



Tree root morphology in alley systems

**A report for the RIRDC/L&W Australia/FWPRDC
Joint Venture Agroforestry Program**

by Robert Sudmeyer

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Foreword

When integrating trees into agricultural systems it is widely recommended that competition between trees and crops be reduced by selecting tree species which have limited lateral root extension and/or are deeper rooted than crops and to cut (prune) the tree roots to reduce their density under the crop. However, little is known about the extent and distribution of the roots of commonly planted tree species in adjacent agricultural land. Also, limited measurements in Western Australia suggest the presence of deeper tree roots can make root pruning ineffectual in the long term as the roots continue to grow under the rip line. One of the key recommendations in RIRDC Research Paper No 97/29 was the need for experimental and modelling research to characterise the tree crop interface and use the data as a predictive tool to assess various agroforestry designs.

This report describes the extent and distribution of *Eucalyptus globulus*, *Pinus pinaster* and *Pinus radiata* roots in the soil of agricultural land adjacent to tree lines. The influence of soil type and root pruning on root morphology is discussed. Soil water content and soil chemical characteristics are documented and discussed in light of the proximity to trees. The availability of this information will improve the understanding of how tree roots affect crop growth and aid in the development of competition management strategies which maximise the goals of crop production, water use and tree growth.

This project was funded by the Joint Venture Agroforestry Program (JVAP). The JVAP is supported by three R&D Corporations — Rural Industries, Land & Water Australia and Forest and Wood Products. These Corporations are funded principally by the Federal Government.

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Peter Core

Managing Director

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Executive Summary

It has been suggested that competition can be reduced by selecting tree species which have limited lateral root extension and/or are deeper rooted than crops, by cutting (root pruning) the tree roots to reduce their density under the crop and by pruning the tree crowns. However, the presence of deeper tree roots can make root pruning ineffectual in the long term as the roots continue to grow under the rip line. One of the key recommendations in RIRDC Research Paper No 97/29 was the need for experimental and modelling research to characterise the tree crop interface and use the data as a predictive tool to assess various agroforestry designs.

The objectives of this research were to quantify the extent and distribution of the roots from three commonly planted species in agricultural land adjacent to tree lines and to document how root morphology is affected by soil type and root pruning. This information is to be used to develop commercially sound competition management strategies based on an understanding of tree root morphology for a number of tree species and soil types

Measurements were made during the summer months of 1999, 2000 and 2001 at seven sites located in the Esperance Region on the south coast of Western Australia. The climate in the region is Mediterranean with cool, wet winters and warm, dry summers. Approximately two thirds of the annual rain falls between May and October. Three tree species were measured; *Eucalyptus globulus* (Tasmanian blue gum), *Pinus radiata* (Monterey pine) and *P. pinaster* (maritime pine). The trees were planted in various layouts and at three sites lateral roots had been root pruned to a depth of 0.4-0.7 m, 2-4 years before the roots were mapped

The distribution of tree roots in the soil adjacent to tree lines was mapped using a trench profile method. Three transects running at right angles to the tree line were marked at each site and measurements made at the following multiples of the mean tree height (H): 0.5, 1.0, 1.5, 2.0, 2.5 H. Trenches were excavated parallel to the tree line at each distance using a mechanical excavator. The trenches were generally 1.5-1.7 m deep, though some were shallower because very hard clay impeded the excavator, and had at least 2-4 m of vertical trench wall running parallel to the trees.

For each trench, the weight of tree roots in the sandy soil horizons was estimated by removing a known volume of soil from the trench wall in 105 mm deep increments down to the depth of clay, or about 1 m in the deep sands. Roots were separated from the soil by washing the soil through a 0.71 mm sieve, then the tree roots were separated by hand from other organic matter. To determine soil water content, gravimetric soil samples were collected from each trench at 0.1 m intervals down to the pit floor. Samples for chemical analysis were collected in a similar manner to those collected to determine soil water content, but rather than collecting samples at 0.1 m intervals down each pit face, samples were collected for each soil horizon.

The lateral extent of tree roots ranged from 18 to 30 m and was strongly correlated to the height of the trees (H), ranging between 1.5 and 2 H for all three species. The 1.5-2 H that tree roots were found to extend in this study was generally less than the 2-3 H wide competition zone of trees measured in the Esperance

The density of roots in the soil declined logarithmically with distance from the trees for all three species. The density of tree roots in the soil adjacent to the trees varied among tree species. At 0.5 H, the density of roots in the top 1.4 m of the soil profile was between 404 and 487 roots/m² for *E. globulus*, 909 and 1110 roots/m² for *P. radiata* and 1409 and 2691 roots/m² for *P. pinaster*. However, because of the small number and the age structure of the trees sampled, it is not possible to separate age and species as factors in determining root density. Although the tree root density varied among the tree species, the relative distribution of tree roots down the soil profile was generally similar for the three species, and was dependent on soil type. Root density was generally greatest in the top 0.5 m of the soil profile and decreased with depth, this decrease was relatively gradual in the deep sands, but

root density decreased abruptly in clay subsoil. The dry weight of roots in the top metre of soil between 0.5 and 2.0 ranged between 4.2 t/km of tree line for 6 year old *E. globulus* to 42 t/km of tree line for 20 year old *P. pinaster*.

Soil water content was generally less near the trees, and the soil water content of the top 0.5 m of the soil profile was negatively correlated to root density. While soil water content deeper than 0.4 m in the soil profile was consistently less within 1.5 H, this was not always so for the topsoil. Measurements made in the weeks following summer rainfall provide some evidence that the shelter provided by the trees (ie. shade, reduced windspeed and leaf litter under the trees) reduced evaporation of soil water and increased the water content of the top 0.2 m of the soil profile. Soil chemistry was generally similar inside and outside the area occupied by tree roots. However, the potassium content and electrical conductivity of the soil under the trees was greater than at 2 H.

This study suggests that *P. pinaster*, *P. radiata* and *E. globulus* have similar potential to compete with crops given their lateral extent is similar, and all three had the greatest root density within 0.5 m of the soil surface where crop and pasture roots are concentrated. Though *P. pinaster* had the greatest root density of the three species, it is not clear how much root density was controlled by tree age.

Two to four years after the trees had been root pruned, both the extent, density and vertical distribution of roots was similar for pruned and unpruned trees. The effectiveness of subsequent root pruning will depend on the proportions of the roots in the topsoil that originate from deeper unsevered roots and roots which have grown back from severed roots, as only regrowth from severed roots will be severed in subsequent pruning operations. Consequently, root pruning on deep sands would become increasingly ineffective as progressively more shallow roots originate from deeper unsevered roots. It is likely that in the long-term root pruning will only remain effective on duplex soils where all of the lateral roots can be severed

1. Introduction

Trees and crops interact wherever they are grown in close temporal or spatial proximity. The effect of this on crop growth can be separated into positive interactions such as those which improve soil fertility or microclimatic conditions and negative interactions such as competition for resources (Vandenbelt et al., 1990). Growing trees with crops is only of benefit when trees use resources that the crop cannot acquire and/or provide substantial value per unit of resources obtained in competition with the crop (Cannell et al., 1996; Vandermeer et al., 1998). This sets up a basic tension between managing tree/crop systems to maximise the longer term objectives of planting the trees for shelter, water-use, nature conservation and tree products and the shorter term goals of maximising crop and pasture productivity.

It has been suggested that competition can be reduced by selecting tree species which have limited lateral root extension and/or are deeper rooted than crops, by cutting (root pruning) the tree roots to reduce their density under the crop and by pruning the tree crowns (Kort, 1988; Hughes and Edwards, 1994; van Noordwijk and Purnomosidhi, 1995; Shroth, 1995). However, the presence of deeper tree roots can make root pruning ineffectual in the long term as the roots continue to grow under the rip line (Schroth, 1995). One of the key recommendations in RIRDC Research Paper No 97/29 was the need for experimental and modelling research to characterise the tree crop interface and use the data as a predictive tool to assess various agroforestry designs.

This project builds on work that has already been done as part of the National Windbreaks Project and will complement an on-going research project entitled Improving Crop Production in Windbreak and Alley Farming Systems being funded by GRDC. An improved understanding of tree root morphology will facilitate the selection of tree species which are less competitive and the development of competition management strategies which maximise the goals of crop production, water use and tree growth.

2. Objectives

The objectives of this research were to quantify the extent and distribution of the roots from three commonly planted tree species in adjacent agricultural land, and to document how tree root morphology is affected by soil type and root pruning. This information is to be used to develop commercially sound competition management strategies based on an understanding of tree root morphology for a number of tree species and soil types

3. Methodology

3.1 Sites

Measurements were made during the summer months of 1999, 2000 and 2001 at seven sites located in the Esperance Region on the south coast of Western Australia. The climate in the region is Mediterranean, with cool, wet winters and warm, dry summers. Approximately two thirds of the annual rain falls between May and October. The location of each site is given in Table 3.1 along with mean annual rainfall, soil type and the tree species measured.

Brendan Nicholas (Western Australian Department of Agriculture) made detailed soil descriptions at Sites 1 and 2, the soil at Sites 1, 3 and 4 were similar and consequently the soil at Sites 3 and 4 were not described in detail. The soils at Sites 5, 6 and 7 were described in 1994 by Nicholas and Gee (1998). Detailed descriptions are provided in Appendices 7.1-7.7.

Table 3.1. The location, of sites where tree roots were mapped along with mean annual rainfall, soil type and the tree species.

Site no.	Site location	Tree species	Mean annual rainfall	Soil type (Australian Soil Classification, Isbell, 1996)
1	122:14:57 E -33:40:12 N	<i>E. globulus</i>	525	Basic, arenic, bleached-orthic Tenosol
2	121:52:48 E -33:47:43 N	<i>E. globulus</i>	600	Ferric, acidic, mesonatric, yellow Sodosol
3	121:51:16 E -33:33:54 N	<i>P. radiata</i>	490	Basic, arenic, bleached-orthic Tenosol
4	121:52:46 E -33:33:52 N	<i>P. radiata</i>	490	Basic, arenic, bleached-orthic Tenosol
5	122:53:18 E -33:37:59 N	<i>P. pinaster</i>	522	Mesotrophic, mesonatric, yellow Sodosol (0.45 m of sand over clay)
6	122:52:46 E -33:38:17 N	<i>P. pinaster</i>	522	Acidic, arenic, bleached-orthic Tenosol
7	122:53:96 E -33:37:46 N	<i>P. pinaster</i>	522	Hypocalcic, mesonatric, yellow Sodosol (0.75 m of sand over clay)

Three tree species were measured; *Eucalyptus globulus* (Tasmanian blue gum), *Pinus radiata* (Monterey pine) and *P. pinaster* (maritime pine). The trees were planted in various layouts and at sites 1, 4 and 7 lateral roots had been severed (root pruned) to a depth of 0.4-0.7 m, 2-4 years before the roots were mapped (Table 3.2).

Table 3.2. The species, age, mean height number of rows and spacing along rows of trees in each tree line measured. Also the orientation of the tree line and aspect of the measurement transects.

Site no.	Species	Age (yr)	Height (m)	No. Rows	Root pruned	Years since root pruned	Orientation	Aspect
1	<i>E. globulus</i>	6	15	12	Yes	2	NW-SE	NE
2	<i>E. globulus</i>	6	16	20	No	-	NE-SW	SE
3	<i>P. radiata</i>	15	17	3	No	-	N-S	E & W
4	<i>P. radiata</i>	15	17	3	Yes	3	N-S	E & W
5	<i>P. pinaster</i>	16	12	7	No	-	WN-SW	SE
6	<i>P. pinaster</i>	20	16	7	No	-	NW-SE	SW
7	<i>P. pinaster</i>	16	14	3	Yes	4	NE-SW	NW

3.2 Root distribution

The distribution of tree roots in the soil adjacent to the tree lines was mapped using a trench profile method similar to that described by Bohm (1979). Three (two at Site 2) transects running at right angles to the tree line were marked at each site. Trenches were excavated parallel to the tree line along each transect at the following multiples of the mean tree height (H): 0.5, 1.0 (1.25 in the case of Site 2), 1.5, 2.0 and 2.5 H where roots extended to 2 H. The trenches were generally 1.5-1.7 m deep, though some were shallower because very hard clay impeded the excavator, and had at least 2-4 m of vertical trench wall running parallel to the trees.

In each trench, the floor and the wall nearest the tree line was smoothed to provide a surface upon which to work. To reveal the tree roots, sand was gently removed from the face using a brush and clay was removed using a water spray. About 2 mm of sand and 1 mm of clay was removed in this way. A single clear plastic sheet (0.5 m wide and 1.4 m long) was then laid on the prepared trench floor and two sheets were fixed over the prepared trench wall, running from the soil surface down to 1.4 m deep. All of the tree root and soil features were traced onto the plastic. Root diameters were indicated on the sheets according to the following size classes; < 2 mm, 2-5 mm, 5-10 mm, 10-20 mm, and >20 mm. The number of root intercepts were later counted and divided into root size classes and for the trench walls, the number of roots in each 0.1m depth interval was recorded.

3.3 Root weight

For each trench, the weight of tree roots in the sandy soil horizons was estimated by removing a known volume of soil from the trench wall in 105 mm deep increments down to the depth of clay, or about 1 m in the deep sands. A steel frame (105 mm deep x 505 mm wide x 40 mm thick (0.0021 m³)) was hammered into the smoothed wall of the trench, then a knife was run along the back of the frame to loosen the soil and sever any roots, the soil and roots were then carefully removed from the frame and bagged. Roots were separated from the soil by washing the soil through a 0.71 mm sieve, then the tree roots were separated by hand from other organic matter. The tree roots were dried at 70 °C for 24 hrs and weighed.

3.4 Soil water content

At each site, gravimetric soil samples were collected from each trench. Immediately prior to sampling the trench wall was cut back to reveal fresh soil, then samples were taken at 0.1 m intervals down to the pit floor and sealed into plastic bags. Under the trees, soil samples were obtained using a 50 mm diameter soil auger. The samples at each distance were then combined to give a single sample for each depth interval at each distance. The wet weight of the samples was determined and then the samples were dried at 110 °C for 48 hrs and weighed again

At each site, the bulk density of the soil was determined by taking volumetric soil samples at 0.1 m intervals down the soil profile or representative samples for each identified soil horizon. The bulk density was used to convert gravimetric water content to volumetric water content for each sample interval.

3.5 Soil chemical analyses

Samples for chemical analysis were collected in a similar manner to those collected to determine soil water content, but rather than collecting samples at 0.1 m intervals down each pit face, samples were collected for each soil horizon.

Soil samples were dried at 40 °C and passed through a 0.2 mm sieve. Soil pH (CaCl₂), electrical conductivity and organic carbon were determined using methods 4B1, 3A1 and 6A1 of Rayment and Higginson (1992). To determine the concentration of metals, the sample was digested in a mixture of nitric and perchloric acid and analysed using an atomic emission spectrophotometer. Total nitrogen and phosphorus concentrations were determined following Kjeldahl digestion of the sample. Total nitrogen content was determined using method 7A2 of Rayment and Higginson (1992). Phosphorus content was determined using a modified Murphy and Riley (1962) procedure.

3.6 Statistical analyses

Differences in soil water content and soil chemical properties were statistically tested by analysis of variance using Genstat 5 statistical software. Regression curves were fitted using Microsoft Excel software.

4. Results

4.1 Root distribution

The lateral extent of tree roots ranged between 18 and 34 m (Table 4.1), and was positively correlated with tree height (Figure 4.1). The extent of lateral roots relative to tree height was similar for the three tree species and ranged between 1.5 and 2 H. Tree age explained less than 10% of the variability in root extent.

Table 4.1. The lateral extent of tree roots expressed as a multiple of tree height (H) and in metres, and the density of tree roots in the top 1.4 and 0.5 m of the soil profile at various distances from the trees. Measurements made in the Esperance Region, 1999-2001.

Site	Maximum lateral root extent		Root density 0-1.4 m (root intercepts /m ²)				Root density 0-0.5 m (root intercepts /m ²)			
			Distance from trees (H)				Distance from trees (H)			
	H	m	0.5	1.0	1.5	2.0	0.5	1.0	1.5	2.0
1	2	30	404	235	114	13	609	278	173	32
2	1.5	24	487	240	15	0	1205	558	19	0
3	1.5	26	909	890	273	0	992	723	173	0
4	2	34	1110	835	237	14	1411	949	275	34
5	1.5	18	1409	1077	349	0	3710	2746	862	0
6	1.5	24	1750	982	258	0	1764	1019	372	0
7	1.5	21	2691	1569	704	0	3710	1900	784	0

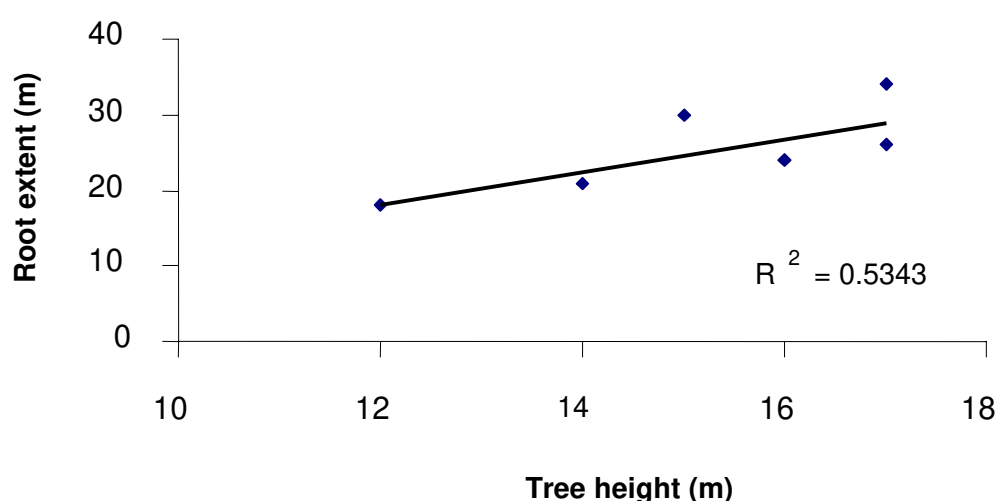


Figure 4.1. Relationship between mean tree height and lateral extent of tree roots, at Sites 1-7.

The density of roots in the soil declined logarithmically with distance from the trees for all three species (Figure 4.2). The density of tree roots in the soil adjacent to the trees varied among tree species. At 0.5 H the density of roots in the top 1.4 m of the soil profile was between 404 and 487 roots/m² for *E. globulus*, 909 and 1110 roots/m² for *P. radiata* and 1409 and 2691 roots/m² for *P. pinaster*. However, analysis of differences between species is confounded by the small number of sites sampled. Also, over time various tree species have fallen into and out of favour as being suitable for planting on farms, accordingly, the tree species measured in this study fell into distinct age categories and tree age explained 53% of the variability in root density at 0.5 H (Figure 4.3).

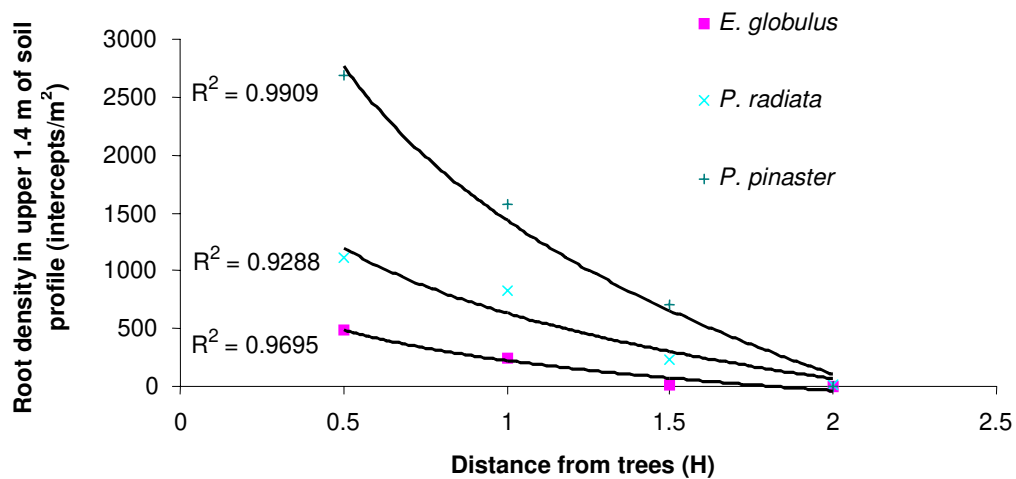


Figure 4.2. Root density in the top 1.4 m of the soil profile at various distances from *E. globulus* (Site 2), *P. radiata* (Site 4) and *P. pinaster* (Site 7).

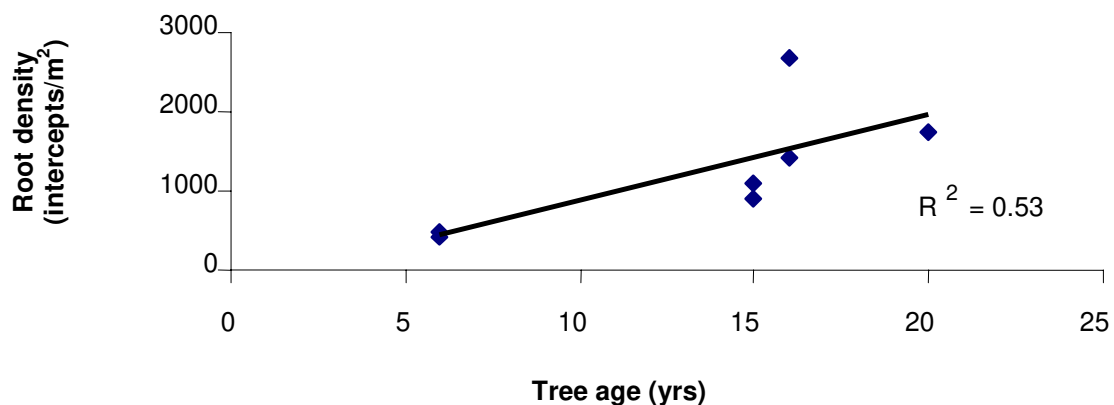


Figure 4.3. Root density in the top 1.4 m of the soil profile at 0.5 H for trees of various ages, at Sites 1-7.

Soil type had a marked influence on the distribution of tree roots down the soil profile for both *P. pinaster* and *E. globulus*. On duplex soils, tree roots were concentrated in the sandy “A” horizons with root density decreasing sharply in the clay subsoils (Figure 4.4). On the deeper sands, tree roots were distributed relatively uniformly down the soil profile for all three species. The greatest root density was generally within 0.2 m of the soil surface. Cultivation of the soil reduced tree root density within 0.1 m of the soil surface. At Site 2, which had not been cultivated for 5 years, root density at 0-0.1 m was four times greater than at Site 1 which had been cultivated annually (Figure 4.4b)

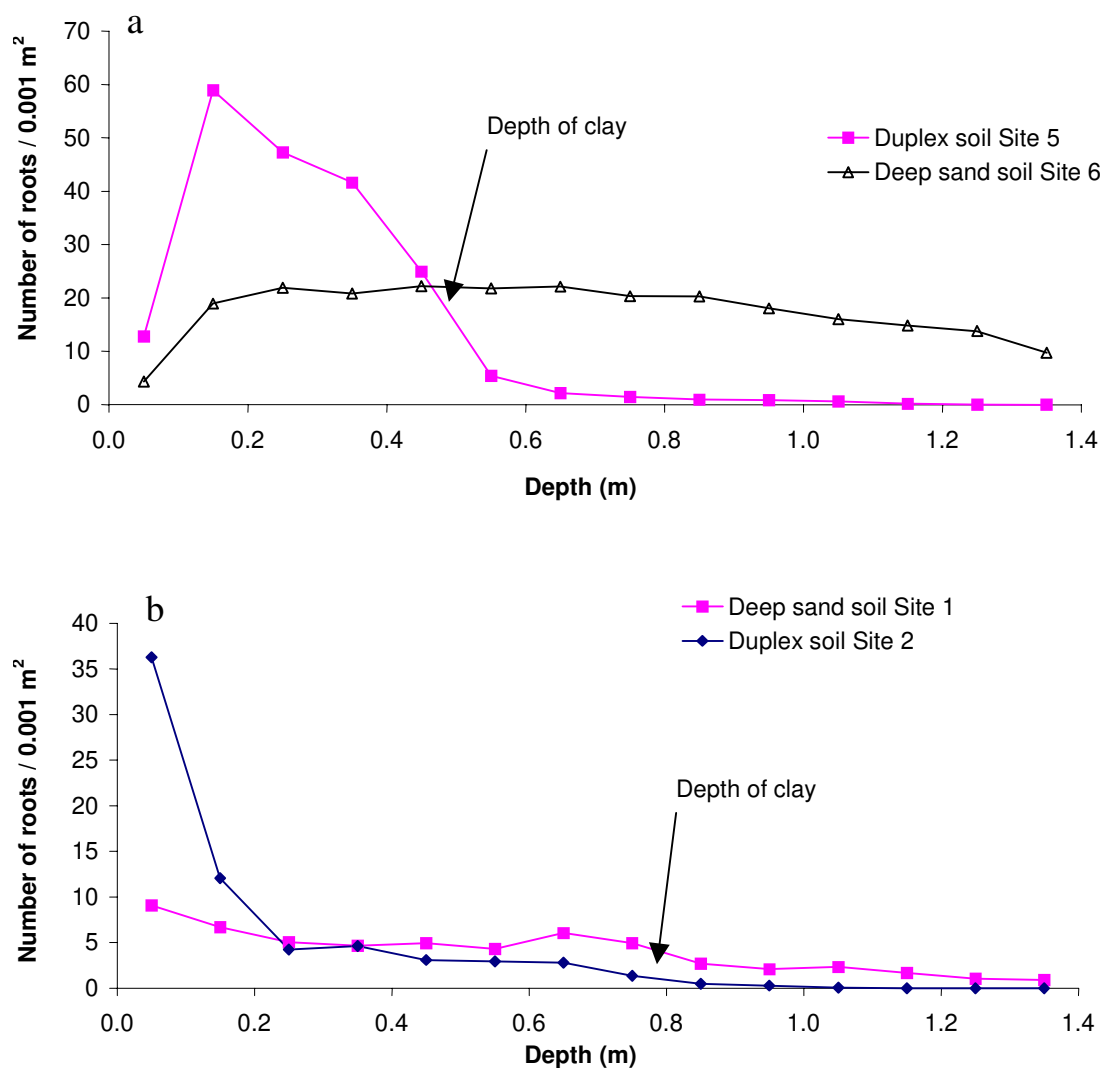


Figure 4.4. Density of tree roots between the soil surface and 1.4 m deep (a) *P. pinaster* at Sites 5 and 6, and (b) *E. globulus* at Sites 1 and 2.

Roots greater than 5-10 mm in diameter were confined to the sandy soil horizons. In the clay, roots were generally confined to the faces between the large polyhedral peds and to relic root channels previously occupied by the native vegetation. Consequently the number of vertical roots found in the trench floors was much greater in the deep sands than in the duplex soils (Table 4.2)

Table 4.2. The density of vertical tree roots (droppers) in the floor of the trench at various distances from the trees. Measurements made in the Esperance Region, 1999-2001.

Site	Lateral root extent (H)	Roots/m ²			
		Distance from trees (H)			
		0.5	1.0	1.5	2.0
1	2	375	118	2	0
2	1.5	63	14	0	
3	1.5	338	348	0	0
4	2	342	448	0	0
5	1.5	44	21	25	0
6	1.5	1029	481	207	0
7	1.5	315	258	221	0

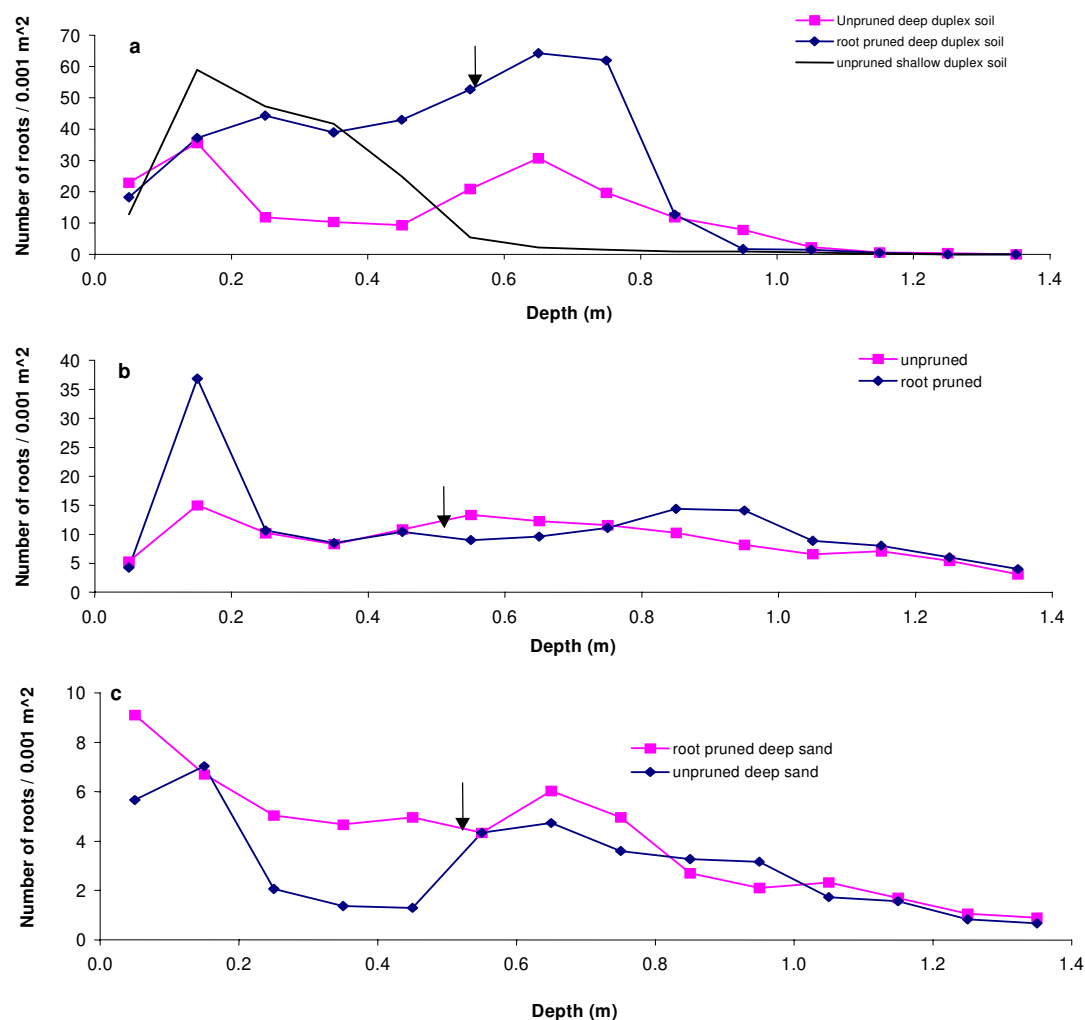


Figure 4.5. Vertical distribution of tree roots with and without root pruning, arrows show depth of pruning, (a) root pruned *P. pinaster* at Site 7, unpruned *P. pinaster* at Site 5 and unpruned 9 year old *P. pinaster* at site 7 (data from Scott and Sudmeyer, 1998); (b) *P. radiata* at Sites 3 and 4 and (c) root pruned *E. globulus* at Site 1 and unpruned *E. globulus* growing on a similar soil (Sudmeyer, unpublished data).

Comparison of the root distribution of trees which had never been root pruned with trees which had been root pruned does not show any clear decrease in root density in the soil above the depth of ripping two to four years after pruning (Figure 4.5). The possible exception is for the root pruned *P. pinaster*, which had a lower density of roots in the top 0.1-0.2 m of the profile relative to unpruned trees at Site 5 or at the same site seven years earlier (Scott and Sudmeyer, 1998). The lesser density of roots at 0.2 m adjacent to unpruned *P. radiata* (Site 4) compared to pruned *P. radiata* (Site 3) is probably due to intense cultivation of the top 0.15 m of the soil profile following the application of clay as a soil amendment at Site 4.

4.2 Root wt

The root biomass in the top 0.5 m of the soil profile between 0.5 and 2 H ranged between 1 t/km of tree line for 6 year old *E. globulus* and 28.3 t/km for 20 year old *P. pinaster* (Table 4.3). There were strong correlations between total tree root biomass in the top 0.5 m of the soil profile between 0.5 and 2 H and tree age (Figure 4.6, $r^2=0.89$) and the density of roots at 0.5 H ($r^2=0.96$). Tree height explained less than 1 % of the differences in root biomass.

Table 4.3. Tree species, maximum sample depth, root weight to maximum sample depth at various distances from the trees and total root weight to maximum sample depth and top 0.5 m of the soil profile between 0.5 and 2 H.

Site	Species	Max. sample depth (m)	Root wt g/depth x 1 m ²				Root wt (0.5-2 H) t/km	
			Distance from trees (H)				To maximum sample depth	In sand 0-0.5 m deep
			0.5	1.0	1.5	2.0		
1	<i>E. globulus</i>	0.99	532	56	0		2.4	1.0
2	<i>E. globulus</i>	0.66	852	121	0		4.1	3.9
3	<i>P. radiata</i>	1.10	1344	1002	444	0	18.0	11.8
5	<i>P. pinaster</i>	0.44	3112	837	415	0	-	16.8
6	<i>P. pinaster</i>	1.10	4067	2759	1193	0	41.9	28.3
7	<i>P. pinaster</i>	0.77	2025	1404	4902	0	20.4	14.0



Figure 4.6. Relationship between tree age and root biomass in the top 0.5 m of the soil profile between 0.5 and 2 H at sites 1, 2, 3, 5, 6 and 7.

4.3 Soil water content

There was considerable variation in soil water content at similar distances among sites (Appendix 7.8), this reflected differences in soil type and how much rain had fallen in the weeks preceding measurement. When soil water content was normalised at each site using the soil water content at 2 H, mean differences in soil water content at various distances from the trees were not significant. However, there was a general trend for the mean soil water content in the top 0.5 m of the soil profile to be least at 0.5 H and increase with increasing distance from the trees to be greatest at 2 H (Figure 4.7). Tree root density explained 40% of the variation in soil water content within 2 H of the trees (Figure 4.8).

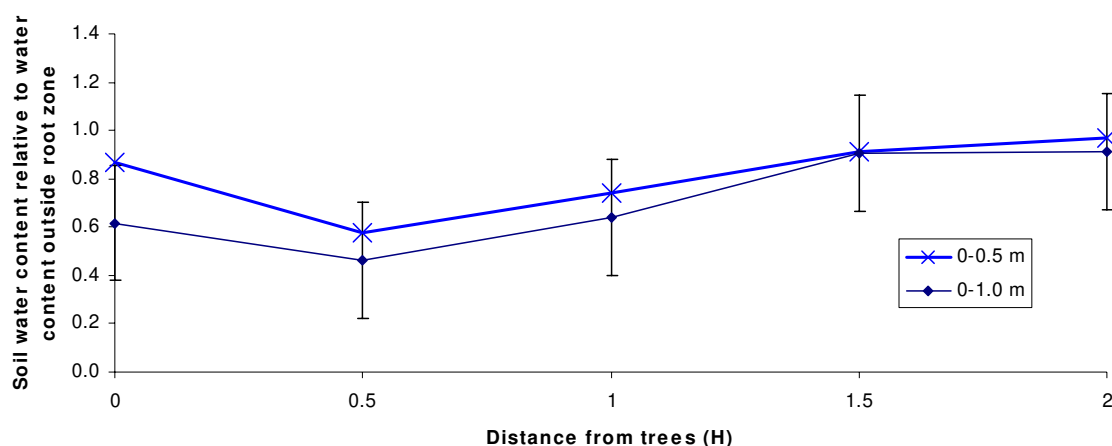


Figure 4.7. Mean normalised soil water content in the top 0.5 m and top 1.0 m of the soil profile, at various distances from tree lines. Data for water content in the top 0.5 m are for all sites and data for water content in the top 1.0 m are for Sites 1, 3, 4, 5, 6 and 7. Distances are expressed as multiples of tree height, 0 H indicates conditions under the trees. Bars indicate LSD for water content values in top 1 m of soil profile.

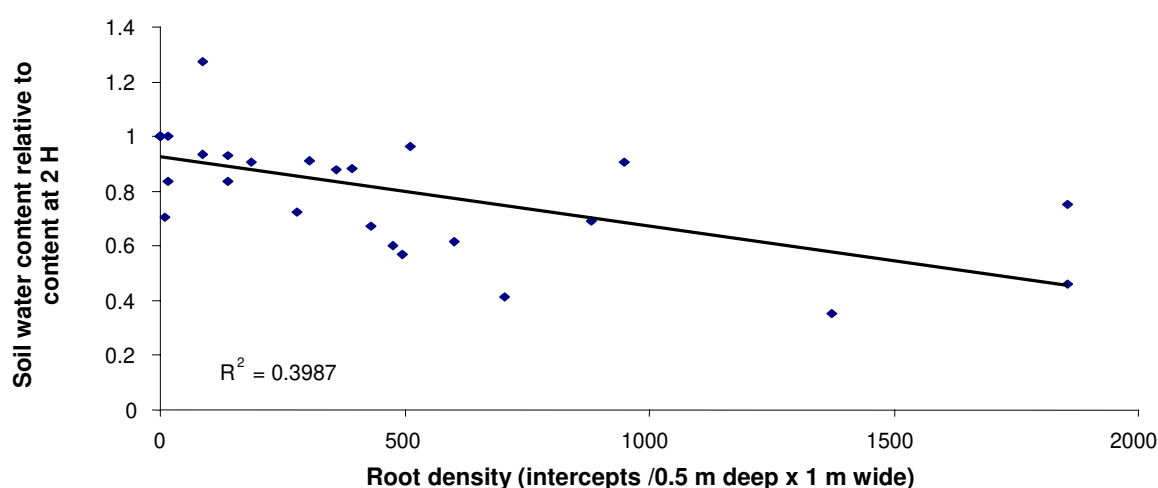


Figure 4.8. Normalised soil water content as a function of root density in the top 0.5 m of the soil profile 0.5-2 H from trees at all sites.

Normalised mean soil water content under the trees (0 H) was greater than at 0.5 H (Figure 4.3.3), this reflects differences in soil water content down the soil profile. As Figure 4.9 shows, soil water content at in the topmost 0.2 m of the soil profile was typically greater than at the same depth further from the trees. At depths greater than 0.3 m, soil water content was least near the trees, and generally increased with increasing distance from the trees.

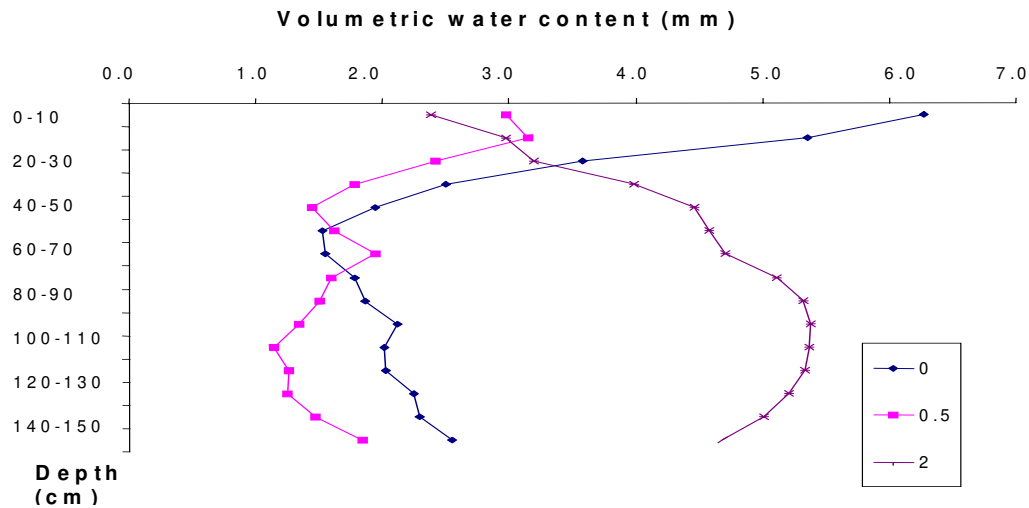


Figure 4.9. Soil water content in the soil profile down to 1.4 m (0.1 m depth increments) at 0, 0.5 and 2 H at Site 7.

4.4 Soil analysis

There was considerable variation in soil chemical conditions at similar distances among sites, this reflected differences in soil type (Appendix 7.9). When soil chemical parameters were normalised at each site using the value at 2 H, mean differences at various distances from the trees were significant for potassium content of the top 0.5 m of the soil profile ($P < 0.001$) and in the top 0.1 m of the soil profile ($P < 0.05$) and Ec of the top 0.1 m ($P < 0.01$) (Figure 4.10). Both potassium content and electrical conductivity (Ec) were greater under the trees than between 0.5–2.0 H. Differences in other parameters were not significant.

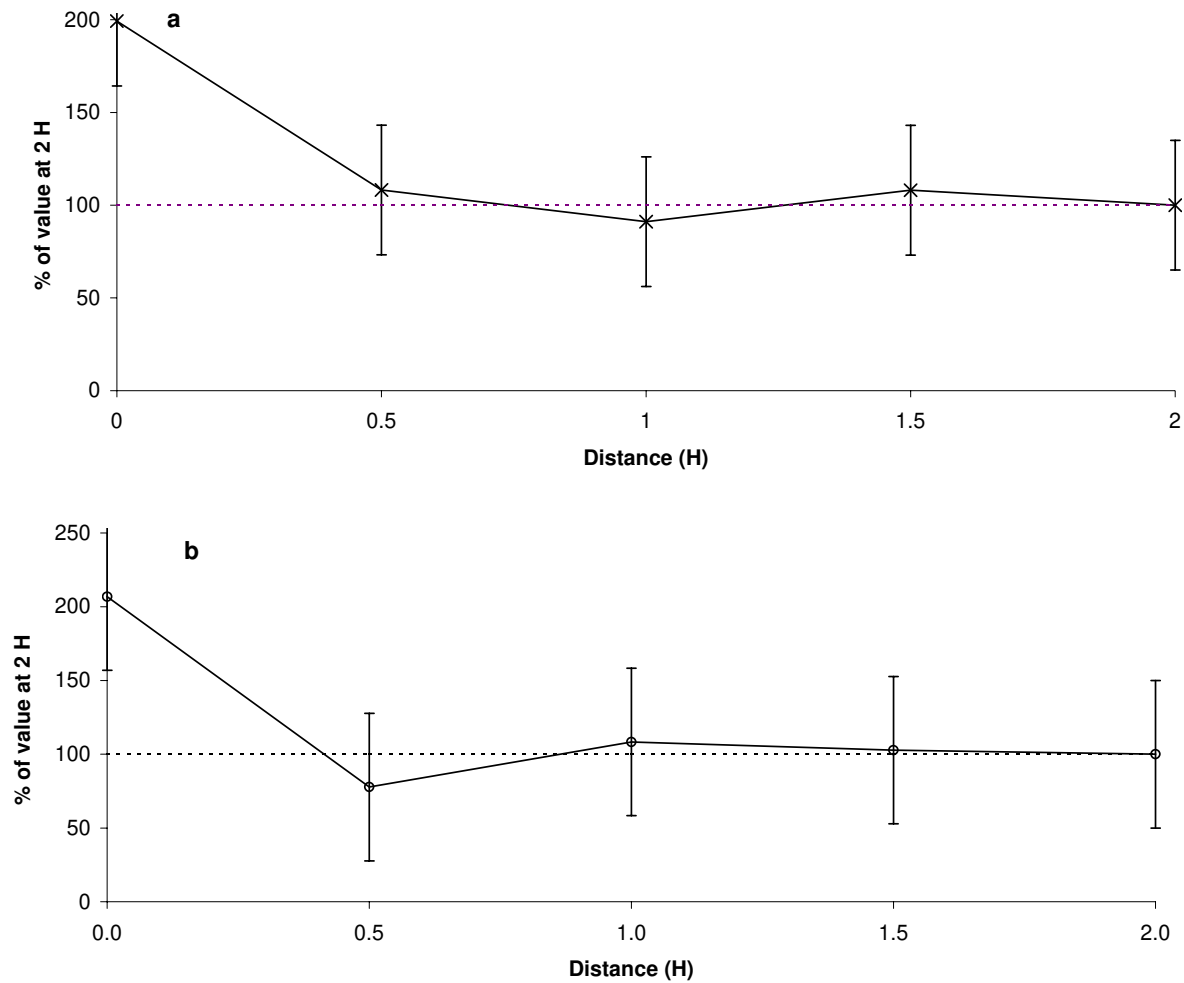


Figure 4.10. Mean (a) potassium content of top 0.5 m of soil profile and (b) Ec in topsoil (0-0.1 m) at various distances from trees, normalised against values at 2 H, at Sites 1,2,3,5,6 and 7. Bars show LSD.

5. Discussion

Measurement of *P. pinaster*, *P. radiata* and *E. globulus* roots in this study have shown considerable differences and some similarities in the extent and distribution of tree roots in adjacent agricultural land. While the lateral extent of tree roots ranged from 18 to 30 m it was strongly correlated to the height of the trees (H) and was between 1.5 and 2 H for all three species (Table 4.1). In terms of absolute distances in metres, the lateral root extent in this study was generally greater than distances measured for eucalypts (Knight, 1999). The lateral extent of tree roots into adjacent agricultural land is often inferred by mapping the extent of reductions in soil water content and crop or pasture productivity near trees (the competition zone). The 1.5-2 H that tree roots were found to extend in this study was generally less than the 2-3 H wide competition zone of trees measured in the Esperance Region by Sudmeyer et al. (in press a and b). It is not clear why this is so, Stirzaker et al (1999) identified a narrow area lying beyond the tree root zone from which water and nutrients can move into the root zone of the trees (the capture zone), however they calculated that that the capture zone would only extend 1-3 m past the tree root zone and crop growth would not be reduced in this area. Studies of *E. globulus* in higher rainfall environments in Western Australia have found the competition zone to

only extend 1 H from the trees (Albertson et al., 2000; P. Sanford, pers. com. 2001). It is not clear if this reflects an absence of tree roots beyond 1 H, or reduced activity of roots extending beyond 1 H. The geographical spread of this study was not great enough to elucidate this. To better understand the mechanisms of tree crop competition there would be some value in further work aimed at understanding how the lateral extent and activity of tree roots is influenced by rainfall, and how crop growth is influenced by lateral movement of water and nutrients in the capture zone.

The literature reports root length density differing among tree species (eg. Jones et al., 1998; Knight, 1999). This study also found differences in the density of tree roots among species at similar distances from the trees (Table 4.1), however because of the small number and the age structure of the trees sampled, it is not possible to separate age and species as factors in determining root density. Although the tree root density varied among the species, the relative distribution of tree roots down the soil profile was generally similar for the three species, and was dependent on soil type. Root density was generally greatest in the top 0.5 m of the soil profile and decreased with depth, this decrease was relatively gradual in the deep sands, but was abrupt in clay subsoils (Figure 4.4). This accords with published reviews of tree root morphology which show that while tree species vary in their maximum rooting depth and ability to access water and nutrients from deep in the soil, the majority of tree roots are found in the upper metre of the soil profile, and the ultimate depth and distribution of root biomass in the soil is determined by interactions between root phenology, soil structure, particularly the presence of impervious layers, the presence of saturated soil zones and rainfall (Canadell et al, 1996; Jackson et al., 1996; Knight, 1999).

Typically, crop growth decreases logarithmically with proximity to trees (Sudmeyer et al, in press a), given the logarithmic increase in root density with proximity to the tree stems found in this study (Figure 4.2), this suggests an inverse correlation between crop growth and the density of tree roots. Reduced crop growth in the competition zone in water limiting environments is primarily due to competition between trees and crops for water (eg. Brenner et al., 1993; Lawson et al., 1995; Gillespie et al., 2000; Sudmeyer et al., in press b). This study found soil water content was generally less near the trees (Figure 4.7), and that the soil water content of the top 0.5 m of the soil profile was negatively correlated to root density (Figure 4.8). This gradient was particularly marked at Site 2, where there was a perched water table (waterlogging) above the clay at 2 H, but not within 1.5 H of the trees. Reduced incidence of waterlogging near trees is beneficial in terms of reducing groundwater recharge from agricultural land (Hall et al., in press). While soil water content deeper than 0.4 m in the soil profile was consistently less within 1.5 H, this was not always so for the topsoil. Measurements made in the weeks following summer rainfall provide some evidence that the shelter provided by the trees (ie. shade, reduced windspeed and leaf litter under the trees) reduced evaporation of soil water and increased the water content of the top 0.2 m of the soil profile (Figure 4.9).

Soil chemistry was generally similar inside and outside the area occupied by tree roots. However the potassium content and electrical conductivity of the soil under the trees was greater than at 2H (Figure 4.10), presumably due to accumulation of potassium and salts derived from through flow and decomposing leaf litter (Sudmeyer, in press b).

It is commonly suggested that competition can be reduced by selecting tree species which have limited lateral root extension and/or are deeper rooted than crops and by cutting (pruning) the tree roots to reduce their density under the crop (Kort, 1988; Hughes and Edwards, 1994; Shroth, 1995). This study suggests that *P. pinaster*, *P. radiata* and *E. globulus* have similar potential to compete with crops given their lateral extent is similar, and all three had the greatest root density within 0.5 m of the soil surface where crop and pasture roots are concentrated. *P. pinaster* may be more competitive because it had the greatest root density of the three species, however, it is not clear how much root density was controlled by tree age. This has implications for agroforestry systems where the ideal tree species use resources that the crop cannot acquire (Cannell et al., 1996; Vandermeer et al., 1998). In economic terms, the presence of high tree root densities in adjacent agricultural land is not a problem if the trees provide products or services with a value similar to or greater than the value of the displaced agricultural product (Cannell et al., 1996; Vandermeer et al., 1998). Consequently the value of timber

products, shelter and reduced ground water recharge needs to be considered as does the value of sequestered carbon should carbon trading eventuate. In the case of *P. pinaster* growing on deep sand, the high root density equated to 42 t of root biomass/km of tree line.

Knight (1999) describes eucalyptus roots as being “opportunistic in their search for water and nutrients”, following moisture gradients up to 20 m into adjacent fields, with vertical roots having the ability to move horizontally towards sources of water. This study tends to confirm this for all three species. Two to four years after the trees had been root pruned, both the extent, density and vertical distribution of roots was similar for pruned and unpruned trees. Crop measurements at Site 1, which had been regularly root pruned since the trees were established, found that root pruning at 0.3 H did not improve crop yield (Sudmeyer et al., in press b). It would appear that the numerous roots present below the depth of pruning continued to grow and rapidly ramified back up though the soil profile so that at 0.5 H root density in the surface layers was similar to unpruned trees. At Site 7, which has a deep duplex soil the first root pruning significantly improved crop yield trees (Sudmeyer et al., in press b). However, 4 years after pruning root densities appear to have largely recovered. The effectiveness of subsequent root pruning will depend on the proportion of roots in the topsoil that originate from deeper unsevered roots and those which have grown back from the severed roots, as only regrowth from severed roots will be able to be severed in subsequent pruning operations. Root pruning would become increasingly ineffective as progressively more shallow roots originate from deeper unsevered roots. It is likely that in the long term root pruning will only remain effective on duplex soils such as at Site 5 where all of the lateral roots can be severed. In the case of deep soils where root pruning has become ineffective it may be that cultivation to at least 0.2 m with an implement such as an Agropow will reduce tree/crop competition.

6. Conclusions

This study suggests that *P. pinaster*, *P. radiata* and *E. globulus* have similar potential to compete with crops given the lateral extent of their roots is similar, and all three have the greatest root density within 0.5 m of the soil surface where crop and pasture roots are concentrated. It is suggested that further work be done to determine if *P. pinaster* has greater root density than the other species at the same age, and how changing root density with age influences crop growth. To better understand the mechanisms of tree crop competition, it would be also useful to undertake further work aimed at understanding how the lateral extent and activity of tree roots is influenced by rainfall, and how crop growth is influenced by lateral movement of water and nutrients in the capture zone.

Root pruning trees will initially reduce the number of roots in the topsoil on all soil types. However, the density of tree roots in the top 0.5 m is rapidly re-established following root pruning. Therefore It is likely that in the long term root pruning will only remain effective on duplex soils where all of the lateral roots can be severed, and that subsequent root pruning is done biannually. On deeper soils the numerous roots present below the depth of pruning will continue to grow and ramify back up though the soil profile reducing the long-term effectiveness of root pruning. In these cases, it may be that annual cultivation to at least 0.2 m with an implement such as an Agropow would reduce tree/crop competition.

7. Appendices

Appendix 7.1. Physical properties of soil at Site 1. Source: Nicholas (pers. com., 2001).

Soil series	Pale deep sand: corinup
Australian Classification	Basic, arenic, bleached-orthic Tenosol
Great Soil Group	
Northcote PPF	
Location	Neridup
Landform	plain
Parent Material	aeolian sand over tertiary sediments grading to weathered palid zone on granite basement
Surface Condition	loose and water repellent

Morphological description

Horizon	Depth (cm)	Description
A11	0-17	dark greyish brown (10YR 4/2) moist fine sand; loose moderately moist consistence; apedal, single grain structure; no coarse fragments; clear, smooth boundary.
A12	17-30	light brownish grey (10YR 6/2) moist, light grey (10YR 7/2) dry fine sand; loose moderately moist consistence; apedal, single grain structure; no coarse fragments; gradual, smooth boundary.
A2e	30-52	very pale brown (10YR 7/4) moist, very pale brown (10YR 7/4) dry fine sand; very weak moderately moist consistence; apedal, single grain structure; no coarse fragments; gradual, smooth boundary.
B21w	52-80	yellow (10YR 7/6) moist humic heavy fine sand; very few fine faint light grey (10YR 7/2) moist mottles; very weak moderately moist consistence; apedal, single grain structure; no coarse fragments; gradual, smooth boundary.
B22w	80-120+	yellow (10YR 7/8) moist fine sand; few fine faint very pale brown (10YR 7/4) moist mottles; very weak moderately moist consistence; apedal, single grain structure; no coarse fragments.

Appendix 7.2. Physical properties of soil at Site 2. Source: Nicholas (pers. com., 2001).

Soil series		Grey deep sandy duplex, Fleming series
Australian Classification		Ferric-Acidic Mesonatric Yellow Sodosol
Great Soil Group		
Northcote PPF		
Location		Esperance
Landform		Hillslope
Parent Material		strongly weathered, unconsolidated material (unidentified)
		tertiary sediments with granite shallow outcrop 100m upslope
Surface Condition		loose and water repellent
Morphological description		
Horizon	Depth (cm)	Description
A1	0-15	dark greyish brown (10YR 4/2) moist sand; very weak moist consistence; single grain structure; many, medium roots; water repellent, non-calcareous; clear, smooth boundary.
A2	15-27	pale brown (10YR 6/3) moist sand; very weak moist consistence; single grain structure; few, fine roots; non-calcareous; clear, smooth boundary.
A3w	27-55	light yellowish brown (10YR 6/4) moist sand; very weak moist consistence; single grain structure; few, fine roots; non-calcareous; gradual, smooth boundary.
A3t	55-77	light yellowish brown (10YR 6/4) moist gravelly sand; weak moist consistence; single grain structure; few, fine roots; 60% rounded ironstone medium gravels; non-calcareous; clear, wavy boundary.
B2tm	77-100+	brownish yellow (10YR 6/8) moist clay loam, sandy; common medium distinct light yellowish brown (2.5Y 6/4) moist redox mottles; weak moist consistence; weak, 10-20 mm, angular blocky and massive structure; no; 10% rounded ironstone medium gravels; non-calcareous.

Appendix 7.3. Physical properties of soil at Site 5. Source: Nicholas and Gee (1998).

Soil series	unnamed minor soil affinities Condingup series
Australian Classification	Mesotrophic, Mesonatric, Yellow, Sodosol;
Great Soil Group	Solonetz
Northcote PPF	Dy 4.43.
Location	Mt Howick National Windbreaks Project Site
Landform	plain
Parent Material	Tertiary marine sediments with additions of aeolian sand to the topsoil (gravels may be transported)
Surface Condition	loose and water repellent

Morphological description

Layer	Depth	Horizon	Description
1	0-40	A1	Light grey; (10YR 7/1 d) fine sand; loose surface; strongly water repellent; loose consistence; pH 6.5; gradual boundary.
2	40-65	A2e	White (2.5Y 8/1 d) fine sand; single grain structure; loose consistence clear boundary.
3	65-90	B21t	Yellow (10YR 7/8 m); medium clay; structured; firm consistence; pH 8.0; gradual boundary.
4	90-110	B22c	Brownish yellow (10YR 6/8 m) light clay; structured; abundant ferruginous segregations 6-20mm size; weak consistence; pH 9.5.

Appendix 7.4. Chemical and physical properties of soil at Site 6. Source: Nicholas and Gee (1998).

Soil series	Corinup 2 series
Australian Soil Classification	Acidic, Arenic, Bleached-Orthic, Tenosol
Great Soil Group	Siliceous Sand
Northcote PPF	Uc 2.21
Location	Mt Howick National Windbreaks Project Site
Landform	edge of sand sheet within a plain slope <1%
Parent Material	Aeolian sand overlying Tertiary marine sediments
Surface Condition	loose and water repellent

Morphological description

Layer	Depth	Horizon	Description
1	0-20	Ap	Greyish brown (10YR 5/2 m); fine sand; loose surface; single grain structure; strongly water repellent; abrupt boundary.
2	20-47	A2e	Very pale brown (10YR M7/3 m), white (10YR 8/1 d); single grain structure; very weak consistence; gradual boundary.
3	47-80	B11	Light yellowish brown (10YR 6/4 m), very pale brown (10YR 8/4 d); few medium faint, dark yellowish brown (10YR 4/6) mottling; clayey fine sand; single grain structure; very weak consistence; slightly cemented; very few ferruginous nodules <2mm size; gradual boundary.
4	80-100	B21w	Yellow (10YR 8/6 d/m); few medium dark yellowish brown mottles (10YR 4/6); clayey fine sand; single grain structure; very weak consistence; gradual boundary.
5	100-130	B22	Yellow (2.5Y 7/6 m); very pale brown (10YR 8/4 d); clayey fine sand; single grain structure; very weak consistence.

Chemical analytical data (<2mm fraction)

Layer	Depth	pH	pH	EC	ECe	Na	Exch. Cations			C.E.C.
	Cm	H ₂ O	CaCl ₂	mS/m	mS/m		K	Ca	Mg	me/100g
1	0-20	5.3	4.6	3	18	0.04	0.02	1.02	0.28	2.2
2	20-47	4.7	4.3	2	20	0.03	0.01	0.24	0.20	1.2
3	47-80	4.5	4.3	3	25	0.05	0.01	0.24	0.21	1.2
4	80-100	4.7	4.5	3	21	0.05	0.02	0.17	0.20	1.1
5	100-130	5.3	4.9	2	14	0.05	0.01	0.15	0.17	0.9
6	130-150	7.5	6.2	8	31	1.78	0.23	0.93	3.25	6.8

Physical analytical data

Layer	Depth cm	Particle Size Distribution %				Bulk density G/cm ³
		Coarse sand	Fine sand	Silt	Clay	
1	0-20	19.5	77.9	1.1	1.5	1.47
2	20-47	15.8	82.1	0.8	1.3	1.495
3	47-80	14.6	82.7	0.7	2.0	1.56
4	80-100	14.3	82.9	0.6	2.2	
5	100-130	14.5	83.8	0.6	1.1	
6	130-150	12.7	64.7	1.4	21.20	

Appendix 7.5. Chemical and physical properties of soil at Site 7. Source: Nicholas and Gee (1998).

Soil series	Condungup series
Australian Soil Classification	Hypocalcic, Mesonatric, Yellow, Sodosol
Great Soil Group	Solodized Solonetz
Dominant PPF	Dy 5.43
Location	Mt Howick National Windbreaks Project Site
Landform	edge of very gently undulating sand sheet within a plain
Parent Material	Tertiary marine sediments with additions of aeolian sand to the topsoil
Surface Condition	loose and water repellent

Morphological description

Layer	Depth	Horizon	Description
1	0-15	Ap	Dark greyish brown (2.5Y 4/2 m) light grey (10YR 7/1 d); fine sand; single grain structure; loose surface; strongly water repellent; abrupt smooth boundary.
2	15-44	A12	Yellowish brown (10YR 5/4 m) light grey (10YR 7/1 d); fine sand, single grain structure; water repellent; very weak consistence; gradual boundary.
3	44-73	A2e	Yellow (2.5Y 7/6 m) (2.5Y 8/2 d) few medium distinct yellowish brown (10YR 5/6) mottles; fine sand; single grain structure; very weak consistence; abrupt boundary.
4	73-78	B1t	Light yellowish brown (10YR 6/4 m); with very pale brown (10YR 8/4 d); fine sandy clay loam; strong columnar structure 200mm size; very strong consistence; clear boundary.
5	78-93	B21t	Light yellowish brown (10YR 6/6 d) common very coarse distinct reddish yellow (5YR 6/8) mottling; fine sand light clay; strong columnar structure 200mm size; very strong consistence; clear boundary.
6	93-114	B22	Olive yellow (2.5Y 6/6 m,d); with common very coarse distinct red (2.5YR 5/8) mottling; fine sandy light medium clay; strong angular blocky structure 50-100mm size; strong consistence; clear boundary.
7	114-143	B3k	Light yellow brown, (2.5Y 6/4); with common very coarse prominent red (2.5YR 4/8) mottling; light clay; strong angular blocky structure 20-50mm size; very firm consistence; few medium carbonate segregations present as linings of relict root channels.

Chemical analytical data (<2mm fraction)

Layer	Depth	pH	pH	EC	ECe	Na	Exch. Cations			C.E.C.
		H ₂ O	CaCl ₂				K	Ca	Mg	
	Cm			mS/m	mS/m		m.e./100g			me/100g
1	0-15	5.1	4.5	3	23	0.04	0.04	0.70	0.29	2.00
2	15-44	4.8	4.4	4	28	0.04	0.03	0.34	0.34	1.5
3	44-73	5.7	5.1	5	45	0.06	0.02	0.28	0.35	1.2
4	73-78	6.5	5.6	25	206	1.82	0.30	1.51	2.90	7.9
5	78-93	7.3	6.4	29	215	2.80	0.43	2.35	4.60	11.8
6	93-114	8.1	7.1	31	225	3.30	0.44	2.53	5.60	12.8
7	114-143	9	7.8	57	290	3.55	0.48	2.85	5.52	12.4

Physical analytical data

Layer	Depth	Particle Size Distribution %				Bulk density
	cm	Coarse sand	Fine sand	Silt	Clay	g/cm ³
1	0-15	18.1	78.7	1.2	2.0	1.3492
2	15-44	16.4	80.8	0.8	2.0	1.0445
3	44-73	14.9	81.9	0.9	2.3	
4	73-78	13.8	61.7	1.6	22.9	1.895
5	78-93	11.9	54.5	1.5	32.1	1.815
6	93-114	9.6	53.5	2.4	34.5	
7	114-143	10.5	49.1	3.2	37.2	

Appendix 7.8. Volumetric soil water content in the top 0.5 m of the soil profile, at various distances from the trees at each site. Distances are expressed as multiples of tree height, 0 H indicates conditions under the trees.

Site	<i>Water content in top 0.5 m of soil profile (mm)</i>					
	distance from trees (H)					
	0	0.5	1.0	1.5	2.0	2.5
1		36.9	37.7	37.8	40.5	
2		46.8	55.2	53.8	76.3	
3	9.9	4.7	7.2	10.5	8.2	
4	8.5	7.0	10.3	14.2	14.3	17.0
5	16.2	16.8	12.8	24.4	36.4	
6	19.6	11.8	16.3	15.4	17.0	
7	21.1	15.4	18.5	18.1	20.4	
Mean (all sites)		19.9	22.6	24.9	30.4	
Mean (sites 3-7)	15.1	11.1	13.0	16.5	19.3	
SE (sites 3-7)	2.5	2.3	2.0	2.3	4.7	

Appendix 7.9. Soil chemistry of topsoil (0-0.1 m) at various distances from the trees.

<i>Distance from trees (H)</i>	<i>Site</i>					
	<i>1</i>	<i>2</i>	<i>3</i>	<i>5</i>	<i>6</i>	<i>7</i>
EC						
0	4	8	8	18	3	7
0.5	2	4	2	6	2	3
1	2	4	2	6	5	6
1.5	2	4	2	10	3	5
2	3	6	2	6	3	4
pH						
0	4.0	5.1	4.8	5.4	4.7	5.1
0.5	5.7	5.0	4.8	4.6	4.3	4.2
1	5.3	5.5	4.8	4.6	4.8	4.6
1.5	5.4	5.6	4.8	5.0	4.9	4.7
2	4.5	4.6	4.8	4.6	5.0	4.7
Org C (%)						
0	0.67	1.39	0.65	1.17	0.55	0.74
0.5	0.58	0.96	0.39	0.59	0.63	0.45
1	0.62	1.06	0.48	0.80	0.73	0.78
1.5	0.56	1.00	0.50	1.03	0.56	1.09
2	0.65	1.22	0.68	0.87	0.58	0.91
total N (%)						
0	0.032	0.102	0.028	0.073	0.028	0.046
0.5	0.036	0.071	0.012	0.039	0.031	0.024
1	0.029	0.087	0.019	0.058	0.034	0.053
1.5	0.029	0.090	0.025	0.078	0.032	0.081
2	0.032	0.095	0.036	0.060	0.031	0.061
P HCO₃ (mg/kg)						
0	3	14	2			
0.5	5	6	8			
1	7	6	2			
1.5	7	10	6			
2	7	10	6			
total P (mg/kg)						
0				67	30	34
0.5	30	68.5		57	21	24
1	35	84.5		54	25	41
1.5	17	82		64	25	55
2				46	32	41
K HCO₃ (mg/kg)						
0	13	65	46	120	17	41
0.5	10	23.5	12	57	14	44
1	10	25	10	74	24	50
1.5	10	24	16	72	16	47
2	10	35	15	54	37	51

Appendix 7.10. Amount of analyte (g) in 1 m² x 1 m deep volume of soil at various distances from the trees.

<i>Distance from trees (H)</i>	<i>Site</i>					
	<i>1</i>	<i>2</i>	<i>3</i>	<i>5</i>	<i>6</i>	<i>7</i>
	Org C					
0	2523	4862	2594	2493	1070	1927
0.5	1854	2884	1411	1835	1363	1124
1	2022	2907	1515	1712	1974	1689
1.5	1997	2825	1562	1913	1122	1889
2	2602	3915	1954	1743	1185	1590
	total N					
0	122	330	106	159	71	118
0.5	136	248	50	110	91	73
1	115	247	60	118	86	112
1.5	119	290	69	152	67	135
2	124	293	86	124	57	110
	P HCO₃					
0	2	16	2			
0.5	2	9	8			
1	4	8	2			
1.5	5	9	6			
2	4	11	6			
	total P					
0				16	11	12
0.5	5	36		16	7	9
1	6	40		16	8	12
1.5	6	36		18	8	12
2				17	8	9
	K HCO₃					
0	9	35	24	43	19	17
0.5	7	19	8	23	11	12
1	7	13	8	19	9	10
1.5	7	14	9	23	11	16
2	7	15	9	20	9	12

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