ROOT SYSTEM VARIATION IN *PINUS RADIATA* CLONES: EXPERIMENTAL STUDY UNDER SEMI-DRY TEMPERATE SILVOPASTORAL ECOSYSTEM IN NEW ZEALAND

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Report No. 73   August 2000

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EXECUTIVE SUMMARY

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Fine root length density and coarse root biomass and architecture of geno type (clone 3, clone 4 and seedlings) of *Pinus radiata* D. Don were estimated in an agroforestry system with understorey treatments, ie. no-pasture, lucerne (*Medicago sativa*), and ryegrass (*Lolium perenne*) with white clover at the Lincoln University Agroforestry experiment site, New Zealand. Furthermore, seasonal growth of cross-sectional area of coarse roots and seasonal and spatial patterns of white root initiation and fine root elongation were studied. The Gompertz model was fitted to seasonal growth data to derive temporal patterns of root elongation.

The climate was summer-dry temperate with 660mm annual rainfall evenly distributed throughout the year. At age 3, clone 3 was taller than clone 4 and the seedlings although the basal area was very similar between these plant types. The fine root length density and biomass in coarse root components, and root:shoot ratio of clone 3 and clone 4 were higher than seedlings. The fine root length density was higher in the tree-row compared to the north and south sides, and was higher on the south side compared to the north side. The lucerne provided greater competition to the tree root systems than the ryegrass/clover.

Topsoil moisture content, rather than temperature, appeared to be the major factor in the control of root growth and development. Higher soil moisture content at the 10 to 30 cm depth was associated with earlier and higher maximum rates of tip initiation, and this resulted in a higher maximum rate of total fine root elongation. Similarly, a higher soil moisture content in the no-pasture treatment, compared to the lucerne, was associated with a higher maximum rate of growth, particularly with clone 3. The maximum rate of total fine root elongation for clone 3 was 35% higher in the no-pasture compared to lucerne; seedlings did not differ with understorey treatments. This illustrated the vigorous root regeneration character of clone 3 compared to seedlings. Also, the maximum rate of fine root elongation occurred earlier in the no-pasture than the lucerne treatments. The effect of lower soil moisture content on the north as opposed to the south side of lucerne and both north and south sides in the case of the no-pasture treatments further resulted in a lower maximum rate of total fine root elongation. This indicated that lucerne was very competitive for soil moisture particularly to the north side of the tree-row.

1.0 BACKGROUND TO THE STUDY

Radiata pine (*Pinus radiata* D. Don) is the most commonly used tree species in agroforestry systems within New Zealand. To accommodate grazing it is sometimes grown at a wide spacing with ryegrass/clover, or with other pasture species as an understorey crop. The tree management is usually aimed at sawlog production using genetically improved plant types (Knowles, 1991), while sheep or cattle are grazed under the trees. Evaluation of the performance of different plant types is therefore important, especially with different understorey pastures. Above ground tree growth and its stability against toppling is directly related to root growth, and tree root growth could be influenced by soil nutrients and water availability being altered by understorey pasture competition. This report aims to study how pasture competition influences root development and growth of radiata pine clonal and seedling trees.

This study was carried out in the agroforestry trial, Lincoln University, at the Canterbury Plains. The soil at this level site was a Templeton silt loam, with 320mm water holding capacity in the top metre of soil. The soil profile varied from 0.9 to 1.6 m of fine alluvial sediments over water deposited gravel. The nutrient levels were high and the soil was considered vary productive (Yunusa *et al.,* 1995). The mean annual rainfall of 645 mm was relatively evenly distributed throughout the year. However the summer was drier as mean monthly evapotranspiration was double that of the mean monthly rainfall. Plants were therefore usually stressed for moisture in the summer. The prevailing wind direction was north-easterly followed by south westerly. Out of the total annual rainfall, 80% of rain bearing wind came from the south or south west quarter (Figure 1). Winds from the NW tend to be hot and dry and, as a result, the north side of the tree-row, at least for a meter, was a rain shadow area where the soil was drier and warmer compared to the soil on the relatively cooler and moister south side of the tree-row.

The trial was planted in 1990 and was a split-plot randomised block design with three replications. There were 6 main- plot understorey treatments (ryegrass, ryegrass/clover, phalaris, cocksfoot/clover, lucerne, and no-pasture) of which three were used for this study: (i)Yatsun perennial ryegrass (*Lolium perenne*) + clover (i.e., ryegrass/clover), (ii) Lucerne (*Medicago sativa*), and (iii) no-pasture. Sub-plot treatments comprised four tissue culture clones (GF 15 to 17) and a line GF 14 one year old seed grown seedlings. Three contrasting tree types were selected for this study; clone 3 (full-sib, set 11/8), clone 4 (half-sib, set 38/9), and seedlings ("850"), when planted clones 3 and 4 were 6 and 4 years from seed, respectively. The open pollinated seedlings were one year from germination when planted (Mead *et al.*, 1993). To establish the experiment the land was ploughed and the tree lines ripped to 60cm depth at 7m intervals in an east-west direction. The trees were planted at 1.4 m apart in the winter of 1990 to give initial stocking of 1000 stems / ha. The pasture was sown between the tree-rows 50 cm away from the tree-row.

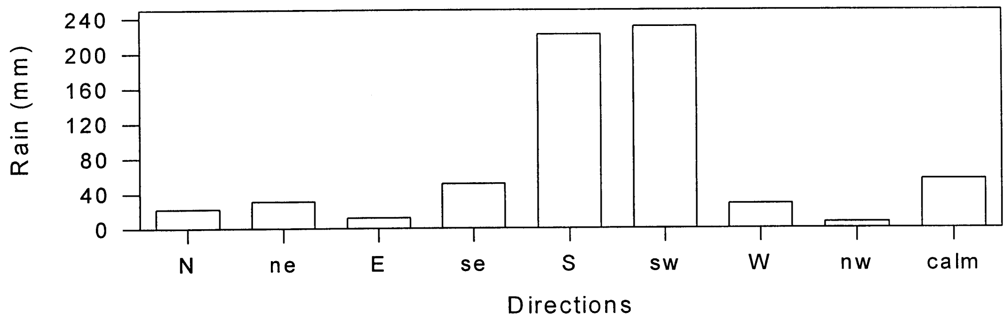

Figure 1: Rainfall by direction. The raw data was collected by Lincoln Meteorological Station, Lincoln University, from October 1992 to October 1994.

Hexazinone herbicide was applied at 2.5kg ai/ha in a one-metre wide strip over the trees in the spring of the first and second growing seasons. The stand was thinned to 800 stems/ha in 1992, 600 stems/ha in 1993 and to 400 stems/ha in 1994. First pruning was carried out in 1994 at the height of a mean diameter 11 cm ± 1 over bark. Until the winter of 1993 pasture was cut for silage following this was grazed.

At the beginning of this study in November 1993, tree height of the sampled trees was higher in the no-pasture compared to the ryegrass/clover and lucerne treatments, and was also greater in clone 3 than in clone 4 and seedlings (Figure 2). The basal diameter was larger in the no-pasture than in the other understorey types. However differences between plant types within an understorey were minimal.

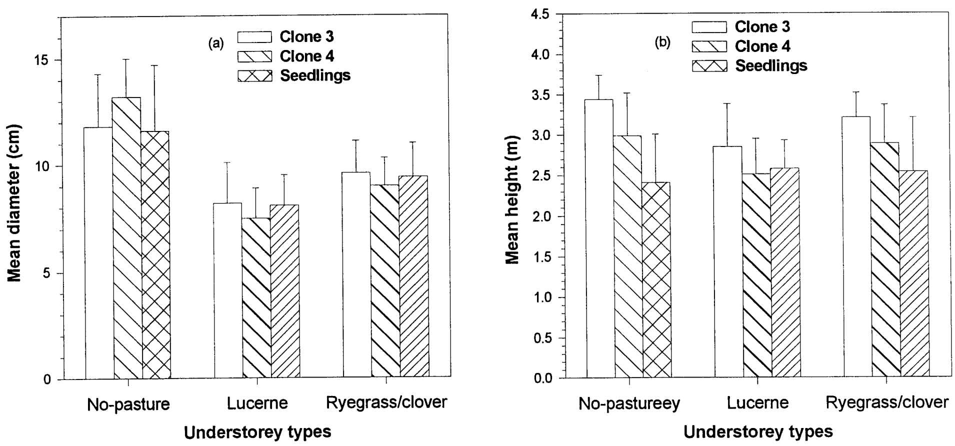

Figure 2: Mean basal diameter (a), and height (b) of the sampled trees at the time of this fine root study (November 1993). The vertical bars are standard deviations.

2.0 EXPERIMENTS

Five field experiments were conducted at the agroforestry site to understand the effect pasture competition on fine and coarse root growth of clonal and seedling tree of radiata pine. A split-plot analysis of variance was performed on all experimental variables, and only significant results ($p \leq 0.050$) are presented in this report.

2.1 Effect of pasture competition on spatial variation of fine roots

Fine root (≤ 2.0 mm diameter) length density (RLD) of clone 3, clone 4 and seedlings of radiata pine were estimated in the late spring (October-November) of 1993 in ryegrass/clover, lucerne and no-pasture plots at three depths (0-10 cm, 10-20 cm and 20-30 cm) of each three positions to tree-row, i.e. in the tree-rows and at 90 cm north and south of the tree-rows. A 4.5cm internal diameter steel core sampler was driven into the ground and soil was extracted and gently hand washed through sieves. Tree roots were separated from the pasture roots using characteristics such as root texture, colour, structure (waviness and branchiness), thickness and density (suspension). In general pasture roots were smaller in diameter than pine roots and were of a lighter colour. Root length was measured using a 'Comair' root length scanner (Commonwealth Aircraft Corporation Ltd, Melbourne, Victoria; Richards *et al.* (1979)).

2.1.1 Results

(i) The significant plant type x understorey interaction showed that RLD for clone 3, clone 4 and seedlings were similar in the ryegrass/clover and lucerne plots, whereas in the no-pasture plots the pine RLD of the clonal trees was twice that of the seedlings (Figure 3).

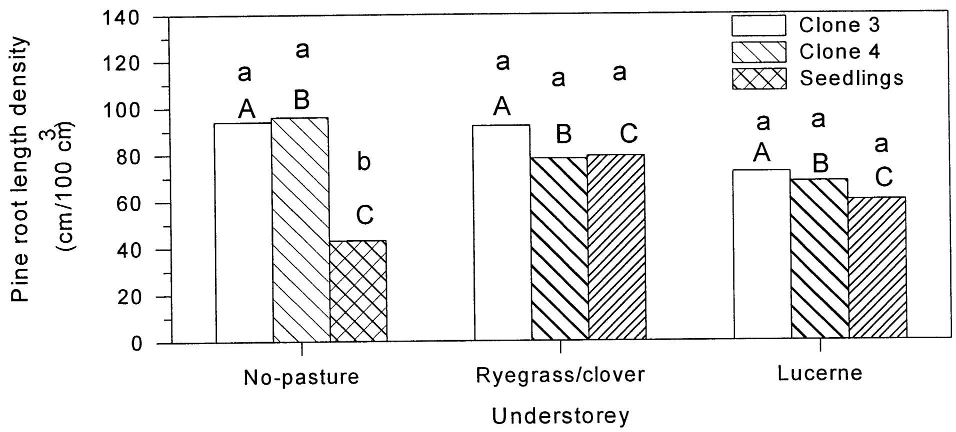

Figure 3: Effect of plant type x understorey interaction on pine root length density (cm per 100 cm^3). LSD denoted by the same lower case was not significantly difference between the plant types within an understorey treatment, and the same upper case for a plant type between understorey treatments.

(ii) There was also plant type x depth interaction, and the interaction resulted in a significantly higher RLD for clone 3 and clone 4 than the seedlings in the top 10 cm depth, whereas in the below depths pine RLD of the plant types was similar (Figure 4).

(iii) There was understorey x position interaction, and this was due to a much lower pine RLD on the tree-row in the no-pasture plots than in the ryegrass/clover or lucerne plots, whereas it was vice versa on the north side. The pine RLD on the south side was similar for all understorey types (Figure 5).

(iv) Lucerne RLD was significantly higher than the ryegrass/clover (Table 1). Both pastures had a higher RLD on the south side than on the north side of the trees; they were very low in the sprayed tree-row position. Although not significant the fine root length density of pasture tended to decrease with depth. There were no significant interactions.

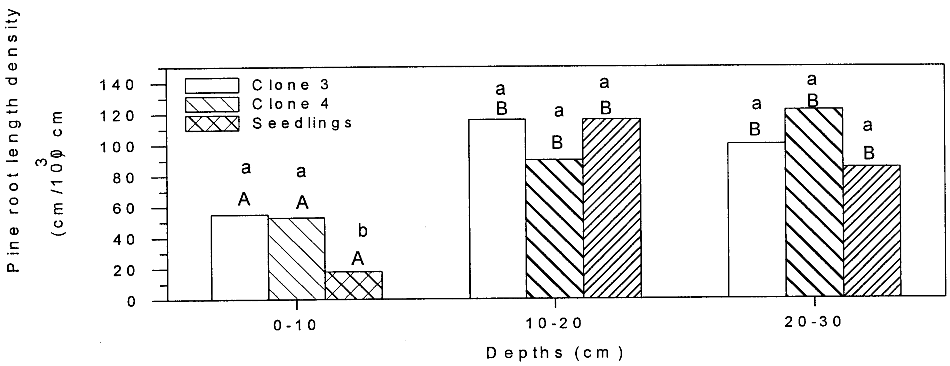

Figure 4: Plant type x depth interaction on pine root length density (cm per 100 cm^3). LSD denoted by the same lower case was not significantly difference between the plant types within a depth, and the same upper case for a plant type between the depths.

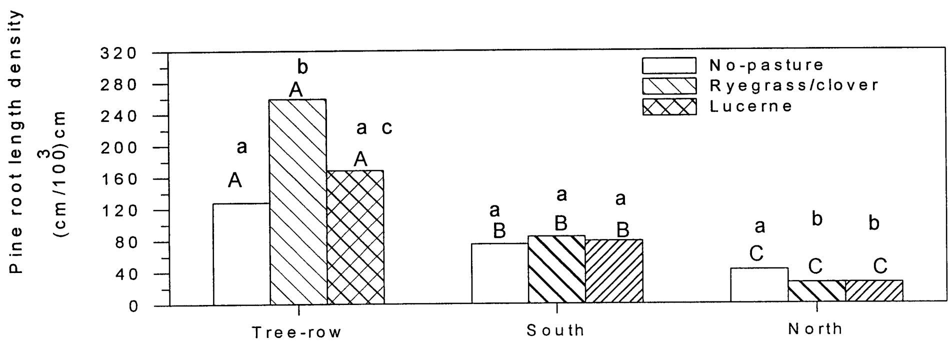

Figure 5: Understorey x side interaction on pine root length density (cm per 100 cm^3). LSD denoted by the same lower case was not significantly difference between the understorey treatments at a side, and the same upper case for an understorey treatment between the sides.

2.2. Effect of pasture competition on biomass and morphology of coarse root components

Effect of three understorey types (as in Experiment I) on biomass of coarse root components, i.e. lateral roots (spreading laterally at ≤ 45^0 to the horizontal), vertical roots (spreading more than ≤ 45^0 from the horizontal), and root core (below ground part of stump that is the junction of 1^0 roots) of three plant types studied with destructive sampling in winter 1993. To established a linear regression between dia_{10} (diameter of first order coarse root at 10 cm from its point of origin) and root biomass, four to six complete sample lateral roots per tree were excavated prior to pulling a root system up from saturated soil with the hydraulics of a tractor. The sample roots were over the range of dia_{10} and removed from the stump to the point along their length where they were 2 mm in diameter. A nail was driven into the stump on its north side and with a permanent maker, a line was drawn along the direction of the east-west tree-row on the top of the stump.

Table 1: Main treatment effect on pasture root length density (cm per 100 cm^3).

Treatments	Pasture root length density
Plant types	
Clone 3	40 a
Clone 4	41 a
Seedlings	34 a
Understorey pasture	
Ryegrass/clover	26a
Lucerne	94b
Position	
Tree-row	9 a
North	65b
South	110c
Depth	
0-10 cm	58 a
10-20 cm	40 a
20-30 cm	31 a

LSD denoted by the same lower case was not significantly difference within a treatment.

The root system of a tree was placed upside down with the stump being put in a hole made in the centre of a 1x1x1m box. The upper surface of the box was marked so that, by using the east-west line on the stump, it was possible to accurately locate the North, South, East and West quadrants. The east and west quadrants were combined and hereafter are called the tree-row. The dia_{10} of all first order lateral and vertical roots were measured to the nearest millimetre. Three to four unbroken vertical roots were sampled from each root system. The biomass vertical roots and lateral roots for each of the three directions (north, south, and tree-row) were calculated using the relationships between dia_{10} and oven dry root weight.

Root:shoot ratios were calculated using the above ground biomass measurements made on the same trees (Bandara 1997).

2.2.1 Results

There were no significant interactions so only imports main effects are discussed below.

(i) The root:shoot ratio and total below ground biomass, lateral and vertical root biomass were twice or more than twice as high in clone 3 compared to the clone 4 and the seedlings (Table 2).

(ii) The total, root core, vertical and lateral root biomass were twice or more than twice as high in the no-pasture than in the ryegrass/clover and lucerne treatments, respectively (Table 2).

Table 2: Effect of treatments on root:shoot ratio and biomass (g/tree) in coarse root components

Treatments	Ratio	Core	Lateral	Vertical	Total
Plant types					
Clone 3	0.203^{a}	614^{a}	877^{a}	381^{a}	1873^{a}
Clone 4	0.122^{b}	500^{a}	587^{ab}	105^{b}	1192^{ab}
Seedlings	0.095^{b}	337^{a}	394^{b}	62^{b}	793^{b}
standard error of mean	0.0149	76.9	141.3	29.1	232.4
Understorey types:					
No understorey	0.133^{a}	713^{a}	1118^{a}	242^{a}	2074^{a}
Ryegrass/clover	0.159^{a}	421^{ab}	462^{b}	201^{a}	1085^{b}
Lucerne	0.129^{a}	316^{b}	278^{b}	105^{b}	699^{b}
standard error of mean	0.0258	89.7	106.2	32.3	191.2

LSD denoted by the same lower case was not significantly different within a treatment.

(iii) The biomass of lateral roots for clone 3 was more twice that of clone 4 and the seedlings on the north side of the tree-row. Similarly, the lateral root biomass on the north side was more than twice that in the no-pasture than that of the ryegrass/clover and lucerne treatments (Table 2).

(iv) The lateral root biomass on the tree-row and on the north of tree-row was twice or more in clone 3 than in seedlings - but it was not different between clones 3 and 4, nor between clone 4 and the seedlings. Similarly, it was twice higher in the no-pasture compared to the ryegrass/clover and lucerne treatments, respectively. The biomass in the ryegrass/clover was intermediate (Table 3).

(v) The number of small (<10 mm at dia_{10}) lateral roots in the seedlings was three times higher than that in the clonal trees, but was not different between the clones. In contrast, the number of large ($\geq$ 10 mm at dia_{10}) roots was three times higher in clone 3 than in seedlings; clone 4 was intermediate

Table 3: Effect of treatments on lateral root biomass (g/tree) in three positions

Treatments	North	Tree-row	South
Plant types			
Clone 3	242a	407a	228 a
Clone 4	97b	257 ab	235 a
Seedlings	102b	143b	147 a
standard error of mean	44.0	69.1	78.3
Understorey types:			
No understorey	242 a	468 a	407 a
Ryegrass/clover	113 b	238 b	111 a
Lucerne	84 b	103c	92 a
standard error of mean	37.4	9.1	125.4

LSD denoted by the same lower case was not significantly different within a treatment.

Table 4: Effect of treatments on number of first order lateral and vertical roots by small (< 10 mm at d_{10}) and large diameter class (≥10 mm at d_{10}) lateral root.

Treatments	Lateral roots		Vertical roots	
Plant types	Small	Large	Small	Large
Clone 3	10.6a	10.5a	3.7 a	5.2a
Clone 4	9.3a	7.6ab	3.7 a	3.7 a
Seedlings	16.8b	6.3 b	3.7 a	1.4b
Understorey types:				
No understorey	10.2 a	11.0a	3.8 a	3.8 a
Ryegrass/clover	13.5 a	7.6ab	3.1 a	3.9 a
Lucerne	12.5 a	5.8b	4.3 a	2.1 a

LSD denoted by the same lower case was not significantly different within a treatment.

Table 5: The modified Menzies' tap root scoring system.

Case	Score	Description
1	0	Strong, dominant, single leading vertical root which originates from the root core of the coarse root system, and is very similar looking to a tap root.
2	2	As the above case (1), but where there are 2 or 3 leading vertical roots but not forked or hooked
3	4	As the above case (1 or 2) but the leading vertical roots are distinctly forked
4	6	As the above case (1 or 2) but the leading vertical roots are hooked
5	8	As the above case (1 or 2) but the leading vertical roots are forked and hooked
6	10	Vertical roots which do not originate from the root core and are weak, not well developed, may be many in numbers, generally more than 2, or where there are no vertical roots originating from the root core.

This scoring system can be used to score seedlings, cuttings or clonal trees, and is consistent with the Menzies' tap root scoring system between these two. However, the number of large vertical roots was higher in clones than in seedlings. On average the seedlings had a single large vertical root compared to four to five in the tissue-cultured clones but the number of small vertical roots was similar between the plant types (Table 4).

2.3. Effect of pasture competition on coarse root quality of radiata pine.

The methods of root excavation of three plant types from three understorey plots has already been mentioned in Experiment II. Some of these trees had been toppled in storms at age three. The qualitative characters of coarse root components (lateral root spiralling around core or core distortion, its distribution in four quartiles, and straightness, forking and dominance of vertical roots) were studied based on Mason's root core scoring, Menzies' lateral root scoring, and modified Menzies' vertical root scoring system (Table 5). The scoring value of the coarse root quality was analysed using the non-parametric Kruskal-Wallis one-way analysis of variance. If the Kruskal-Wallis test showed a significant overall treatment effect, then the difference between pairs of treatments was further analysed using Mann-Whitney U test. A logit model was used to determine which characteristics were related to toppling.

2.3.1. Results

(i) The results of the overall treatment effect showed that the median score of the modified Menzies' vertical root score was different between the plant type (Table 6). Pair-wise tests suggest this is largely due to differences between clone 3 and seedlings. However, the modified Menzies' vertical root score was not different between the understorey treatments.

Table 6: The effect of plant type on coarse root components

Scoring type	Median score of plant types		
	clone 3	clone 4	seedlings
Menzies' lateral root score	2.0 (0, 4)	4.0 (2, 6)	2.0 (1, 4)
Modified Menzies' vertical root score	2.0 (2, 4)	4.5 (2, 10)	10.0 (4, 10)
Mason's root core distortion	0.0 (0, 0)	1.0 (1, 1)	2.0 (1, 2)

The deviation of data has been presented with the first and third quartile values from left to right in bracket of respective median. Menzies' lateral root range from 0 to 10 for a good to poor root system; and so too for Mason root core score ranges from 0 to 4.

(ii) The median scoring of Mason's root core distortion was different between the plant type. Pair-wise tests indicate that the seedlings were more distorted than clone 3; clone 4 was poorer than clone 3, and clone 3 root core showed no distortion. The median score of Mason's root core distortion was different between understorey treatments.

(iii) Examination of the trees' the root system revealed that the toppled trees had a higher median score on the Mason's root core distortion and modified Menzies' vertical root compared to not toppled trees. However, the median score on Menzies' lateral root score was not between the toppled and not toppled trees.

(iv) The logit modelling used to investigate the characteristics associated with toppling found that toppling was related to plant type (clonal vs seedlings tree) rather than root core or vertical root score was critical.

2.4 Seasonal topsoil moisture and temperature dynamics as influenced by radiata pine plant type and understorey type

Topsoil moisture content and temperature regimes were recorded from November 1994 to December 1995 at two positions, 90 cm north and south of the tree base of two plant type (clone 3 and seedlings) in two understorey treatments (lucerne and no-pasture). Volumetric soil moisture content and soil temperature was measured at two depths (0-10 and 10-30 cm) with Time Domain Reflectory (TDR) and data logger, respectively. The results of mean soil moisture content (% by vol) was expressed over the two weeks measurement period, and soil temperature was expressed as day-degrees.

2.4.1 Results

(i) In general, the north side was drier than to the south side (Figure 6), and this was as the north side was both exposed to the sun and in the rain shadow area. The evapotranspiration was higher in the lucerne than the no-pasture treatment. Thus the soil moisture content for both sides was lower in the lucerne compared to the no-pasture treatment from mid spring (early November) to early winter (early July). As tree canopy growth was much higher in the no-pasture than the lucerne treatments, these larger canopies intercepted more rain than the crown in the no-pasture treatment. This resulted in a lower soil moisture content for both sides in the no-pasture treatment after early winter (early July).

(ii) Similarly, soil moisture in the 0-10 cm depth was significantly lower from late spring (early December) to mid-autumn (mid April) in the lucerne treatment compared to the no-pasture treatment, but thereafter the trend was again reversed (Figure 7). In contrast, moisture content was higher in the 10-30 cm depth from early spring to mid autumn in the no-pasture treatment compared to the lucerne treatment, later in the season the trend was reversed.

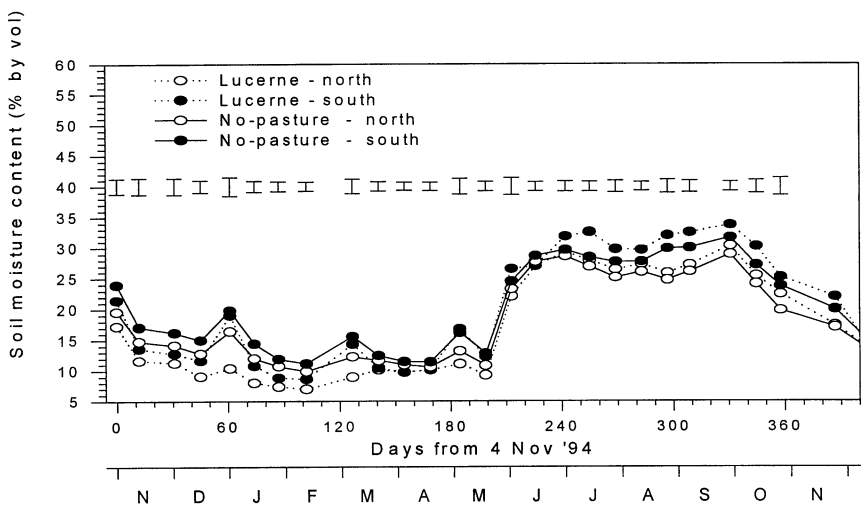

Figure 6: The time x understorey x side interaction on mean soil moisture content. The vertical bars are the LSD at p= 0.05 level

(iii) Tree crowns were narrower and had less dense foliage mass in the lucerne compared to the no-pasture plot. This might have resulted in higher solar radiation transmission in the lucerne plot. As a consequence the soil was warmer in the lucerne treatment compared to the no-pasture treatments, and was warmer to the north compared to the south sides (Figure 8). The interaction with time shows that the north side of the lucerne treatment was warmer than the other situations all year round. On the south side, soil under lucerne was warmer than the no-pasture treatment from mid spring (early November, day 12) to late autumn (early June, day 213), but the temperature did not differ significantly thereafter. The foliage density was lower in clonal trees than in the seedlings and also clonal trees had longer internodes compared to seedlings in the no-pasture treatment which allowed more solar radiation penetration to the soil. This resulted in the soil around the clonal trees being warmer than the seedlings in the no-pasture treatment (Figure 9). However, the plant types had no effect in the lucerne treatment on soil temperature where crowns of the plant type were smaller and there was ground vegetation.

2.5 Seasonal and spatial patterns of fine root growth of radiata pine as influenced by understorey type.

The seasonal and spatial pattern of white root tips and total fine root growth of two plant types (clone 3 and seedlings) were studied in rhizotron boxes (Appendix 1) those were placed 90 cm to the north and south of the tree base, from January 1994 to November 1995 in lucerne and no-pasture plots. The maximum growth rate and time to maximum growth rate of white root tips and fine root elongation were estimated by fitting the Gompertz equation for two depths (0-10 cm, and 10-30 cm), and expressed in number/dm^2 or cm/dm^2, respectively, over time.

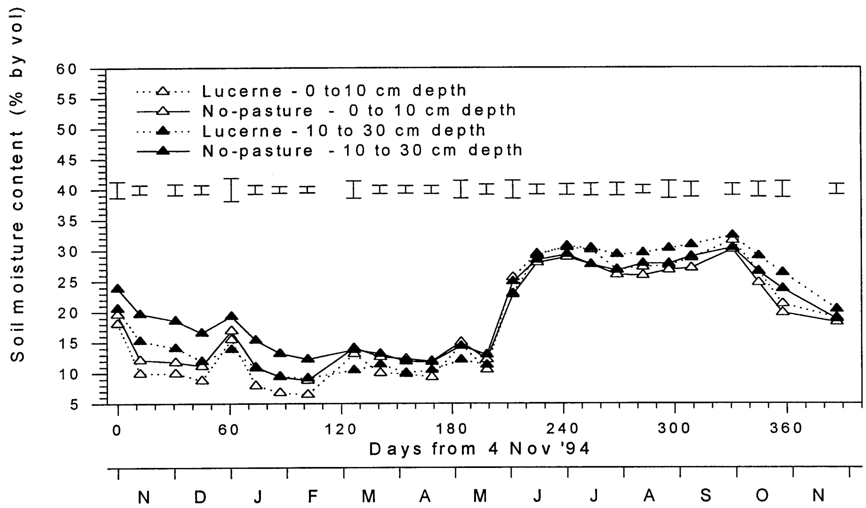

Figure 7: The time x understorey x depth interaction on mean soil moisture content. The vertical bars are LSD at p= 0.05 level

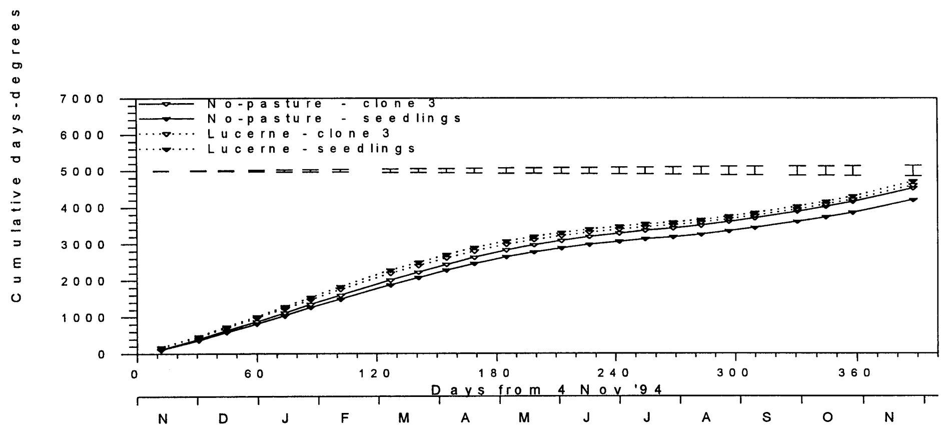

Figure 8: The time x understorey x plant type interaction on soil temperature (thermal time - cumulative day-degrees). The vertical bars are LSD at p= 0.05 level

The periodic *in situ* growth of coarse root cross-sectional area was recorded, and the maximum growth rate and time to maximum growth rate were also estimated by fitting the Gompertz equation.

2.5.1 Results

(i) White root tip initiation started in mid summer (early January) at both depths, and the maximum tip initiation was significantly higher in the 10-30 cm depth compared to the top 10 cm depth (2.4 and 1.3 tips/dm^2/day, respectively) (Figure 10). Time to maximum tip initiation occurred 4 weeks earlier in the top 10 cm depth (late June) compared to the 10-30 cm depth.

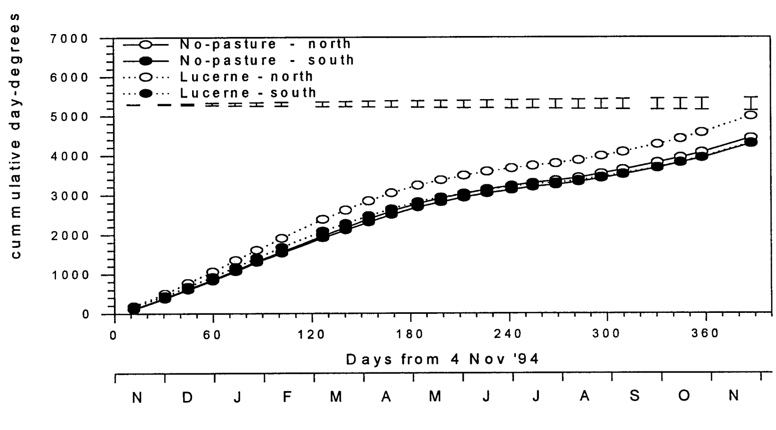

Figure 9: The time x understorey x side interaction on soil temperature (thermal time - cumulative day-degrees). The vertical bars are LSD at p= 0.05 level

(ii) The maximum growth rate for total fine root elongation showed that clone 3 grew 35% faster in the no-pasture treatment (0.58 cm/dm^2/day) compared to lucerne treatment (0.43 cm/dm^2/day), whereas with seedlings it was not different between the no-pasture and lucerne treatments (Figure 11). Time to maximum growth rate for total fine root elongation showed that seedlings were 8 weeks later compared to the clone 3 in the no-pasture treatment, whereas in the lucerne treatment clone 3 took slightly longer (4 weeks) than seedlings.

(iii) The trend on maximum growth rate for total fine root elongation due to side x understorey interaction showed that tree root growth was adversely affected on the north side (0.32 cm/dm^2/day) in the lucerne treatment compared to the other treatments (0.53 cm/dm^2/day). The growth rate declined faster in the north side of lucerne plots after the time to maximum growth compared to no-pasture treatment on the north side (Figure 12). The maximum growth rate was significantly higher at the 10-30 cm compared to the top 10 cm depths (0.61 and 0.34 cm/dm^2/day, respectively).

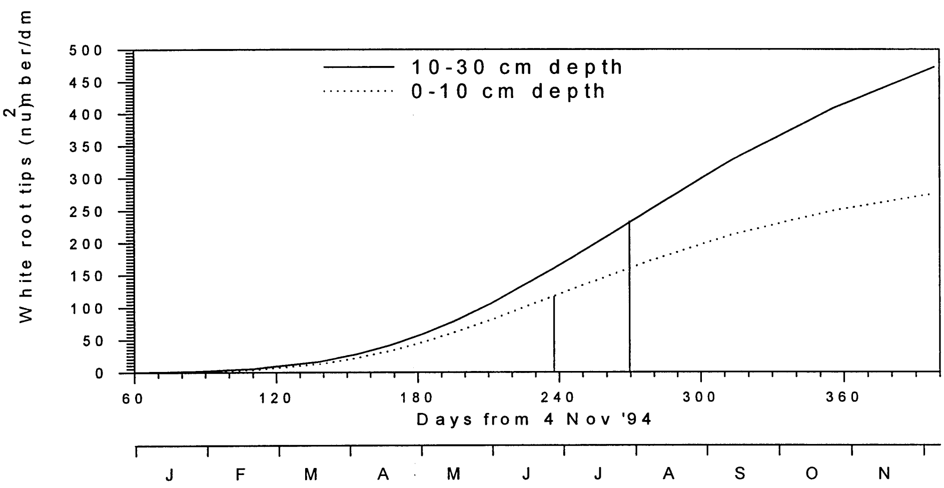

Figure 10: Temporal pattern of white root tip initiation at two soil depths. The vertical lines indicate T_i when there is a maximum rate of new root tips being initiated, and derived from fitting the growth data to Gompertz functions

Time to maximum growth rate occurred in mid and late winter at the 10-30 cm and 0-10 cm depths, respectively (Figure 13).

(iv) The maximum growth rate of coarse root basal area was much higher for clone 3 compared to seedlings with no-pasture, whereas in the lucerne treatment it was only slightly higher in clone 3. Time to maximum growth rate occurred earlier (10-12 weeks) in autumn (early April) in the no-pasture treatment than in the lucerne treatment (Figure 14).

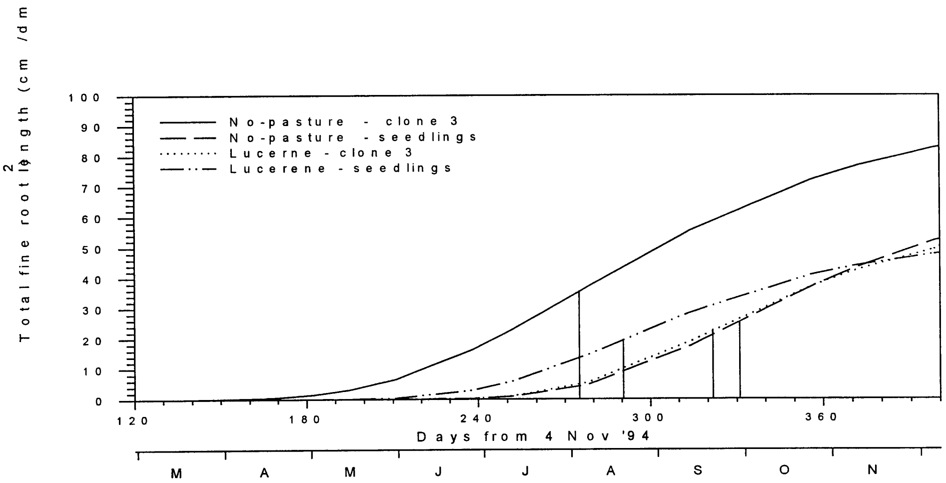

Figure 11. Temporal pattern of total fine root elongation for each understorey x plant type combination. The vertical lines indicate the T_i and derived from fitting the growth data to Gompertz functions

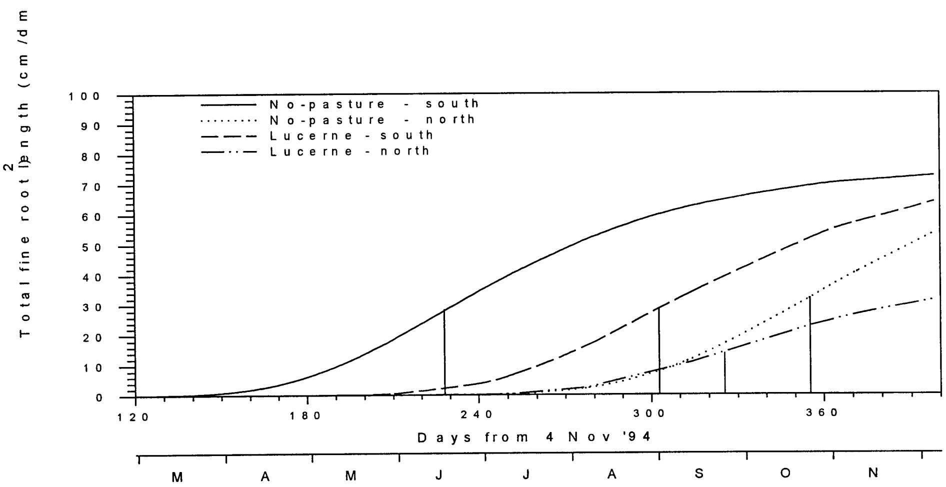

Figure 12: Temporal pattern of total fine root elongation for each understorey x side combination. The vertical lines indicate the T_i , and derived from fitting the growth data to Gompertz functions

3.0 DISCUSSION

3.1 Fine roots

There are several factors influencing tree root growth and in this study these indicated plant type characters, understorey competition, soil structure (soil ripping) and difference in soil moisture levels between the north and south sides of the trees.

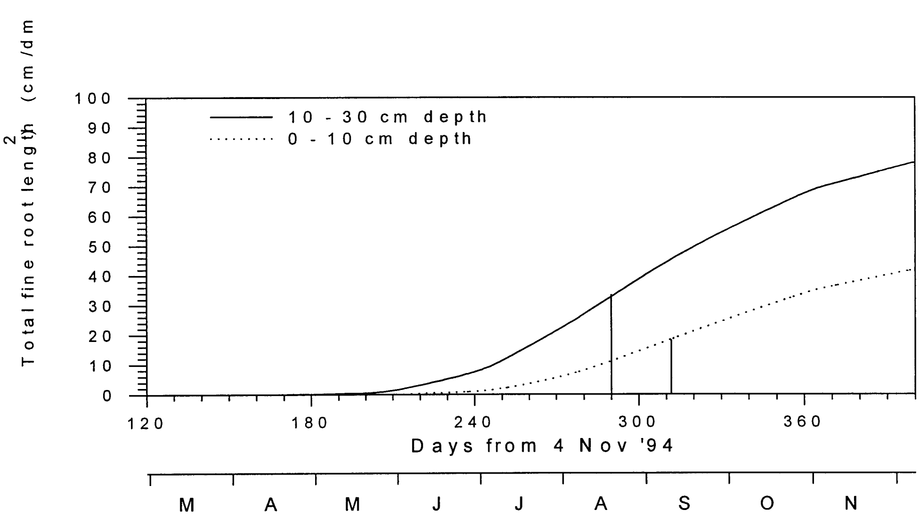

Figure 13: Temporal pattern of total fine root elongation at the two soil depths. The vertical lines indicate the T_i., and derived from fitting the growth data to Gompertz functions

The clonal radiata pine was highly responsive than open pollinated seedlings, producing more fine roots, particularly close to the soil surface. This indicated that the clonal materials had higher morphological plasticity (ie. higher fine root proliferation to exploit soil resources at a given microsite; Grime *et al.*, 1986) than seedlings. The clones were better able to exploit soil resources in a favourable site. This plasticity of clonal trees was probably related to their physiological age or propagation method but it may also have been partly a genetic characteristic on growth. The effect of physiological age on RLD of radiata pine with regards to the site has not been reported, although Nambiar (1980) found that fine root biomass production was remarkably different between 10 and 36 months old seedlings. Another study has also shown that Douglas-fir fine root growth was higher in the cuttings than the seedlings (Ritchie *et al.*, 1992), and similar result was found by Sweet (1973) on height growth between seedlings and cuttings of radiata pine. Lucerne was highly competitive to the trees, whereas ryegrass/clover was less competitive. This study indicated that fine root production near to tree rows was higher in lucerne compared to ryegrass/clover treatment. This resulted significant reduction of tree fine root production in lucerne treatment compared to ryegrass/clover treatment.

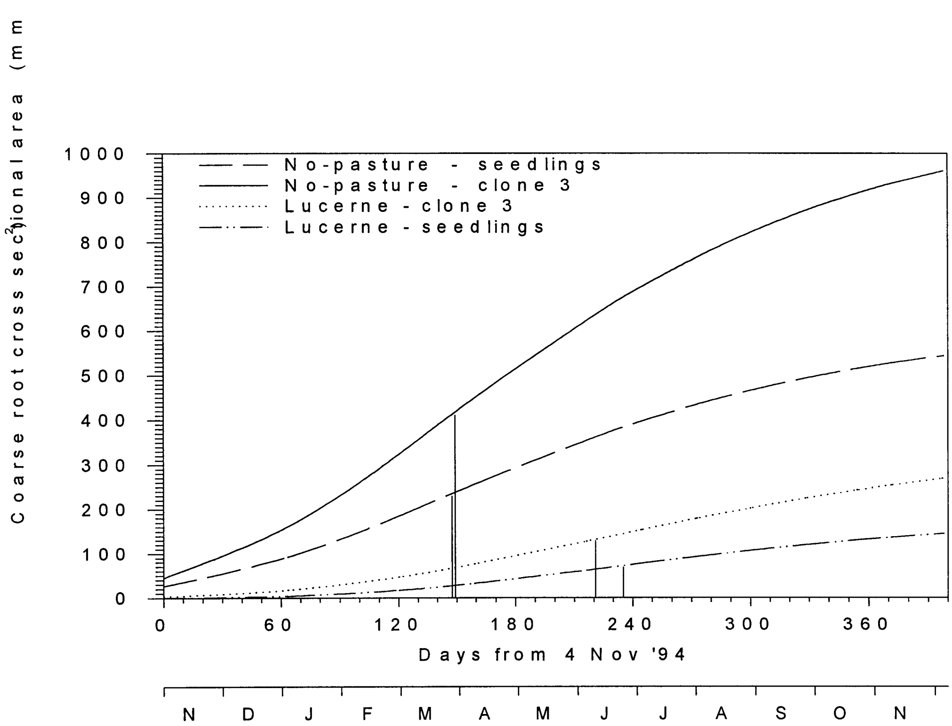

Figure 14: Temporal growth pattern of cross sectional area of coarse root for each understorey x plant type combination. The vertical lines indicate the T_i, and derived from fitting the growth data to Gompertz functions. The data were standardised by deducting initial cross section areas

Similar effect of lucerne on tree biomass was found by Bandara (1997). We can conclude, therefore, that competition from an understorey is clearly related to their rooting patterns, suggesting that this factor should be considered when selecting an understorey.

Soil ripping, and herbicide spraying enhanced tree root production, as there was higher root production in the tree-row compared to the north and south. The soil ripping and spraying was beneficial to tree root growth particularly with understorey competition. The higher root production in the ripline could be due to improved soil structure caused by ripping (Theodorou *et al.*, 1991), together with a higher soil moisture content (Pollock *et al.*, 1994) both of which encourage root growth.

White root tip initiation and fine root elongation and their maximum rate of growth and time to maximum rate of growth were strongly related to the soil moisture content, which changed with season. The maximum white root tip initiation rate and root elongation rate was observed when the soil moisture content was between 29% to 32% (by vol), and this was about field capacity for this soil. Furthermore, white root tip initiation and root elongation did not start when the soil moisture content was less than 11%; and these started only when soil moisture was 12% or above. This agrees with Squire *et al.* (1987) who demonstrated that the increasing trend of total root biomass growth of radiata pine was related to increasing levels of soil moisture content.

The presence of lucerne delayed white root tip initiation and fine root elongation and lowered the growth rate by competing for soil moisture and could be partially competing for soil nitrogen (Mead and Mansur, 1993).

Root tip initiation and total root growth rate was higher in the 10-30 cm depth compared to the top 10cm depth due to higher soil moisture at the 10-30 cm depth. Root sampling in 1993 also showed a similar rooting character with more roots between 10-30 cm than at 0 - 10 cm at the stem base in radiata pine. This result is consistent with research by Squire *et al.* (1987) on radiata pine in Australia and Kuhns *et al* (1995) on black walnut. This higher root tip initiation and total root growth rate in the 10-30 cm could be due to lower soil evaporation from the top 10-30 cm soil depth compared to the top 10cm depth.

Aspect also had a major affect on total fine root growth and understorey competition. The root growth of both trees and pasture was higher on the south compared to the north side of the trees. Furthermore, the northern side of the tree had a delayed and slower maximum growth rate, particularly in the lucerne treatment. In general, the north side was drier than the south side, and the soil under the lucerne was drier than the no understorey plots. This was because of higher evapotranspiration from the north particularly from lucerne plots compared to no understorey plots (Yunusa *et al.*, 1995a). In addition to the understorey pasture, the tree canopy controls the penetration of solar radiation (Oker-Blom and Kellomaki, 1983) and rain throughfall (Bouten *et al.*, 1992) which affects soil temperature and soil moisture content. (a) higher soil temperature in the lucerne plots which could be due to the higher solar radiation penetration (Yunusa *et al.*, 1995a) as a result of a smaller, more open tree canopy (Bandara, 1997) and narrower dripline (Yunusa *et al.*, 1995a), (b) higher evapotranspiration in lucerne plots (Yunusa *et al.*, 1995a).

The winter soil temperature did not limit fine root growth of radiata pine when soil moisture content was adequate. However, this study shows that the high summer soil temperature, together with its low soil moisture, limited the growth of all root components. The soil temperature ranged 3.3 ^{o}C (in winter -July) to 19.3 ^{o}C (in summer - January). The threshold level of soil moisture content was 12% (just above the wilting point) where fine root initiation and elongation stopped completely. However, the soil moisture level during the time of maximum growth rate was 29% , and 32% for root initiation and root elongation, respectively. These later two soil moisture levels are near field capacity.

3.2 Coarse Roots

The selection of plant types with a vigorous rooting habit is required to support the above ground growth of trees, especially in a silvopastoral system where tree has to compete with desired understorey pasture. This study shows that tissue cultured clones were taller, and had a highly competitive coarse root system compared to seedling trees.

The coarse root data showed that there was a higher number of large ($\geq$ 10 mm diameter class) first order lateral and vertical roots in clone 3 than seedlings (data not presented at this report). This higher number of first order roots again indicates the vigorous growth characteristics of clone 3 (Nambiar, 1984). In both 1993 and 1994, root:shoot ratio was higher in clone 3 than in the seedlings, and the ratio did not affected by the understorey competition . This higher root production was not at the expense of shoot growth, as indicated by the greater tree growth of clone 3. Similarly, vertical and lateral root biomass, particularly on the ripline, was markedly higher in clone 3 than in seedlings in both years

The root:shoot ratio was higher in 1994 compared to 1993, and such a change in ratio with age in radiata pine seedlings has been found earlier (Nambiar, 1980). Biomass growth between 1993 and 1994 was much higher in clone 3 than in seedlings in all the coarse root components but particularly for lateral and vertical roots. This higher growth in lateral root biomass was mainly attributed to the greater growth in the ripline and south in clone 3, whereas with the seedlings the growth increment was less. The above difference coarse root production may be due to genetics (Nambiar *et al.*, 1982; Theodorou *et al.*, 1991), type of planting material (Roberts and Wareing, 1975) or their physiological age (Watson and O'Loughlin, 1990). All these factors also probably affect the above ground growth (Bandara 1997). However, in this experiment it is likely that physiological age was more important than genetic differences. The growth and form ratings (GF) were relatively small (up to 4 points) but the physiological ages at planting were 1 and 6 from seed for the seedlings and clone 3, respectively.

Tree biomass allocation is altered by its environment (Snowdon and Benson, 1992) in addition to the tree's physiological age. On average, trees allocated about 34% of their coarse root biomass to the root core and 46% to the lateral roots. For clone 3, this fractional allocation did not alter between the understorey treatments. In contrast with the seedlings, the fractional allocation to laterals was reduced and the root core increased lucerne, compared to the no understorey treatments. The allocation to the root core was higher in the seedlings compared to clone 3 for all the understorey treatments and for both years. This indicated that more susceptible to understorey competition and allocated less biomass on lateral and vertical roots of total coarse root biomass. Hence, this suggests that the selection of plant types could be based on tree root characteristics.

Similarly if the aim of the silvopastoral system is to produce a maximum amount of timber, then the selection of the understorey should be made based on its competitive nature with the tree's rooting system. This study shows that the ryegrass/clover produced less root competition than the lucerne understorey to tree coarse root biomass at the age of three years.

The difference in soil moisture content between the understorey treatment also appeared to influence the cross sectional area growth of the coarse roots. Growth was much higher in the no understorey compared to the lucerne treatments, and was higher in the clonal trees than the seedlings. Clonal trees appeared to have faster coarse root growth and this may have resulted higher coarse root biomass production on this site, compared to seedling stock. Seedlings were more prone than clonal trees to lucerne competition; they demonstrated a greatly reduced maximum growth rate of their coarse roots (cross sectional). The threshold level of soil moisture content was 12% (just above the wilting point), and below this cross sectional area growth of coarse root stopped completely. Similar effects of higher soil moisture content on branch diameter growth of *Pinus radiata* (Rook *et al.*, 1976) and root collar growth of *Eucalyptus globulus* (Sasse, 1994) have been described. There are no previously published data on cross sectional area growth of radiata pine coarse roots. However, similar evidence to this study was found by Hallgren *et al.*, (1991) who found that the coarse roots of loblolly pine seedlings grew more rapidly in a wet compared to a dry regime. Alternatively, the lower rate of tree root cross sectional area growth in the lucerne treatment compared to the no understorey treatment could also be related to limited nitrogen (Mead and Mansur, 1993). The effect of nitrogen application on increasing the secondary thickening of the coarse roots of sycamore and sitka spruce has been demonstrated by Mackie-Dawson *et al.* (1995). Similarly, Nambiar (1980) observed that radiata pine developed thinner main tap roots with nitrogen deficiency.

3.3 Toppling

The optimum goal of small holder farmers or foresters is to grow maximum timber without losing its economic quality. Toppling reduces its economic value inducing butt sweep of the stem. This study shows that the selection of the right plant types with a better coarse root morphology can minimise such a financial loss.

The spiralling of lateral root and straightness, forking and dominance of vertical roots are mainly determined by planting materials. Less clonal trees had distorted cores and weakly developed vertical roots than the seedling trees. The median Menzies' lateral root score was between 2 to 4, and indicated that its spread was in two adjacent quadrants, i.e., east, west, and south. This could have been influenced by the east-west ripping, and the cooler moist south side compared to the north side (Mead *et al.*, 1993). Trees did not alter their vertical and lateral root quality and core distortion due to the understorey treatments.

To examine the relationship between core distortion or dominance of vertical roots of a particular planting material in relation to toppling indices was not possible in this study due to insufficient data. However, the toppled trees had significantly higher core distortion and weakly developed vertical roots compared to stable trees.

In contrast to the earlier studies (Anonymous, 1987; Burdett, 1979; Mason, 1985; Mason and Cullen, 1986)), logit models of this study showed that the significance ($p \geq 0.327$) of toppling was not associated with the root core distortion or dominance of vertical roots, rather it was related with the planting materials' characteristics. The stable characters of clone 3 and clone 4 may be associated with the crown architecture of the planting materials. A later study at this agroforestry experiment has shown that the foliage density was significantly lower in clone 3 than in the seedlings, also clone 3 had longer internodes than the seedlings (Bandara, 1997). Similarly, aerial photographic images of the agroforestry site showed a higher porosity in clonal tree crowns than in the seedling trees (Mason, 1998; personal communication).

4.0 CONCLUSIONS

- Comparison of fine root growth, coarse root growth and root:shoot ratio could be an useful criteria in the selection of desirable planting stock types, and in tree breeding.
- Differences in total biomass growth and allocation, between clone 3 and seedlings, resulted in different coarse root architecture.
- Physiological age seems to be an important factor controlling tree root growth patterns.
- Trees fine root production and coarse root architecture were altered by the understorey, but the degree differed according to the planting material, and the age of the tree.
- Planting material with a higher fractional allocation to lateral roots might have a greater network for fine roots. Such a root habit could provide more resistance to understorey competition.
- The selection of planting stock for a windy region could be done based on lateral and vertical root quality, and higher biomass and allocation in vertical roots. The study indicates that this can be done at the age of 3 or 4 years but it would be better if this could be done at an earlier age.

- Planting material of a higher crown porosity will be less sesptible to toppling compared to tree with compact canopy.

- If we assume that the better root architecture is mainly related to physiological age of the planting materials, then there will be advantages in using older rather than younger aged material.

- Soil ripping and spraying provides a good environment for root growth, and this is especially important during tree establishment in agroforestry systems where there is understorey root competition.

- The rectangular planting configuration (which could be desirable for an agroforestry system) altered soil moisture and temperature patterns near the trees. These changes varied with aspect, understorey type and tree canopy architecture.

- The orientation of the tree rows (east-west) in the experiment may have magnified the alteration of soil moisture and temperature effects.

- Occurrence of earlier maximum growth rate of coarse root cross sectional area in the no understorey was related to having $\geq$ 13% soil moisture level.

- A soil moisture level of $\geq$ 12% was necessary for the growth and development of radiata pine fine roots. The maximum growth rate occurred when the soil moisture content was near field capacity. Winter soil temperature was not a limiting factor in this study.

- Clonal trees had vigorous fine root elongation, and had a higher coarse root cross sectional area growth and a faster fascicle elongation than the seedlings, especially when the soil was moist.

- The seasonal timing of tree growth patterns were in the following order: branch elongation, fascicle elongation, cross sectional area branch, cross sectional area of coarse roots, fine root tips, and total fine root elongation. The growth and development of all components, except white root tips and fine roots occurred while the photosynthesis rate was extremely low. Hence, accumulated carbohydrate in the branches and coarse roots may have been utilised for growth and development of fine root components.

5.0 FUTURE DIRECTION FOR FORESTERS

The outcome of these experiments suggest that future research should address the following questions:

(i) Selection of an alternative understorey species to the current ryegrass/clover utilising information on rooting characteristics. Also, competition for moisture and nutrients for trees can be reduced by selecting other trees and understorey crops with different rooting patterns and which occupy different depths of the soil. This may provide resource sharing or reduce competition resulting in the optimum growth of the trees as well as the crops.

(ii) The number of permanent first order lateral roots is an important feature which determines the size of the coarse root system and therefore the size of the functional element of the root system, thereby determining the tree's growth. Research is needed to see if it is possible to define the acceptable number of first order lateral roots in nursery plants.

(iii) Branch pruning not only reduces leaf area for photosynthesis, but it can also reduce the possibility of retranslocation of stored carbohydrate from leaves to roots. This is particularly important if root growth occurs when the photosynthesis rate is minimal. Research is needed to understand how the vertical and horizontal pattern of fine root growth is affected by the timing and intensity of branch pruning.

(iv) In a rectangular planting configuration, the orientation of tree row plays an important role in determining the rain throughfall in a given site. This study showed that the east-west tree row resulted in a dry zone on the north side of each row, and lowered root growth. Research is needed to find out whether tree root growth and understorey can be improved by planting trees in north-south rows on the Canterbury Plains.

(v) This study can not clearly separate the effects of genetic variation, difference in physiological age and difference in propagation methods on root growth of radiata pine. This could be the subject of further research as it would help in the selection of planting materials.

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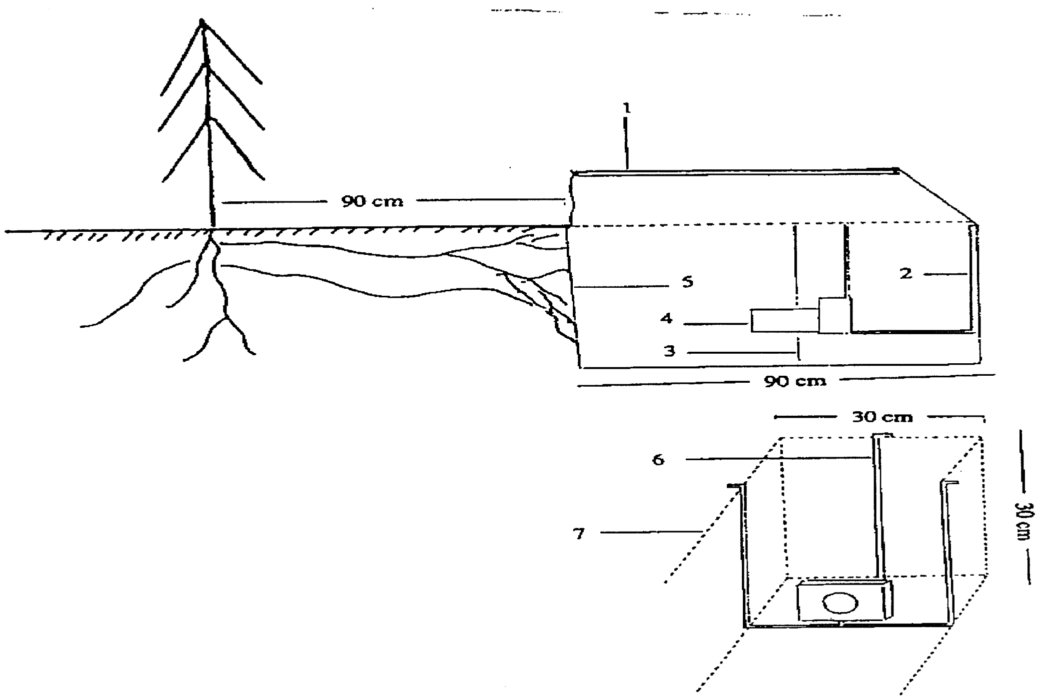
APPENDIX I

Sketch diagram showing rhizotron assembly

Top: Cut away side view showing black box, tripod and camera inside rhizotron box (90 x 30 x 30 cm: inserted inside of trench) and portable wooden box with opaque acrylic plastic top.

Bottom: Rhizoron box showing side view of camera and tripot frame inside a black box.
1 portable wooden box, 2 frame, 3 black box, 4 camera, 5 polycarbonate window of rhizotron box, 6, frame side view, 7 rhizotron box. (for detail see Gautam, 1998).



APPENDIX II

Lincoln University, agroforestry experimental site with five radiata pine genotypes and six types of understorey.

Above : metal cages indicate the position of rhizotron boxes to study root competition for radiata pine with lucerne understorey.

Below : A view of root face window of the rhizotron box with no understorey competition.

(Source: Gautam, 1998).