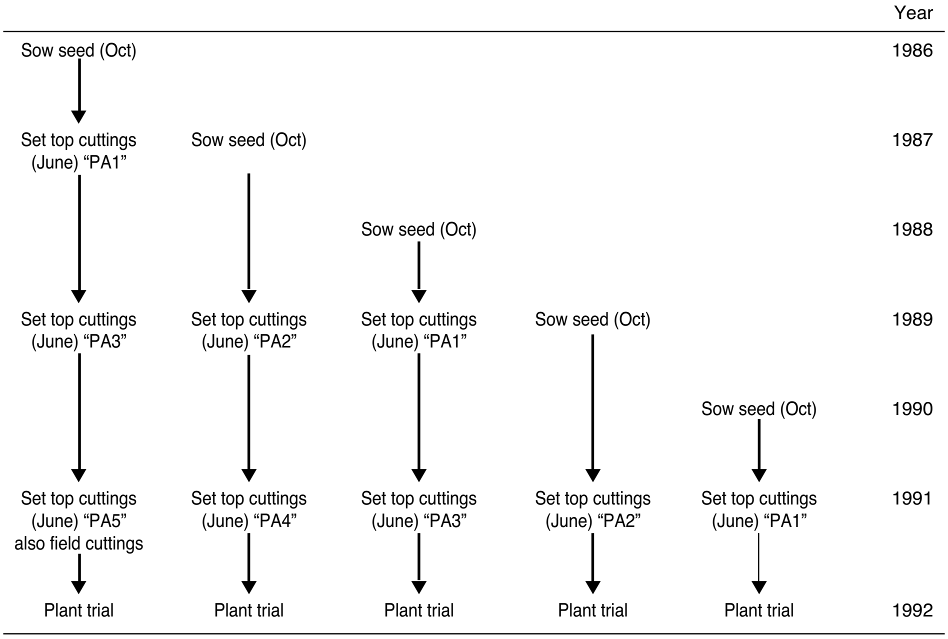
A trial was initiated in 1986 to evaluate nursery methods for producing aged cuttings from stool-beds, while using field-planted seedlings of the same genetic quality to produce field-aged cuttings as controls. Three seedlots of different genetic improvement levels ranging from GF3 to GF21 were used to study differences in growth rate, tree form, and wood properties between cuttings of different physiological ages up to 5 years and seedlings, and any interaction with levels of genetic improvement.

MATERIALS AND METHODS

Raising the Planting Stock

Three seedlots of different levels of genetic improvement were selected in 1986 to represent the range available at that time, from GF3 to GF21. These were bulk from Cpt 11 of Ngaumu Forest (Seedlot 3/3/84/020, GF3), open-pollinated bulk "268" seed from Kaingaroa seed orchard (Seedlot 2/6/86/027, GF16), and control-pollinated seed (from "268" and "850" parents) from Amberley Seed Orchard (Seedlot 6/3/86/054, GF21).

Two hundred seeds from each of these three seedlots were sown annually in three randomised replicates in the Forest Research Nursery, Rotorua, in 1986 through to 1991 (Fig. 1) to produce plants of different maturation status for a field trial to be planted in 1992.



* In 1991, seed was also sown in October to produce seedlings for the field trial.

FIG. 1–Methods of managing the nursery stool-beds to produce cutting material

The seedlings were allowed to grow without root disturbance. Seedling top cuttings (apical tip cuttings and cuttings without apical buds from just below the tops) were set in June as bare-root cuttings, 1 or 2 years after sowing, in three randomised replicates. This allowed the physiological age to build up for the PA5, PA4, and PA3 treatments by taking cuttings from previously set cuttings after a 2-year period. Cuttings taken from 2-year-old seedlings were PA2 and those from 1-year-old seedlings were PA1. At the time of cutting collection, the 1-year-old stool plants would have been approx. 0.75 m tall and the 2-year-old stool plants would have been approx. 1.5 m tall. In 1989, cuttings were set from the cuttings set in 1987. The combinations of sowing annually, setting cuttings after 1 or 2 years, and setting cuttings from cuttings gave a range of physiological ages, nominally from 1 to 5 years, for setting bare-root cuttings in three randomised replicates in the nursery in 1991.

In 1986, extra seed was sown in the nursery so that in 1987 seedlings of the three seedlots could be planted in replicated plots at two field sites in the Long Mile area at the Forest Research Institute (approx. lat. 38°155´S, long. 176°267´E, 300 m a.s.l.) and adjacent to the Kaingaroa Nursery (approx. lat. 38°403´S, 176°561´E, 520 m a.s.l.) to provide PA5 field cutting controls. One hundred and twenty seedlings from the three seedlots were planted in three replicates in 10-tree rows at each site at 4 × 3 m spacing. Cuttings were collected from all trees in these trials in 1991 to provide controls with a physiological age of 5 years. These cuttings were also set bare-root in the nursery, together with the nursery cuttings described above.

The 1991 sowing in the nursery provided seedling controls for the field trial.

1992 Field Trial

The main field trial was planted in Cpt 149 of Rotoehu Forest in the Bay of Plenty (approx. lat. 37°937´S, long. 176°619´E, 200 m a.s.l.). The site was a flat, highly fertile, ex-farm site. Prior to establishment, the site was short-grazed and planting spots were sprayed with a Paraquat/Simazine/Versatil herbicide mixture in June. Trees were hand-planted at the end of July 1992 and released using Eliminex in December 1992.

There were 24 treatments in the trial. For each of the three seedlots, there were the five nursery-cuttings treatments with physiological ages from 1 to 5 years, two PA5 field-cutting controls from the Long Mile and Kaingaroa Nursery sites, and a 1/0 seedling control (eight in all). The experimental design was a single-tree-plot design, with 40 replications, and one tree per treatment (seedlot/stock-type subclass) per replicate, randomly allocated within the replicates. Each replicate was five trees × five trees, planted at 5 × 5 m spacing, and with one seedling filler tree to make up the tree numbers to 25 per replicate.

Assessments

All tree heights were measured after planting (initial height), and in winter in Years 1 and 2. Tree survival was also assessed at these times. The trial was given a first-lift pruning at age 4 years from planting and, following this, tree survival was assessed and a sample of 10 replicates was given a post-prune assessment, including height and diameter at breast height (dbh). In 2003, at age 11 years, all trees were measured for dbh, and stem form was assessed for the butt and second logs (6-m lengths). In 2004, at age 12 years, all trees were assessed for basic wood density in rings 1–5 and 6–10 from the pith, using 5-mm pith-to-bark cores taken at breast height (Cown & McConchie 1982, 1983; Treloar & Lausberg 1997), and for acoustic velocity at breast height using an IML hammer (Anonymous 2001) to give a measure of wood stiffness. These assessments are summarised in Table 1.

TABLE 1–Summary of traits assessed in the field trial

Trait (code)	Units	Description	Assessment age (years)
Height (Ht)	metres	Measured using height pole	0, 1, 2, 4 *
Diameter (dbh)	millimetres	Measured at 1.4 m above ground level	4*, 11
Straightness (STR)	1 to 9 scale	1 = most crooked, 9 = very straight	11
Branch habit (BR)	1 to 9 scale	1 = fewest branch clusters, 9 = most clusters	11
Malformation (MAL)	1 to 9 scale	1 = multiple forking, 9 = no forks or ramicorns	11
Acceptability (AC)	0 or 1	0 = judged not to provide an acceptable crop tree (too small, crooked, or malformed), 1 = acceptable	11
Wood density	kg/m^3	Rings 1–5, Rings 6–10	12
Acoustic stiffness (IML Hammer)	metres/sec	*see* Anonymous (2001)	12

*Only 10 out of 40 replicates assessed

Data Analyses

SAS PROC GLM (SAS Institute Inc. 1989) was used to conduct analysis of variance (ANOVA) for each trait. The following model proved appropriate:

$$Phenotype = \mu + R + S + A + S \times A + error$$

where μ, R, S, A, and $S \times A$ represent the general mean, replicate, seedlot, stock type (physiological age category), and seedlot-by-physiological-age interaction effects respectively. All effects were considered as fixed except the residual error effect, which was treated as random. Treatment (seedlot and stock type) means were compared by Tukey's multiple comparison test. SAS® procedure PROC CORR (SAS Institute Inc. 1990) was used to calculate Pearson correlation coefficients at the individual-tree level between growth- and wood-quality traits. Analyses of covariance (ANCOVA) were carried out for acoustic stiffness (IML Hammer) to test for differences upon adjusting for dbh and wood density. Evidence for the effect of physiological age on IML could have been tested using a regression approach, but the stock types in this study do not quite fit a graded-series model.

RESULTS

Early Survival and Growth

Overall survival after 4 years averaged 95%; the only two treatments below 90% were GF21 seedlings and PA5 cuttings from Kaingaroa, both at 85%. Initial plant height averaged 0.29 m, and there was no significant difference ($p>0.05$) between the three seedlots (Table 2). There were some significant differences ($p<0.05$) between the different stock types, including a significant interaction between seedlot and stock type (Table 2), but there was no consistent pattern (Fig. 2). The overall tallest three stock types were consistently taller across the three seedlots than the overall three shortest stock types, although the order of the stock types changed. Height more than doubled each year for the first 2 years, with an average height of 0.79 m after 1 year and 2.09 m after 2 years. The GF21 stock types had the best height increment over the first 2 years, and the GF3 stock types the worst, so that after 2 years, the GF16 and GF21 seedlots were significantly taller than the GF3 seedlot. Seedlings and PA1 and PA2 cuttings had the best height increment over 2 years, and the three classes of PA5 cuttings had the worst, so that after 2 years the seedlings and PA1 cuttings were significantly taller than the PA5 cuttings. There were statistically significant interactions between seedlot and stock type for all the heights and increments. These interactions showed no clear pattern, but the overall pattern of main-effect differences described above was basically consistent (Table 3). As with initial height, the overall tallest three stock types were consistently taller across the three seedlots than the overall three shortest stock types for height after 1 and 2 years and for height increments for Years 0–1 and 0–2, although the order of the stock types changed.

By age 4 years, after low pruning, the average height was 6.3 m in the 10 replicates measured for height, and there were no significant differences between seedlots or stock types, although the interaction between them was significant ($p=0.05$) (Table 2). There was a significant difference in height between stock types for the GF21 plants, with the pattern being the same as for the overall mean heights at age 4 years.

Early diameter growth (dbh at age 4 years) followed the same pattern as height at age 2 years, with the GF21 seedlot having a significantly larger dbh than the GF3 seedlot, and

TABLE 2–Means and statistical comparisons for early height growth (m) from planting to 4 years of age for the three seedlots and eight stock types, planted in 1992

	Init. Ht	Ht Yr 1	Ht Yr 2	Incr. 0–1	Incr. 1–2	Incr. 0–2	Ht Yr 4
Seedlot							
GF21	0.29a†	0.80a	2.16a	0.51a	1.35a	1.86a	6.4a
GF16	0.29a	0.79ab	2.09a	0.49ab	1.31a	1.80 b	6.4a
GF3	0.29a	0.77 b	2.01 b	0.48 b	1.24 b	1.72 c	6.3a
P value	0.336	0.007	0.000	0.011	0.000	0.000	0.345
Stock type*							
S	0.27 b	0.86a	2.20a	0.59a	1.34a	1.93a	6.4a
N1	0.33a	0.87a	2.20a	0.54abc	1.33a	1.87ab	6.3a
N2	0.27 b	0.83ab	2.15ab	0.57ab	1.32ab	1.89ab	6.4a
N3	0.27 b	0.75 cd	2.06 bc	0.49 cd	1.30ab	1.79 bc	6.3a
N4	0.28 b	0.79 bc	2.08abc	0.51 bcd	1.29ab	1.80 bc	6.5a
N5	0.26 b	0.72 d	1.95 c	0.46 de	1.23 b	1.69 c	6.2a
K5	0.32a	0.74 cd	2.02 bc	0.42 ef	1.29ab	1.70 c	6.1a
LM5	0.34a	0.74 cd	2.03 bc	0.40 f	1.30ab	1.70 c	6.3a
Overall mean	0.29	0.79	2.09	0.49	1.30	1.79	6.3
P value	0.000	0.000	0.000	0.000	0.017	0.000	0.383
Interaction P value	0.042	0.000	0.001	0.000	0.018	0.003	0.019

* S=seedlings;
N1, N2, N3, N4, N5=nursery cuttings with a physiological age of 1, 2, 3, 4, 5 years;
K5=cuttings with a physiological age of 5 years from Kaingaroa Forest,
LM5=cuttings with a physiological age of 5 years from the Long Mile.

† Means for treatments within a given seedlot or stock type followed by the same alphabetical letter are not significantly different (Tukey's multiple comparison test, p=0.05).

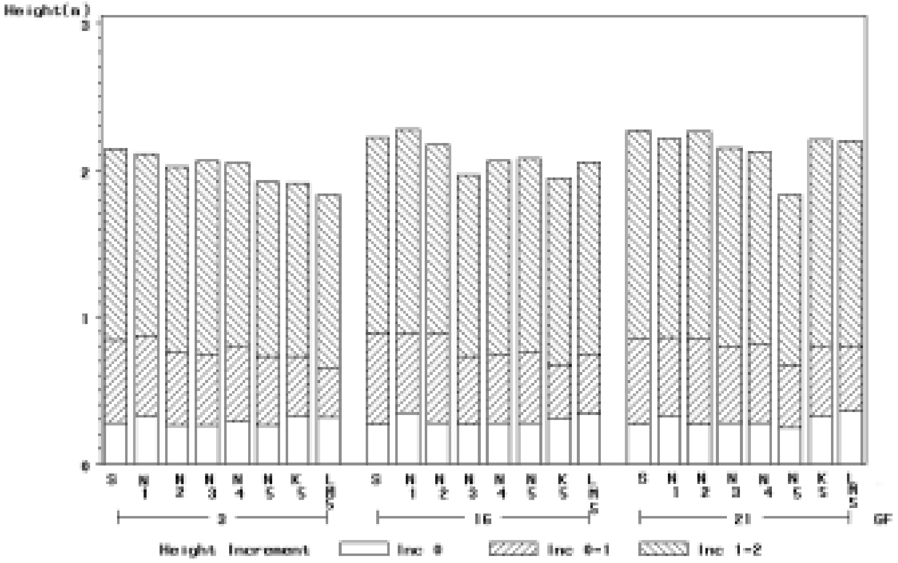


FIG. 2–Means for early height growth (cm) from planting (age 0) to age 2 for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992

TABLE 3–Means and statistical comparisons for early height growth (m) from planting to 4 years of age for the eight stock types for each of the three seedlots separately, planted in 1992

Stock type*	Init. Ht	Ht Yr 1	Ht Yr 2	Incr. 0–1	Incr. 1–2	Incr. 0–2	Ht Yr 4
GF3							
S	0.27 c†	0.84ab	2.14a	0.57a	1.30a	1.87a	6.7a
N1	0.32a	0.87a	2.11a	0.54a	1.25a	1.79ab	6.3a
N2	0.26 c	0.79ab	2.02ab	0.50ab	1.26a	1.76ab	6.3a
N3	0.26 c	0.74 bc	2.06ab	0.47ab	1.33a	1.80ab	6.2a
N4	0.28 bc	0.80ab	2.04ab	0.52a	1.24a	1.76ab	6.2a
N5	0.26 c	0.7b b	1.92ab	0.47ab	1.19a	1.66abc	6.2a
K5	0.32a	0.73 bc	1.91ab	0.40 bc	1.19a	1.59 bc	6.1a
LM5	0.31ab	0.65 c	1.83 b	0.34 c	1.18a	1.52 c	6.0a
Overall mean	0.29	0.76	2.01	0.48	1.24	1.72	6.3
P value	0.000	0.000	0.002	0.000	0.127	0.000	0.122
GF16							
S	0.27 d	0.89a	2.22a	0.62a	1.34a	1.95a	6.7a
N1	0.35a	0.89a	2.27a	0.54ab	1.38a	1.93ab	6.5a
N2	0.28 cd	0.89a	2.18ab	0.61a	1.29a	1.90ab	6.1a
N3	0.27 d	0.73 b	1.97 b	0.46 bc	1.24a	1.70 bc	6.5a
N4	0.27 cd	0.75 b	2.06ab	0.48 bc	1.31a	1.79abc	6.4a
N5	0.27 cd	0.77 b	2.08ab	0.49 bc	1.31a	1.80abc	6.4a
K5	0.31 bc	0.67 b	1.95 b	0.37 d	1.27a	1.64 c	6.1a
LM5	0.34ab	0.75 b	2.06ab	0.40 bcd	1.31a	1.72abc	6.3a
Overall mean	0.29	0.79	2.10	0.50	1.31	1.80	6.4
P value	0.000	0.000	0.000	0.000	0.269	0.000	0.610
GF21							
S	0.27 b	0.85a	2.27a	0.58a	1.41a	2.00a	6.4ab
N1	0.32a	0.86a	2.21a	0.53ab	1.36a	1.89a	6.3ab
N2	0.27 b	0.85a	2.26a	0.58a	1.41a	1.99a	6.8a
N3	0.27 b	0.80a	2.15a	0.52ab	1.35a	1.87a	6.2ab
N4	0.28 b	0.81a	2.12a	0.53ab	1.32ab	1.84a	6.3ab
N5	0.25 b	0.66 b	1.83 b	0.42 c	1.17 b	1.59 b	6.0 b
K5	0.32a	0.81a	2.21a	0.48abc	1.40a	1.88a	6.1ab
LM5	0.36a	0.80a	2.20a	0.45 bc	1.39a	1.84a	6.8a
Overall mean	0.29	0.81	2.16	0.51	1.35	1.86	6.4
P value	0.000	0.000	0.000	0.000	0.003	0.000	0.006

* For explanation of abbreviations, *see* Table 2.

† Means for treatments within a given seedlot or stock type followed by the same alphabetical letter are not significantly different (Tukey's multiple comparison test, p=0.05).

the seedlings and PA1 cuttings having a significantly larger dbh than the three PA5 cuttings stock types (Table 4). There was a statistically significant interaction (p=0.01) between seedlot and stock type, with the GF16 PA2 cuttings having a comparatively smaller dbh and the GF16 PA5 nursery cuttings having a comparatively larger dbh than the general trend, although these two stock types were not significantly different from each other. The pattern was similar at age 11, when the GF16 and GF21 seedlots had a significantly larger dbh than the GF3 seedlot, and the seedlings and PA1 cuttings had a significantly larger dbh than the Kaingaroa and Long Mile 5-year cuttings stock types (Table 4). There was a statistically significant interaction between seedlot and stock type (p=0.01), with the PA3 and PA5 nursery cuttings not consistent across seedlots (Fig. 3).

TABLE 4–Means and statistical comparisons for diameter (dbh) at 4 and 11 years of age from planting for the three seedlots and eight stock types, planted in 1992

	Dbh at age 4 (mm)				Dbh at age 11 (mm)			
	Overall	GF3	GF16	GF21	Overall	GF3	GF16	GF21
Stock type*								
S	145a†	138a	149a	149a	329a	313ab	332a	347a
N1	143ab	136a	145ab	147a	331a	327a	334a	331ab
N2	135abc	131a	131abc	144ab	325ab	317ab	327ab	332ab
N3	130cd	131a	129abc	131abc	318ab	308ab	310ab	335ab
N4	133bcd	129a	135abc	136abc	317ab	310ab	313ab	329ab
N5	127cde	121b	144ab	117c	324ab	321ab	339a	309b
K5	123de	121ab	122c	127bc	309bc	298bc	313ab	316ab
LM5	118e	103b	125bc	124c	294c	272c	298b	312b
Overall mean	132	126	135	134	318	308	321	326
P value	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.004
Seedlot								
GF21	135a				326a			
GF16	135a				320a			
GF3	126b				308b			
P value	0.000				0.000			
Interaction P value	0.007				0.009			

* For explanation of abbreviations, *see* Table 2.

† Means for treatments within a given seedlot or stock type followed by the same alphabetical letter are not significantly different (Tukey's multiple comparison test, p=0.05).

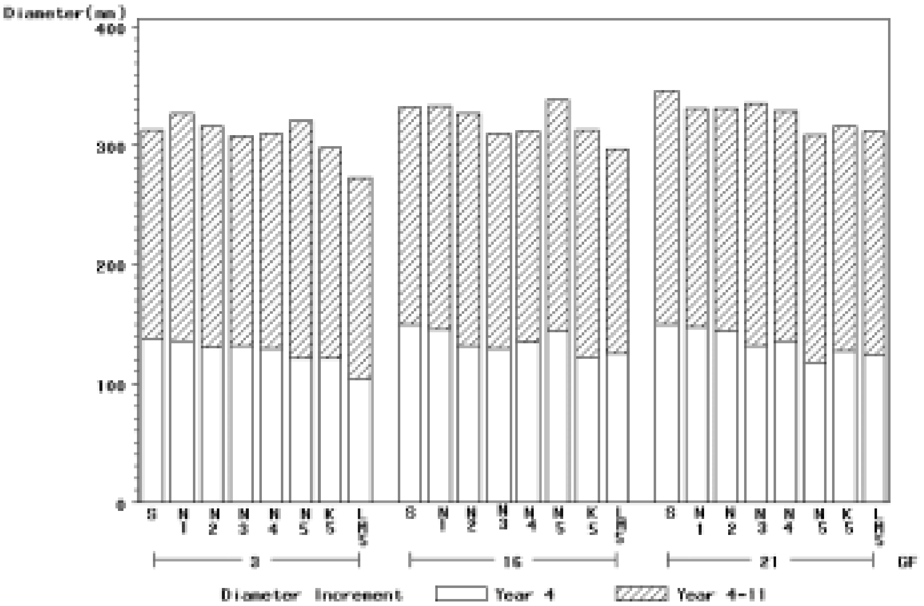


FIG. 3–Means for early diameter growth (mm) from planting (age 0) to age 11 for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992

Stem Form at Age 11 Years

Seedlings and PA1 cuttings had significantly worse butt-log malformation than the PA4 and PA5 cuttings (Table 5, Fig. 4). The seedlot effect was not significant. There were no significant differences with malformation in the second log, but the trends were similar. The interaction between seedlot and stock type was significant for the butt log. With seedlings and PA1 cuttings, the GF16 and GF21 seedlots had consistently less malformation than GF3 (Fig. 4). However, for PA3 and older cuttings, this genetic-improvement trend disappeared, and butt log malformation for all treatments was less than for the GF16 and GF21 seedlings and PA1 cuttings (Fig. 4). There was no significant effect of physiological age with GF21 stock types, and the PA2 cuttings were comparatively better than the other seedlots (Fig. 4).

TABLE 5–Means and statistical comparisons for stem-form variables at 11 years of age for the three seedlots and eight stock types, planted in 1992 (*see* Table 1 for description of scores)

	Malformation (1–9)		Straightness (1–9)		Acceptability (0,1)	Branching (1–9)
	Butt log	Second log	Butt log	Second log		
Seedlot						
GF21	6.1a†	6.2a	6.4a	6.6a	0.31a	6.5a
GF16	6.1a	6.3a	6.0 b	6.2 b	0.31a	6.5a
GF3	5.8a	5.8a	5.6 c	5.7 c	0.27a	6.0 b
P value	0.310	0.204	0.000	0.000	0.485	0.000
Stock type*						
S	4.9 c	5.9a	5.3 d	5.8 b	0.20 bc	6.0a
N1	5.0 c	5.7a	5.7 cd	5.8 b	0.18 c	6.4a
N2	5.3 bc	6.1a	5.9 bcd	6.1ab	0.26abc	6.5a
N3	6.1abc	5.8a	6.1abc	6.2ab	0.20 bc	6.4a
N4	6.8a	6.0a	6.7a	6.6a	0.37ab	6.3a
N5	6.5ab	6.5a	6.4ab	6.4ab	0.43a	6.3a
K5	6.9a	6.7a	6.3abc	6.4ab	0.43a	6.7a
LM5	6.4ab	6.2a	5.7 cd	6.0ab	0.30abc	6.1a
Overall mean	6.0	6.1	6.0	6.2	0.30	6.3
P value	0.000	0.158	0.000	0.005	0.000	0.137
Interaction P value	0.010	0.186	0.000	0.000	0.001	0.018

* For explanation of abbreviations, *see* Table 2.

† Means for treatments within a given seedlot or stock type followed by the same alphabetical letter are not significantly different (Tukey's multiple comparison test, p=0.05).

With both butt-log and second-log straightness, seedlings and 1-year-old cuttings were significantly worse than PA4 and PA5 nursery cuttings in the butt log and PA4 nursery cuttings in the second log (Table 5, Fig. 5). The other stock types did not show consistent trends for straightness with physiological age. However, for both butt-log and second-log straightness, the seedlot effect was significant, with the GF21 seedlot significantly better than the GF16 seedlot, which in turn was significantly better than the GF3 seedlot. The

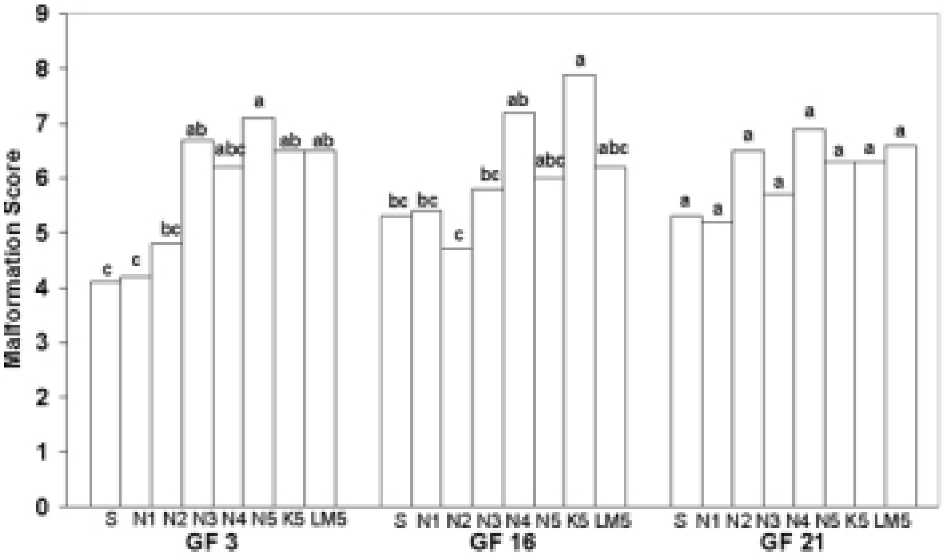


FIG. 4–Mean malformation scores for the butt log at age 11 years for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992 (histogram bars for treatments within a given seedlot with the same alphabetical letter above are not significantly different — Tukey's multiple comparison test, p=0.05).

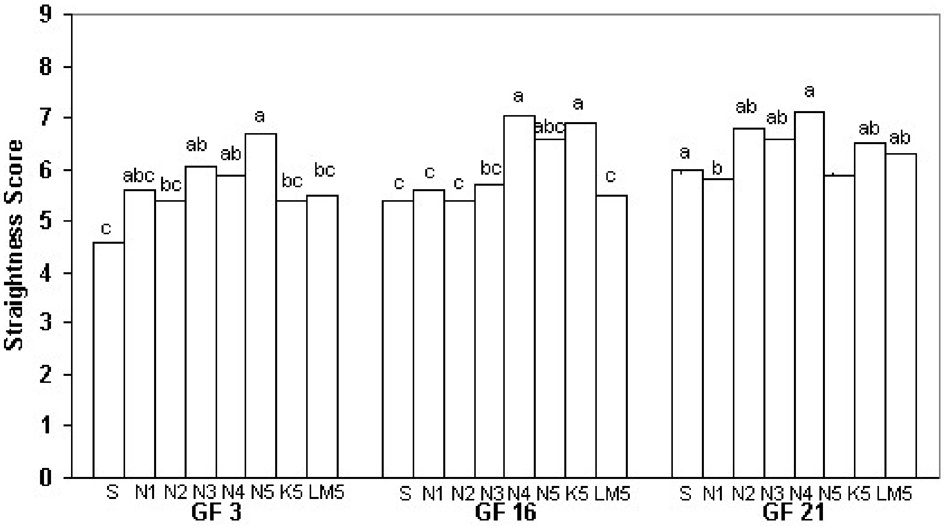


FIG. 5–Mean straightness scores for the butt log at age 11 years for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992 (histogram bars for treatments within a given seedlot with the same alphabetical letter above are not significantly different — Tukey's multiple comparison test, p=0.05).

interaction between seedlot and stock type was significant for both log types, but there was no consistent pattern (Fig. 5). For butt-log straightness, the PA5 Long Mile cuttings were poor for all seedlots, the PA5 Kaingaroa cuttings were poor for the GF3 seedlot, and the PA5 nursery cuttings were poor for the GF16 seedlot.

For overall stem acceptability, the seedlot effect was not significant, but for stock types the trend followed physiological aging, with the seedlings and PA1 cuttings significantly poorer than the PA5 nursery and Kaingaroa cuttings and the PA4 cuttings (Table 5, Fig. 6). Again, there was a statistically significant interaction between seedlot and stock type, but there was no consistent pattern (Fig. 6). There was no significant effect of physiological age for the GF21 seedlot, although the seedlings and PA2 cuttings were comparatively better than might have been expected from the overall means.

The GF16 and GF21 seedlots had significantly more multinodal branch habits than the GF3 seedlot, but the stock-type differences were not significant, although the interaction was (Table 5). There was no consistent pattern for the interaction effect.

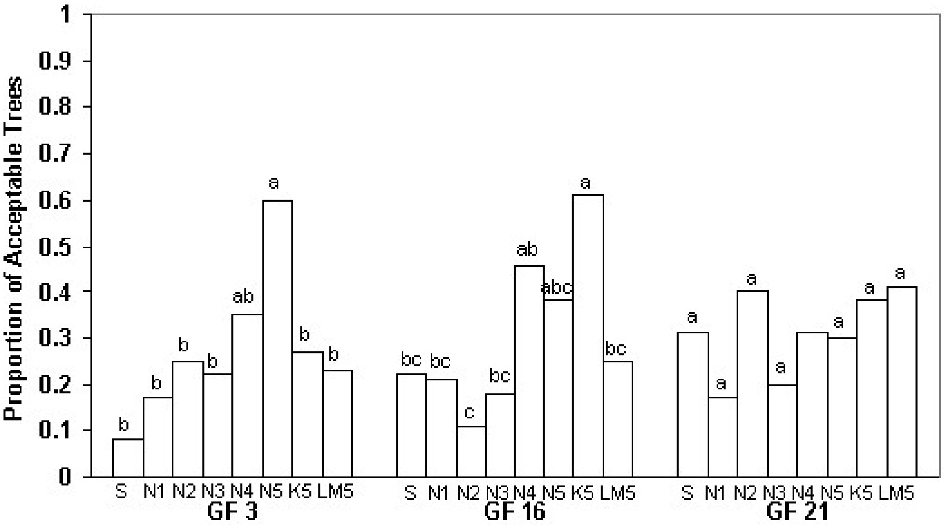


FIG. 6–Proportions of acceptable trees at age 11 years for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992 (histogram bars for treatments within a given seedlot with the same alphabetical letter above are not significantly different — Tukey's multiple comparison test, p=0.05).

Wood Properties

The overall average wood density in rings 1–5 was 320 kg/m^3. There was no significant difference in wood density in rings 1–5 between seedlots (Table 6). Seedlings had a significantly higher wood density (326 kg/m^3) than PA5 cuttings from Kaingaroa and PA3 nursery cuttings (316 kg/m^3), with the other stock types intermediate between these. There was no significant interaction between seedlot and stock type, although the range of densities among stock-type/seedlot subclass means was 20 kg/m^3. There were no significant physiological age effects for the GF3 and GF21 seedlots, but with the GF16 seedlot, seedlings had significantly higher basic wood density in rings 1–5 than the PA5 cuttings from Kaingaroa and Long Mile. The wood density in rings 6–10 was higher than that for

TABLE 6–Means and statistical comparisons for wood properties at 12 years of age for the three seedlots and eight stock types, planted in 1992

	Wood density (kg/m^3)		IML
	Rings 1–5	Rings 6–10	(m/s)
Seedlot			
GF21	321a†	356a	2047a
GF16	319a	360a	1994 b
GF3	321a	358a	1988 b
P value	0.450	0.265	0.003
Stock type*			
S	326a	361a	1887 e
N1	324ab	358a	1901 de
N2	322ab	358a	1981 cd
N3	316 b	356a	2007 c
N4	321ab	358a	2034 bc
N5	319ab	356a	2035abc
K5	316 b	356a	2096ab
LM5	319ab	360a	2119a
Overall mean	320	358	2010
P value	0.005	0.820	0.000
Interaction P value	0.471	0.463	0.113

* For explanation of abbreviations, *see* Table 2.

† Means for treatments within a given seedlot or stock type followed by the same alphabetical letter are not significantly different (Tukey's multiple comparison test, p=0.05).

rings 1–5, at an overall average of 358 kg/m^3, and there were no significant differences between seedlots, stock types, and the interaction between them (Table 6). The range of densities among stock-type/seedlot subclass means was 15 kg/m^3.

IML acoustic velocity values averaged 2009 m/s, with significant differences for both seedlot and stock type, but no significant interaction between them. The GF21 seedlot was significantly higher than the other two seedlots (Table 6). Overall, the IML values for the different stock types followed their physiological ages, with the three PA5 cutting types having significantly higher IML values than the seedlings and PA1 cuttings (Table 6). Similar trends were apparent for the individual seedlots, although for the GF16 seedlot the three PA5 cutting types only had significantly higher IML values than the seedlings (Fig. 7). The Pearson correlation coefficients between IML, wood density in rings 1–5 and 6–10, and dbh, all at 11–12 years of age, are given in Table 7. There were low correlations between IML values and the other variables. The correlations were statistically significant for density in rings 6–10 and for dbh, but the low values are of little practical importance. Similarly, using wood density for rings 1–5 and 6–10 or dbh as covariates in the ANCOVA for IML did not materially change the significance of the seedlot or stock-type effects.

DISCUSSION

The plants in all treatments more than doubled their height in each of the first 2 years, attaining heights of more than 6 m by 4 years of age, and this is typical of *P. radiata* on good sites (Menzies *et al.* 2001). In this trial, the PA5 cuttings had a poorer height increment in the first year after planting, and so seedlings and 1- and 2-year-old cuttings were taller than

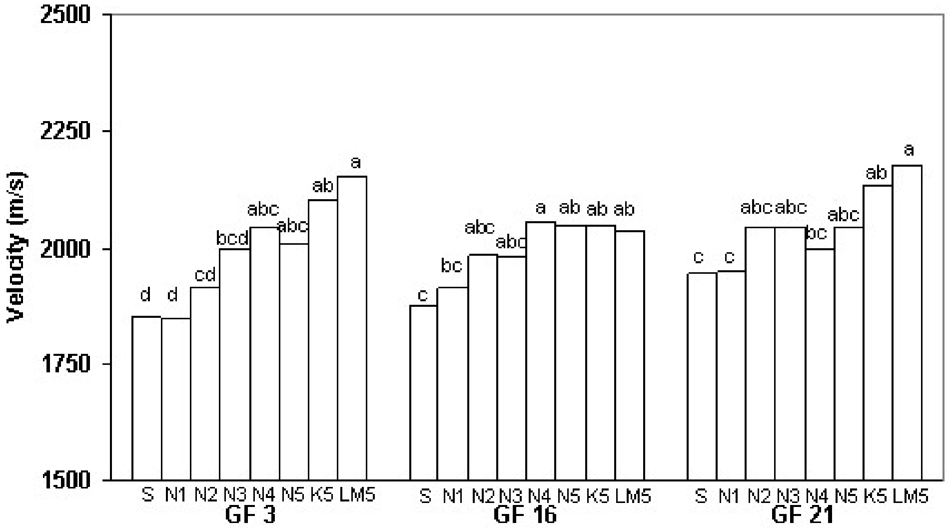


FIG. 7–Mean IML values (m/s) at 12 years of age for the three seedlots (GF3, GF16, GF21) and eight stock types (S, N1–N5, K5, LM5), planted in 1992 (histogram bars for treatments within a given seedlot with the same alphabetical letter above are not significantly different — Tukey's multiple comparison test, p=0.05).

TABLE 7–Pearson correlation coefficients for individual-tree wood properties and diameter at breast height at 11 years of age for the three seedlots and eight stock types, planted in 1992 (868–889 observations)

	Density rings 1–5	Density rings 6–10	Dbh
IML	0.04 ns†	0.33 ***	–0.15 ***
Density, rings 1–5		0.55 ***	–0.02 ns
Density, rings 6–10			–0.11***

† ns not significant at p=0.05
*** significant at p=0.001

the older cuttings at 2 years of age. However, by age 4 years the heights were no longer significantly different. In five other trials planted in 1983, cuttings up to a physiological age of 5 years were often taller than seedlings after 5 years (Menzies, Klomp & Holden 1991). The seedlings and PA1 cuttings had a significantly larger dbh in this trial after 4 years, compared to the PA5 cuttings, particularly from Kaingaroa and Long Mile. The same trend was there at age 11 years, and is the same as occurred in four of the 1983 trials where PA1 to PA3 cuttings had a larger dbh than PA5 cuttings (Menzies, Klomp & Holden 1991). On the fifth site of the 1983 trials, the PA5 cuttings had a smaller dbh than the more juvenile cuttings, but this was only significantly different from the PA1 cuttings.

The trend for butt log malformation and straightness to be significantly worse in seedlings and PA1 cuttings than in more mature PA3 to PA5 cuttings is consistent with earlier studies (Klomp & Menzies 1988; Menzies, Klomp & Holden 1991; Menzies, Klomp, Holden & Hong 1991), although the differences did vary across sites (Menzies, Klomp & Holden 1991; Menzies, Klomp, Holden & Hong 1991). Earlier studies showed that more mature cuttings generally had a higher proportion of trees suitable as crop trees (Menzies, Klomp & Holden 1991; Menzies, Klomp, Holden & Hong 1991), and the same trend was apparent in this trial. Planting stock GF16 and GF21 could be expected to show improved form and shorter internodes compared with GF3 planting stock (Vincent 1987), and this did occur with log straightness and branching habit. However, with more mature PA3 to PA5 cuttings, physiological age was more important than genetic improvement for reducing butt log malformation.

The overall average wood densities at breast height of 320 kg/m^3 for rings 1–5 and 358 kg/m^3 for rings 6–10 are typical for New Zealand *P. radiata* (Cown 1999; Kumar & Lee 2002). Although there were significant differences in wood density in rings 1–5 with stock types, there was no consistent pattern with physiological age, and the differences were not significant in rings 6–10. Earlier studies have found similar results, with little difference in wood characteristics, including wood density, provided the physiological age was less than 7 years (Nicholls *et al.* 1977; Cown 1988).

The GF21 seedlot had a significantly greater IML acoustic velocity value than the other two seedlots, but this was not related to a higher wood density (Tables 5 and 6). Within each seedlot, there was a general trend for increasing IML values with increasing physiological age, although with the GF16 seedlot the PA4 and PA5 IML values were very similar, rather than the PA5 values for K5 and LM5 treatments increasing as in the GF3 and GF21 seedlots (Fig. 7). However, overall there was a remarkably consistent increase in IML values with increasing physiological age from 1887 m/s for seedlings to 2119 m/s for PA5 cuttings from the Long Mile, again unrelated to wood density or dbh (Tables 5 and 6). Increasing physiological age is effectively shifting the vertical zonation of wood properties for a given ring number from the pith, down towards ground level (Burdon *et al.* 2004), so that the wood properties at breast height of a tree with an older physiological age should be similar to those higher up the bole of a tree from a younger physiological age, such as a seedling stock type. Decreasing spiral grain angles are very unlikely to be contributing to the increased stiffness at breast height in the physiologically older stock types, as spiral grain angles tend to increase further up the bole (Cown 1999). Microfibril angle, however, does tend to decrease further up the bole (Donaldson 1993; Megraw *et al.* 1997; Cown 1999), and so the increased stiffness from increased physiological age is likely to be caused by lower microfibril angles in material of greater physiological age. This will be evaluated in a further study on material from this trial.

Another objective of this field trial was to evaluate if physiologically aged cuttings could be produced from nursery stool beds. For all the traits assessed, except initial height, there was no significant difference between PA5 nursery and Kaingaroa cuttings, but for a few traits, such as dbh at age 11 years, there was a significant difference between PA5 nursery and Long Mile cuttings. The Long Mile cuttings were expected to be slightly more physiologically aged than the cuttings from Kaingaroa, because they were growing faster on a warmer site (Menzies & Klomp 1988). Therefore, the nursery aging in stool beds was effective. The trends with the dbh and IML results suggest that the PA5 nursery cuttings were not quite as aged as the PA5 field-collected cuttings from Kaingaroa, but they were close.

Previous research (Menzies, Klomp & Holden 1991) has indicated that the optimum physiological age is around 3 years of age, when there will be improved stem form without any early loss of growth rate. Although there is some loss of early diameter growth with cuttings up to 5 years old, there are indications that these cuttings have better form, with less malformation, especially on fertile farm sites. This trial indicated that there will also be an improvement in acoustic velocity of around 6.4% from PA3 cuttings and more than 11% from PA5 field cuttings.

CONCLUSIONS

Results from this field trial evaluating the effects of maturation status and level of genetic improvement showed that:

- There were no persistent height growth differences, as by age 4 years from planting any height differences were no longer significant. GF16 and GF21 plants had significantly larger diameters than GF3 plants at both 4 and 11 years of age. Seedlings and PA1 cuttings had significantly larger diameters than PA5 cuttings from Long Mile and Kaingaroa, with the other ages of cutting intermediate in diameter.
- Physiologically older cuttings had better butt log straightness and freedom from malformation than seedlings and PA1 cuttings. Physiological age was more important than genetic improvement for reducing butt log malformation with more mature PA3 to PA5 cuttings.
- There was no effect of seedlot or physiological age on wood density, up to a physiological age of 5 years.
- Acoustic velocity at breast height improved significantly and remarkably consistently with increased physiological age. Compared with seedlings, there was an improved acoustic velocity of around 6.4% from PA3 cuttings and more than 11% from PA5 field cuttings.
- These field-trial results support earlier research indicating that the optimum physiological age is around 3 years of age, when there will be improved stem form without any early loss of growth rate. Although there was some loss of early diameter growth with more mature cuttings up to PA5, there were indications that these cuttings had better form, with less malformation, on this fertile ex-farm site.

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REFERENCES

ANONYMOUS 2001: "Electronic Hammer: Instructions for Use and Guarantee Conditions". Instrumenta Mechanik Labor (IML) GmbH. Wiesloch, Germany.

ARNOLD, R.; GLEED, J.A. 1985: Raising and managing radiata pine cuttings for production forests. *Australian Forestry 78*: 199–206.

BURDON, R.D.; KIBBLEWHITE, R.P.; WALKER, J.C.F.; MEGRAW, R.A.; EVANS, R.; COWN, D.J. 2004: Juvenile versus mature wood: a new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *P. taeda. Forest Science 50(4)*: 399–415.

COWN, D.J. 1988: Vegetative reproduction and wood properties: implications for solid wood production. Pp. 70–78 *in* Menzies, M.I.; Aimers, J.P.; Whitehouse, L.J. (Ed.) "Workshop on Growing Radiata Pine from Cuttings", Rotorua, 5–7 May 1986. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 135.*

———1999: New Zealand pine and Douglas-fir: suitability for processing. *New Zealand Ministry of Forestry, Forest Research Bulletin No. 216.*

COWN, D.J.; McCONCHIE, D.L. 1982: Rotation age and silvicultural effects on wood properties of four stands of *Pinus radiata*. *New Zealand Journal of Forestry Science 12(1)*: 71–85.

———1983: Studies on the intrinsic properties of new-crop radiata pine. II: Wood characteristics of 10 trees from a 24-year-old stand grown in central North Island. *New Zealand Forest Service, Forest Research Institute, FRI Bulletin No. 37.*

DIBLEY, M.J.; FAULDS, T. 1991: Production and costs of juvenile radiata pine cuttings. Pp. 28–34 *in* Menzies, M.I.; Parrott, G.E.; Whitehouse, L.J. (Ed.) "Efficiency of Stand Establishment Operations", Proceedings of IUFRO Symposium, Forest Research Institute, September 1989. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 156.*

DONALDSON, L.A. 1993: Variation in microfibril angle among three genetic groups of *Pinus radiata* trees. *New Zealand Journal of Forestry Science 23(1)*: 90–100.

FAULDS, T.; DIBLEY, M.J. 1989: Growing radiata pine from cuttings. *New Zealand Forest Research Institute, What's New in Forest Research No. 176*. 4 p.

KLOMP, B.K.; MENZIES, M.I. 1988: The establishment phase of cuttings: Comparison with seedlings. Pp. 56–67 *in* Menzies, M.I.; Aimers, J.P.; Whitehouse, L.J. (Ed.) "Workshop on Growing Radiata Pine from Cuttings", Rotorua, 5–7 May 1986. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 135.*

KUMAR, S.; LEE, J. 2002: Age-age correlations and early selection for end-of-rotation wood density in radiata pine. *Forest Genetics 9*: 323–330.

MEGRAW, R.A.; LEAF, G.; BREMER, D. 1997: Longitudinal shrinkage and microfibril angle in loblolly pine. Pp. 27–61 *in* Butterfield, B.G. (Ed.) "Microfibril Angle in Wood", Proceedings of IAWA/IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality, Westport, New Zealand.

MENZIES, M.I.; KLOMP, B.K. 1988: Effects of parent age on growth and form of cuttings, and comparison with seedlings. Pp. 18–40 *in* Menzies, M.I.; Aimers, J.P.; Whitehouse, L.J. (Ed.) "Workshop on Growing Radiata Pine from Cuttings", Rotorua, 5–7 May 1986. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 135.*

MENZIES, M.I.; HOLDEN, D.G.; KLOMP, B.K. 2001: Recent trends in nursery practice in New Zealand. *New Forests 22*: 3–17.

MENZIES, M.I.; KLOMP, B.K.; HOLDEN, D.G. 1991: Optimal physiological age of propagules for use in clonal forestry. Pp. 142–145 *in* Miller, J.T. (Ed.) Proceedings FRI/NZFP Forests Ltd Clonal Forestry Workshop, May 1989, Rotorua, New Zealand. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 160.*

MENZIES, M.I.; FAULDS, T.; DIBLEY, M.J.; AITKEN-CHRISTIE, J. 1985: Vegetative propagation of radiata pine in New Zealand. Pp. 169–190 *in* South, D.B. (Ed.) Proceedings of the International Symposium on Nursery Management Practices for the Southern Pines, Montgomery, Alabama, USA, August.

MENZIES, M.I.; KLOMP, B.K.; HOLDEN, D.G.; HONG, S.O. 1991: The effect of initial spacing on growth and crop selection of radiata pine seedlings and cuttings. Pp. 152 –164 *in* Menzies, M.I.; Parrott, G.E.; Whitehouse, L.J. (Ed.) "Efficiency of Stand Establishment Operations", Proceedings of IUFRO Symposium, Forest Research Institute, Rotorua, September 1989. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 156.*

NICHOLLS, J.W.P.; PEDERICK, L.A.; BROWN, A.G. 1977: A summary of the ortet-ramet relationship in wood characteristics of *Pinus radiata. Appita 30(6)*: 496–502.

SAS INSTITUTE INC. 1989: "SAS/STAT® User's Guide", Version 6, Third Edition, Cary, North Carolina.

———1990: "SAS® Procedures Guide", Version 6, Fourth Edition, Cary, North Carolina.

TRELOAR, C.; LAUSBERG, M. 1997: Sampling and data handling techniques for wood quality analyses. Pp. 1–6 *in* Klitscher, K.; Cown, D.; Donaldson, L. (Ed.) "Wood Quality Workshop '95". *New Zealand Forest Research Institute, FRI Bulletin No. 201.*

VINCENT, T.G. 1987: Certification system for forest tree seed and planting stock. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 134.* 17 p.