CSIRO PUBLISHING
www.publish.csiro.au/journals/ajea Australian Journal of Experimental Agriculture, 2005, **45**, 1403–1414

The economics of managing tree–crop competition in windbreak and alley systems

R. Sudmeyer[A,C] *and F. Flugge*[B]

[A]Department of Agriculture Western Australia, PMB 50, Esperance, WA 6450, Australia.
[B]CRC for Plant-based Management of Dryland Salinity, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.
[C]Corresponding author. Email: rsudmeyer@agric.wa.gov.au

Abstract. Re-introducing trees and shrubs into agricultural landscapes as agroforestry systems establishes a tension between long-term objectives, such as increasing shelter, water use, nature conservation and harvesting tree products, and the short-term objective of maximising crop and pasture profitability. This paper describes the growth of crops, pastures and trees at the tree–crop interface in agroforestry systems and the economic returns from alley farming and windbreak systems using various tree–crop competition management strategies in the Esperance region of Western Australia.

Severing lateral tree roots (root-pruning), harvesting mallees and allowing them to coppice, or thinning trees for sawlog regimes increased the yield of crops and pastures in the competition zone. In some instances, these increases were significant: root-pruning increased the annual return from crops grown in the competition zone of *Pinus radiata* by up to \$548/km of the tree line at 1 site. Conversely, root-pruning reduced tree growth by 14–43% across all sites. Therefore, where trees provide benefits, such as shelter from damaging winds, the benefits of reduced tree–crop competition may not offset the consequent reduction in rate of tree growth. For mallee–crop alley systems on agriculturally productive soils, mallee growth rates must be high enough to compensate for crop losses in the competition zone. On less agriculturally productive soils, block-planting mallees may be more profitable than alley systems or crops without competition (sole-crops).

This research has shown that competition management strategies can be used to manipulate the relative productivity of trees, crops and pasture at the tree–agriculture interface. The use of these strategies will depend on the relative economic value of tree and crop products and the value placed on other tree benefits, such as shelter and reduced groundwater recharge.

Additional keywords: coppicing, oil mallees, root-pruning, tree–crop interactions.

Introduction

Trees and shrubs are planted into agricultural landscapes as commercial crops and/or for conservation benefits. In the medium and low rainfall areas of Western Australia, the greatest impetus has come from the need to reduce groundwater recharge (Hatton and Nulsen 1999). In recent estimates, 18% of cleared agricultural land in Western Australia is currently at risk from salinity, with the area expanding to 33% by 2050 (Short and McConnell 2001).

Increasing the area of land occupied by perennial plants and protection of existing native remnants probably provides the most promise for increasing water use and diversifying farm incomes without the problems posed by saline water disposal (George *et al*. 1997). To be most effective in minimising recharge, perennials need to be dispersed across the landscape and integrated into conventional agricultural systems. Agroforestry may be a method of doing this if financially acceptable systems can be offered to farmers. Australian research has shown windbreaks can be profitable where strong winds damage crops (Jones and Sudmeyer 2002), and growing mallee eucalypts to produce oil and biomass has been identified as a commercially viable agroforestry option for low rainfall agricultural areas (Zorzetto and Chudleigh 1999; Enecon 2001). The preferred layout for alley systems is 4-row (10-m-wide) hedges with alley width determined by site, rainfall and farmer preference (D. Cooper pers. comm.). Both windbreak and alley systems maximise the proportion of edge trees with the concomitant productivity and environmental benefits of greater shelter, tree growth and water use. The disadvantage is that tree–crop competition may reduce crop growth in the competition zone next to the trees (Huth *et al*. 2002; Sudmeyer *et al*. 2002*a*; Sudmeyer *et al*. 2002*b*; Woodall and Ward 2002; Unkovich *et al*. 2003).

Whatever the area of perennial vegetation required, the problem arises of how much revegetation with trees is

 10.1071/EA04155 0816-1089/05/111403

financially acceptable to the farming community *v.* how much salinity is financially, environmentally and socially acceptable to the farming and wider community. For land managers, there is a tension between managing agroforestry systems to realise long-term objectives, such as increasing shelter, water-use, nature conservation and harvesting tree products, and the short-term objective of maximising crop and pasture profitability. Research in Western Australia has shown that cutting lateral tree roots (root-pruning) can improve crop production in the competition zone in some situations (Sudmeyer *et al*. 2002*b*; Woodall and Ward 2002).

This paper describes the growth and economics of crop, pasture and trees in agroforestry systems with and without various tree–crop competition management strategies.

Methods

Sites

This study was conducted at 10 sites in the Esperance region of south-west Western Australia between 1999–2003. Three sites were planted with mallee hedges: *Eucalyptus kochii* Maiden & Blakely subsp. *plenissima* (C. A. Gardner) Brooker (Koch's mallee), *E. polybractea* R. Baker, (blue-leaved mallee) and *E. loxophleba* Benth. subsp. *lissophloia* L. A. S. Johnson & K. D. Hill in alley layouts; 2 sites with *E. globulus* Labill. (Tasmanian blue gum) timberbelts, 2 sites with *Pinus radiata* D. Don (Monterey pine) windbreaks, 1 site had a remnant block of native vegetation and 1 site had a eucalypt windbreak (Table 1).

Treatments

Competition was managed by reducing the lateral extent of tree roots (root-pruning) or reducing the leaf area of the trees (thinning and high-pruning trees or coppicing mallees). Table 2 outlines the treatments and when they were applied at each site. Treatment plots were randomised within replicate blocks. Treatment plots were 50 m long and replicated 3 times along a single tree line at sites 1–5 and 8. Treatment plots were 25 m long and were replicated 4 times at sites 6, 7 and 9, with treatment blocks located along 3 hedges at sites 6 and 7 and 4 hedges at site 9. Distances from the trees are expressed as multiples of tree height (H).

A trailed ripping implement was used to prune lateral tree roots to a soil depth of 0.7 m. The larger trees were root-pruned at 0.5 H (pruning at this distance did not increase tree mortality), the mallees at sites 6, 7 and 9 were root-pruned 1.5 m from the stems. Root barriers were installed 5 m from trees at sites 1 and 1a, and 1.5 m from mallees at site 6. The barriers were intended to completely exclude regrowing tree roots (this approximated annual root-pruning at sites 2, 3 and 5). The barriers were polyethylene sheets installed from the surface to a soil depth of 0.8 m, in 0.2-m-wide trenches that were back-filled with soil. Cultivation damaged the upper 0.15 m of the barriers and any lateral tree roots growing over the barriers were pruned in 2001. The root barrier and root-pruning treatments were applied during the summer months; mallees at sites 6, 7 and 9 were harvested at ground level in spring and allowed to coppice. Trees at site 4 were thinned and branches pruned up to 5 m during the summer of 1999.

Crop and pasture growth

Grain yield or pasture biomass were assessed at sites 1–8 (Table 1). Measurements were made at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 H, except at site 6 where they were made 2, 3, 5, 7 and 10 m from the hedges. Wheat, barley and lupin grain yield were determined by harvesting 1.6 m wide by 25 m long (15 m long at sites 6 and 7) plots running parallel to the trees at each measurement distance. Canola and sorghum yields at sites 1 and 1a were determined from 1 m^2 hand cuts (n = 5) collected at each distance.

The standing pasture biomass (food on offer) was measured at regular intervals throughout the growing season at the same distances that crop yield was measured. These assessments did not account for pasture eaten by stock between measurement dates. Pastures were re-established at site 4 in 2001 and at site 5 in 2002, and were not grazed for several months. Accordingly, for that year a single biomass measurement was made immediately prior to sheep being introduced to the pasture. For each site, sheep grazing days were then estimated using the measured biomass at various distances from the tree lines for each treatment. While these estimates provide some indication of site productivity, they are best used to illustrate relative differences between treatments rather than as an absolute measure of pasture productivity.

Crop yield and pasture biomass more than 3 H from the larger tree species was considered to be unaffected by tree competition while competition was assumed to extend 10 m from the control mallees (sites 6 and 7). These assumptions were based on the extent of competition next to trees as reported in Sudmeyer *et al*. (2002*a*, 2002*b*) and the extent of tree roots measured at these and other sites (Sudmeyer *et al*. 2004).

Tree productivity

Tree growth was assessed each year in spring from 1999 to 2003. At sites 1–4, tree height and stem diameter over bark at breast height were used to estimate stem volume by assuming the stem was conical in

Table 1. Details of experimental sites and species planted in the Esperance region of Western Australia

Trees were measured at yearly intervals from 1999 to 2003, and agricultural measurements (C, crop; P, pasture; —, no measurement) were recorded from 1999 to 2002

Site	Site location	Mean annual rainfall (mm)	Speciesd planted	Year planted	Tree height (m)	Tree layout[A]	Agricultural measurement
1	122°03′E 33°37′S	500	*P. radiata*	1986	12–14	2-row WB	C,C,C,C
1a	122°03′E 33°37′S	500	*P. radiata*	1986	12–14	2-row WB	C,C,C,C
2	121°43′E 33°33′S	475	*P. radiata*	1993	11–13	20-row TB	C,C,C,C
3	121°45′E 33°33′S	475	*E. globulus*	1994	9–15	12-row TB	C,—,P,P
4	122°15′E 33°40′S	525	*E. globulus*	1993	11–16	12-row TB	C,C,P,P
5	121°47′E 33°36′S	496	*Eucalyptus spp.*	1991	7–9	2-row WB	C,C,C,P
6	122°04′E 33°26′S	386	*E. kochii*	1993	2–4	2-row hedge 20-m-wide alleys	C,C,C,C
7	121°36′E 32°59′S	342	*E. loxophleba*	1995	2–3	4-row hedge 50-m-wide alleys	—,—,C,P
8	121°37′E 32°59′S	342	*Eucalyptus spp.*	—	7	Remnant block	—,—,C,P
9	121°44′E 33°14′S	400	*E. polybractea*	1994	1–2	2-row hedge 10-m-wide alleys	—,—,—,—

[A]WB, windbreak; TB, timberbelt.

shape. Tree height only was determined at site 5. At sites 6, 7 and 9, height [ground to uppermost leaves (h)], and the width of the canopy along (d_1), and perpendicular to (d_2) the orientation of the hedge were measured each year and used to estimate the above-ground biomass. Canopy volume (h x d_1 x d_2) was related to the above-ground biomass of harvested mallees at each site and explained 91% of the variability in fresh weight at sites 6 and 7, and 86% at site 9.

Measurement plots were 25 m long at sites 1–6 and 15 m long at sites 6, 7 and 9. Both rows of the windbreak or hedges were measured at sites 1, 6 and 9, 1 outer row at site 5 and the outer 2 rows at sites 2–4 and 7.

Differences in tree growth among treatments at each site were tested using analysis of variance with stem volume or biomass at the start of the trial as a covariate in GenStat version 7 (Lawes Agricultural Trust, Rothamsted Experimental Station, Hempstead, UK).

Economic analysis

The economic analysis was performed in 3 stages. Firstly, to examine the economic value of the various competition management strategies as they were applied to each particular site, which provided an indication of the variability in value and why this was so. Secondly, to take a more general look at competition management strategies in a generic mallee alley agroforestry system, and thirdly, to examine the value of the shelter provided by mallee hedges with and without competition management strategies. Benefit–cost analysis (discounted cashflow using a 7% discount rate) was used to evaluate the treatments at each site.

In the first stage, the distance from the trees to where the return from the crop or pasture enterprise equalled the cost of production (breakeven yield) was calculated for the alternative management strategies. Additionally, the net present value (the value of the project expressed as the sum of annual discounted net returns, NPV) and the annual equivalent return (the annual equivalent of the net present value, AER) of net extra benefits was calculated for each strategy. For the purposes of this analysis, the crop response to the installation of a root barrier was considered similar to the response to annual root-pruning. Accordingly, the cost associated with annual root-pruning was assigned to the barrier treatment. The assumptions used are shown in Table 3.

In the second stage, the economic value of growing mallees in an alley system with annual crops was evaluated for 2 competition management strategies. The *Imagine* Spreadsheet Model (Abadi *et al*. 2003) was used to compare the profitability over 30 years of mallee alley systems employing coppicing only or coppicing and root-pruning for 2 soil types at site 6. For each of the scenarios, the NPV, AER, breakeven period, peak debt and years until peak debt were calculated. The assumptions used in the analysis are shown in Table 4.

Treatment replicates at site 6 were located on soils with sandy A horizons between 0.7–2.0 m deep (deep sand) or less than 0.5 m deep with a clay subsoil (duplex soil). As the mallee hedges at site 6 were 2 rows wide, the biomass yield from 4-row, 10-m-wide hedges was estimated using the actual growth data for the outer rows and assuming that the growth rates of inner rows were similar to those of root-pruned mallees, i.e. no access to additional resources in competition zone (Table 5). Biomass growth of mallee blocks was also assumed to be similar to the growth of root-pruned hedges. This probably overestimated the yield of hedges and blocks growing on deep sand as

Table 2. Experimental treatments and the year(s) they were applied at each site

Site	Treatments applied	Years treatments applied
1, 1a	Control	
	Root barrier	1999, barrier installed; 2001, root-pruned
	Root-pruned	1999
2, 3, 5	Control	
	Root-pruned annually	1999, 2000, 2001, 2002
	Root-pruned	1999
4	Control 850 stems/ha	
	Thinned 125 stems/ha	1999
6	Control	
	Root barrier	1999, barrier installed; 2001, root-pruned
	Root-pruned	1999, 2001
	Coppiced	1999, 2000
	Coppiced and root-pruned	1999, 2000, coppiced; 1999, 2001, root-pruned
7	Control	
	Root-pruned	2001
	Coppiced	2001
	Coppiced and root-pruned	2001
8	Control	
	Root-pruned	2001
9	Control	
	Root-pruned	1999 (0.3 m deep), 2001 (0.7 m deep)
	Coppiced	1999, 2000

Table 3. Assumptions made in determining the economic response of crops and pasture to competition management

Grain prices and variable costs of production were obtained from Anon. (2002), and the value and costs of pasture production are estimates (M. O'Connell pers. comm.)

Variable	Value
Interest on borrowed money (%)	9
Marginal tax rate (%)	20
Farm-gate value of enterprise; Esperance sandplain	
Barley ($/t)	150
Canola ($/t)	335
Lupin ($/t)	160
Sorghum ($/t)	150
Wheat ($/t)	175
Lucerne pasture ($/t)	100
Variable cost of production; Esperance sandplain	
Barley ($/ha)	175
Canola ($/ha)	290
Lupin ($/ha)	145
Sorghum ($/ha)	125
Wheat ($/ha)	205
Lucerne pasture ($/ha)	50
Farm-gate value of enterprise; Northern Mallee	
Wheat ($/t)	170
Annual pasture ($/t)	120
Variable cost of production; Northern Mallee	
Wheat ($/ha)	120
Annual pasture ($/ha)	40
Cost of root-pruning tree lines ($/km.side)	15
Cost of cutting mallees to ground level ($/km)	30
Cost of thinning and high-pruning *E. globulus*	0 (cost borne by silvicultural regime)

Table 4. Assumptions made in determining the economic response of crops and mallees to competition management using the Imagine Spreadsheet Model

The cost of root-pruning is shown as $/ha of hedge and was calculated using a cost of $15/km of tree line (one side)

Variable	Value	Year(s) of occurrence
Oil mallee		
Hedge width (m)	10	
Alley width (m)	110	
Site preparation ($/ha)	420	0
Seedlings and planting ($/ha)	1000	1
Weed control ($/ha)	38	1, 2
Pest control ($/ha)	33	1, 2
Insurance ($/ha)	5	Annual
Firebreak maintenance ($/ha)	5	Annual
Annual maintenance ($/ha)	10	Annual
Root-pruning ($/ha)	30	Every 2nd year
Harvest cost ($/t)	10	Every 3rd year
Transport cost ($/t)	5	Every 3rd year
Biomass price ($/t)	30	Every 3rd year
Wheat		
Variable cost of production ($/ha)	205	Annual
Farm-gate value of commodity ($/t)	175	Annual
Lupin		
Variable cost of production ($/ha)	145	Annual
Farm-gate value of commodity ($/t)	160	Annual

lateral roots below the depth of root-pruning would have remained uncut (Sudmeyer *et al*. 2004), providing access to additional resources unavailable to mallees in blocks or inner rows.

The sole-crop yields (i.e. yields of crops grown without competition) for each soil type are based on yields of crops grown in the centre of alleys with barrier or coppiced and pruned treatments i.e. subject to minimal competition. Crop yields in the 10-m-wide competition zone next to coppiced, and coppiced and root-pruned trees are yield data for each treatment and soil type expressed as a percentage of the sole-crop yield (Table 6).

The third stage of economic analysis used a windbreak model (Jones and Sudmeyer 2002) to examine the effect of competition management strategies on agricultural returns from a windbreak system over 35 years. The model calculates cumulative agricultural production and net income from land with windbreaks as percentages from the same area without windbreaks. The model simulates the effect of root-pruning and/or severe wind damage on crop yield (where severe damage was set as open yield being reduced by 80%). The NPV and AER were calculated for different scenarios. In this analysis, the assumptions used in the model were essentially the same as used by Jones and Sudmeyer (2002) (Table 7), except that data from sites 1–3 and 5 were used to determine the crop response to root-pruning for tree windbreak systems and the height growth of root-pruned trees was set at either 100 or 75% of the standard growth curve in the model.

This model was also used to assess the AER of crops grown in 110-m-wide alleys between mallee hedges or sole-crops, with varying numbers of years with wind damage. Data from site 6 were used to determine the mean crop yield within 10 m of the hedges in the 3 years after each harvest. The extent of the competition zone and sheltered area varied as the height of the mallees varied from 0.5 m in first year after coppicing, to 2 m, 3 years after coppicing. The area occupied, and costs associated with planting and harvesting the mallee hedges was not included in this analysis as the model was not designed to handle the repeated income from harvesting the mallees.

Results and discussion

Crop and pasture growth

Where competition was not managed, reductions in crop yield or pasture growth extended up to 32 m from the taller tree species (generally 1.5–2 H) and 10 m (3–4 H) from the mallees (Table 8). The extent of these reductions largely corresponded to the lateral extent of tree roots at those sites where tree root extent was measured (Sudmeyer *et al*. 2004). Crops were not usually sown within 0.5 H of the larger tree species (because of fences or overhanging branches), while the uncropped area next to mallee hedges ranged between 1.5–2 m depending on the width of the mallee canopy. If the uncropped area alongside the trees or hedges is disregarded, mean crop and pasture yield within 3H (10 m for mallees) was 50–79% of the yield obtained outside the competition zone (Table 8). Consequently, crop and pasture yields 5–20 m (0.5–2 H) from the larger tree species and 8–10 m (3–4 H) from the mallees were below breakeven (Table 9). The extent and magnitude of these yield reductions were

Table 5. Annual biomass production (fresh, above-ground biomass) and total height growth of mallees 3 years after coppicing or coppicing and root-pruning at site 6

Values are estimates for 4-row (10 m) wide hedges which include 2 m of uncropped land along each side of the hedge. Estimates are based on measured growth of 2-row hedges (outer rows) plus values for 2 inner rows based on the growth of root-pruned outer rows

The biomass of block plantings is for mallees planted in rows 2 m apart and is an estimate based on the growth rates of root-pruned hedges. These values may overestimate the actual growth of root-pruned hedges and block-plantings on deep sand

Soil type	Treatment of Mallees at site 6				Mallee block
	Coppiced		Coppiced and root-pruned		Annual biomass growth (t/ha)
	Annual biomass growth (t/ha)	Height at year 3 (m)	Annual biomass growth (t/ha)	Height at year 3 (m)	
Duplex	10.0	2.0	6.1	1.6	7.6
Deep sand	10.8	2.2	10.4	2.1	13.0

Table 6. The yield of crops 2–10 m from coppiced or coppiced and root-pruned mallee hedges at site 6

Values are means for the 3 years following coppicing and are expressed as percentages of crop yields without competition (sole-crop). Sole-crop values are means over 2 years for each crop

Soil type	Coppiced (% of sole-crop)	Coppiced and root-pruned (% of sole-crop)	Sole-crop (t/ha) Wheat	Lupin
Duplex	50	87	2.1	1.2
Deep sand	54	54	0.8	0.8

similar to those measured in other Australian studies (George-Jaeggli *et al*. 1998; Huth *et al*. 2002; Sudmeyer *et al*. 2002*a*; Unkovich *et al*. 2003). It should be noted that the lateral extent of mallee roots at site 6 was 10 m (4 H) when measured in 2000 (Sudmeyer *et al*. 2004). This would have increased to 15 m by 2002 if the relationship between tree height and root extent remained unchanged [root extent = 3.7 x (tree height, m)]. Consequently, for site 6, only data from 1999 are presented in Table 8. Subsequent economic analysis using data from site 6 is based on the assumption that the width of the competition zone adjacent to coppiced mallees did not exceed 10 m as mallee height did not exceed 2.2 m.

Root-pruning or reducing tree leaf area, by coppicing mallees or thinning trees, improved crop yields within the competition zone. When tree roots were pruned once and allowed to regrow over 4 years, crop and pasture yields within 3 H increased to 38–95% of yields at 3–5 H [similar increases were reported by Sudmeyer *et al*. (2002*b*) and Woodall and Ward (2002)], while yields increased to 49–93% for mallees root-pruned every 2 years (data not shown). These improvements in yield moved the crop or pasture breakeven point closer to the trees; in many cases the breakeven yield was achieved at the same distance trees were root-pruned (Table 9). The AER from crops and pasture growing in the competition zone of trees root-pruned once in 4 years was up to \$193/km more for unpruned trees, and \$27/km more than that of mallee hedges root-pruned biannually (Table 10). Root-pruning decreased AER at site 5 only, a result of increased waterlogging in the competition zone in 1999.

Yield increases in the competition zone were generally less in the first year after root-pruning or coppicing than in later years (Figs 1 and 2), presumably because the soil remained drier going into the first cropping season (D. Hall unpublished data). This was particularly evident for mallees coppiced in spring when soil–water deficits developed (Fig. 2). Yields were greatest in the second year after pruning or coppicing and then began to decline (the closer to the tree, the greater the decline) as roots regrew; this trend was more rapid next to root-pruned mallees (Fig. 2). Annual root-pruning (or a root barrier) maintained crop yields within

Table 7. Assumptions made in determining agricultural income from windbreak system

Variable	Value
Agricultural response to shelter and root-pruning	Values from Sudmeyer *et al*. (2002*a*) and sites 1–3 and 5
Residual unprotected production after wind damage (%)	20
Maximum sheltered distance (H[A])	44
Standard cropping total costs (\$/ha)	120
Gross potential returns from cropping (\$/ha)	320
Cost of preparing crop land (\$/ha)	100
Cost of re-sowing crops after wind events (\$/ha)	25
Cost to repair infrastructure after wind events (\$/ha)	10
Cost of establishing windbreak (\$/ha)	807
Number tree rows in windbreak	3
Cost of root-pruning (\$/km for one side)	15
Distance between windbreaks in tree system (maximum tree H[A])	34
Tree growth	Average for the SE coast of WA
Tree density in windbreak (trees/ha)	1000
Distance from tree line uncropped (H[A])	0.5
Distance between mallee hedges (m)	110
Mallee growth	Data from site 6
Distance from mallee hedge uncropped (m)	2

[A]Multiples of tree height.

Table 8. The competition zone next to unmanaged tree lines and the mean crop yield from the edge of the crop to 3 multiples of tree height (H) (4 H at sites 6 and 7)

Measurements made between 1999 and 2002 in the Esperance Region of Western Australia. Note: mean crop yield does not account for the area of uncropped land next to the trees

Site	Competition zone (m)	Mean crop yield (% of yield outside competition zone)
1	17–27	56
1a	13–26	63
2	13–21	74
3	22–30	67
4	11–32	64
5	0–22	79
6	10[A]	51[A]
7	8–10	50
8	14–18	59

[A]Data from 1999 when root extent equalled 10 m.

the competition zone. Where tree roots were not allowed to regrow, the AER from crops and pasture in the competition zone of trees was up to \$309/km more, or \$72/km more for mallees compared with unpruned trees or mallees. These results suggest that biannual root-pruning would most increase AER in the competition zone of trees, while annual root-pruning would most improve AER within the competition zone of mallees.

Coppicing mallees or thinning *E. globulus* resulted in crop and pasture yield gains similar to those seen for root-pruning. This is of particular relevance at those sites where trees were growing on deep sands (i.e. sites 3, 4 and 6). Evidence from this study (Table 6) and another trial in the region (Sudmeyer *et al*. 2002*b*) suggests that root-pruning becomes ineffective on deep sands where lateral roots deeper than 0.7 m are left uncut and ramify back through the topsoil (Sudmeyer *et al*. 2004).

In terms of agricultural returns, the financial benefits of competition management strategies generally increased with tree height (tree height being proportional to the width of the competition zone) and site productivity (i.e. the dollar value of losses in the competition zone was greater at more productive sites). Consequently, the return from root-pruning trees was greater than from mallees, and while coppicing and root-pruning mallees resulted in a greater AER than coppicing alone at site 6, the combined cost of the 2 treatments was not offset by increased yields at the relatively less productive site 7.

Tree growth

Root-pruning reduced the growth of 2-row windbreaks or uncoppiced mallee hedges, and the outer 2 rows of timberbelts by 14–43%, while the growth of root-pruned and coppiced mallees was reduced by 14–34%. These reductions were significant at sites 1, 6 and 9 (Table 11). At site 6, mallees growing on deep sand were less affected by root-pruning than those on duplex soil (Table 5), presumably because in deep sand, some lateral roots were below the depth of the ripper and remained uncut (Sudmeyer *et al*. 2004) while in the duplex soil, all lateral roots were cut. These data demonstrate the value of the additional resources available to trees growing on the edge of unpruned belts or hedges.

Despite the availability of resources from within the competition zone, the yields of trees and mallees at the sites in this study were generally less than those considered commercially viable (Burnage 1996; Enecon 2001; Abadi and Cooper 2003). As commercial tree harvesting has not yet begun in the Esperance region, the effect of such yield reductions can only be gauged from published economic studies or modelling.

Alley farming with mallees

The relative productivity of crops and mallees, and the effectiveness of competition management strategies were

Table 9. The distance (m) from trees at which the net present value of the alley crop/pasture was equal that of the sole-crop

Values are given as single measurements or the range of measurements obtained during the measurement period

Site	Treatment strategy					
	Control	Root-pruned 1999 or 2001	Root barrier or root-pruned annually	Trees thinned 1999	Mallees coppiced	Mallees coppiced and pruned
1	15–18	8[A]–10	8[A]–9			
1a	10–15	8[A]–12	8[A]–11			
2	7–10	6[A]	6[A]			
3	9–13	6[A]–13	7[A]–13			
4	13–20			6[A]–13		
5	5–16	4[A]–15	4[A]–9			
6	>10	5–6	2[A]		6	2[A]
7	8–10	2[A]–4			2	1.5[A]
8	7–14	4[A]				

[A]Break-even yield occurred at the edge of the crop or at the distance root-pruned.

Table 10. Increase in annual equivalent return ($/km) from crops and pasture within the competition zone of trees according to the treatment strategy for managing competition

Values are for 1 side of tree line only

Site	Treatment strategy				
	Root-pruned 1999 or 2001	Root barrier or pruned annually	Trees thinned 1999	Mallees coppiced	Mallees coppiced and pruned
1	193	309			
1a	118	239			
2	47	77			
3	97	149			
4			104		
5	–14	–1			
6	27	72		16	51
7	13			4	–5
8	79				

strongly influenced by soil type at site 6. The deep sand presented a number of challenges for cropping compared with duplex soil: it was non-wetting, prone to wind erosion and had less water-holding capacity. Consequently, the AER from sole-crop on the deep sand was –$59/ha, compared with $97/ha on the duplex soil (Table 12). Conversely, mallee growth was generally greater on the deep sand and only unpruned hedges on deep sand exceeded the breakeven mean yield (10.7 t/ha.year).

Economically, there was no advantage to combining crops and mallee hedges in alley systems on either soil type. On duplex soil, sole-cropping was most profitable followed by the root-pruned alley system then the unpruned alley system, with block-planted mallees least profitable (Table 12). Conversely, on deep sand, block-planted mallees were most profitable, followed by sole-cropping, the unpruned alley system with the pruned alley system least profitable. While the estimated growth rate of block-planted mallees on deep sand is probably an overestimate, block-planting would still be the most profitable option even at the much lower mallee growth rate estimated for duplex soil. Root-pruning increased the AER from the alley system by $9/ha on the duplex soil as the increased crop yield in the competition zone offset decreased mallee growth, but decreased AER by $2/ha on the deep sand, as crop yield in the competition zone was not improved and mallee growth was reduced.

Sensitivity analysis revealed that for the AER from the alley system on duplex soil to equal the AER from sole-crop, unpruned mallee hedges must yield 33.3 t/ha.year and root-pruned hedges 23.3 t/ha.year over the harvest cycle. Even if the tree–crop competition was completely eliminated, mallee yield must be 17.7 t/ha.year for the AER from the alley system to equal that from the sole-crop. These values reflect the 2 m of uncropped land alongside the mallee hedges and the size of the competition zone. Increasing the hedge and alley width, thereby decreasing the area of the competition zone and uncropped area per unit area of mallee hedge, may amend this problem. For example, when the width of the mallee hedges is increased to 20 m (9 rows with 2 m uncropped) and alley width is doubled, the AER from the alley system is increased to $75 for unpruned hedges and $80 for pruned hedges. It should be noted that mallee yields greater than 23.3 t/ha.year may not be widely achieved in the Esperance region; estimated yields from unpruned 10-m-wide mallee hedges at sites 7 and 9 were 1.9 and 3.6 t/ha.year, respectively.

Table 11. Effect of treatment strategies for managing competition on annual tree and Mallee hedge growth

Values are mean growth (adjusted for starting stem volume, height or biomass) during 1999–2003 at sites 1–6 and 9 and 2001–2003 at site 7
The uncropped area alongside the tree line or hedge has been included when calculating tree growth on an area basis
At sites 1–3, trees in the outer 2 rows and at site 5, trees in the outer row were included in growth calculations
Values within each row followed by the same letter are not significantly different (P>0.05)

Treatment strategy	Stem volume (m^3/ha)			Tree height (m)	Above-ground biomass (t/ha)		
	Site: 1 and 1a	2	3	5	6	7	9
Control	39.9a	25.2	145	1.95	85.9a	4.7	17.4a
Root-pruned 1999 or 2001	22.7b	17.6	–	1.53	55.7b	3.5	–
Root barrier or pruned annually	22.7b	16.6	126	1.72	51.2b	–	13.0b
Mallees coppiced	–	–	–	–	33.8c	2.2	12.6b
Mallees coppiced and pruned	–	–	–	–	22.4d	1.9	–

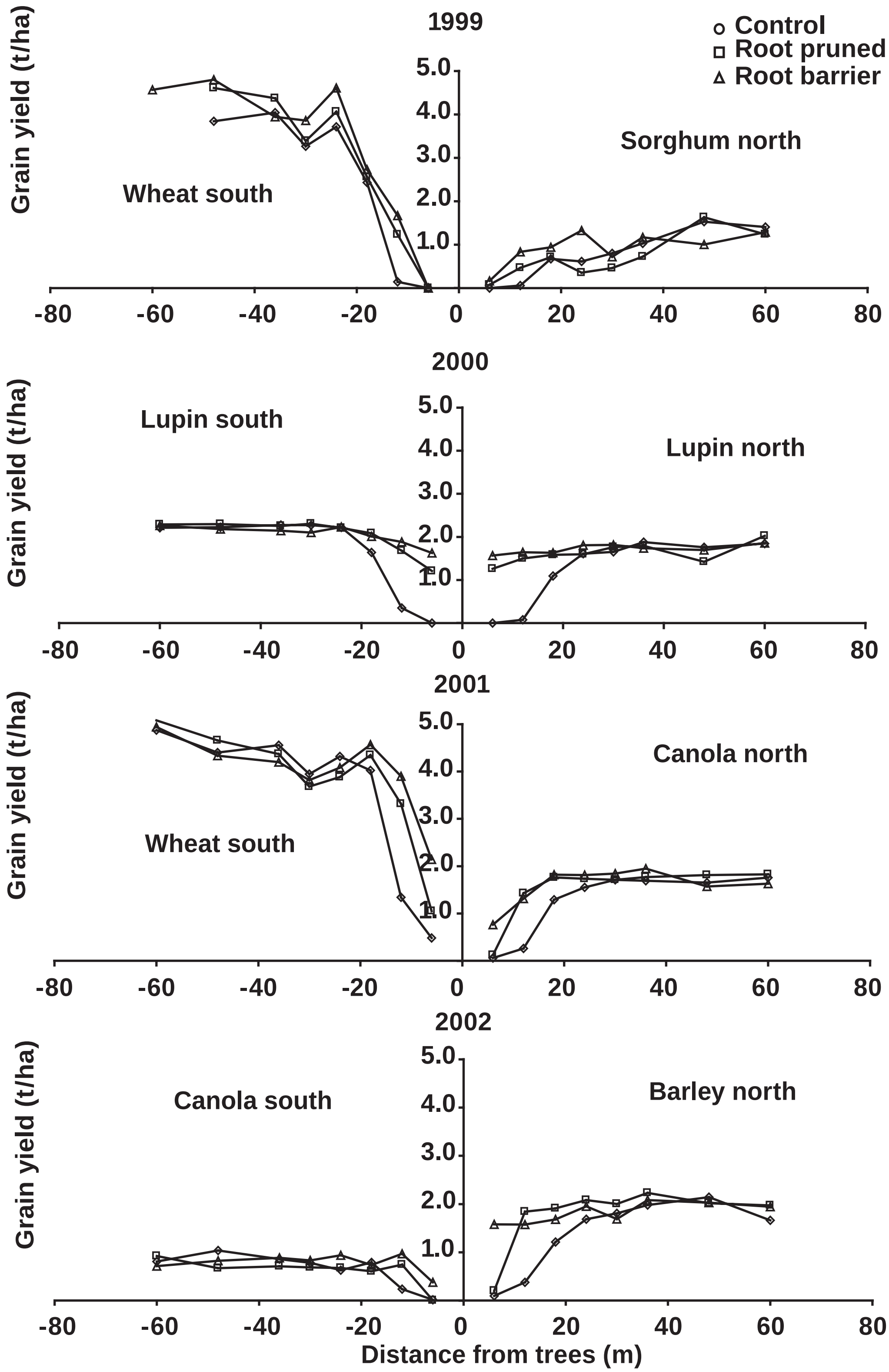

Figure 1. Esperance region 1999–2002. The grain yield of various crops growing on the north (site 1) and south (site 1a) sides of a *P. radiata* windbreak with various competition management strategies.

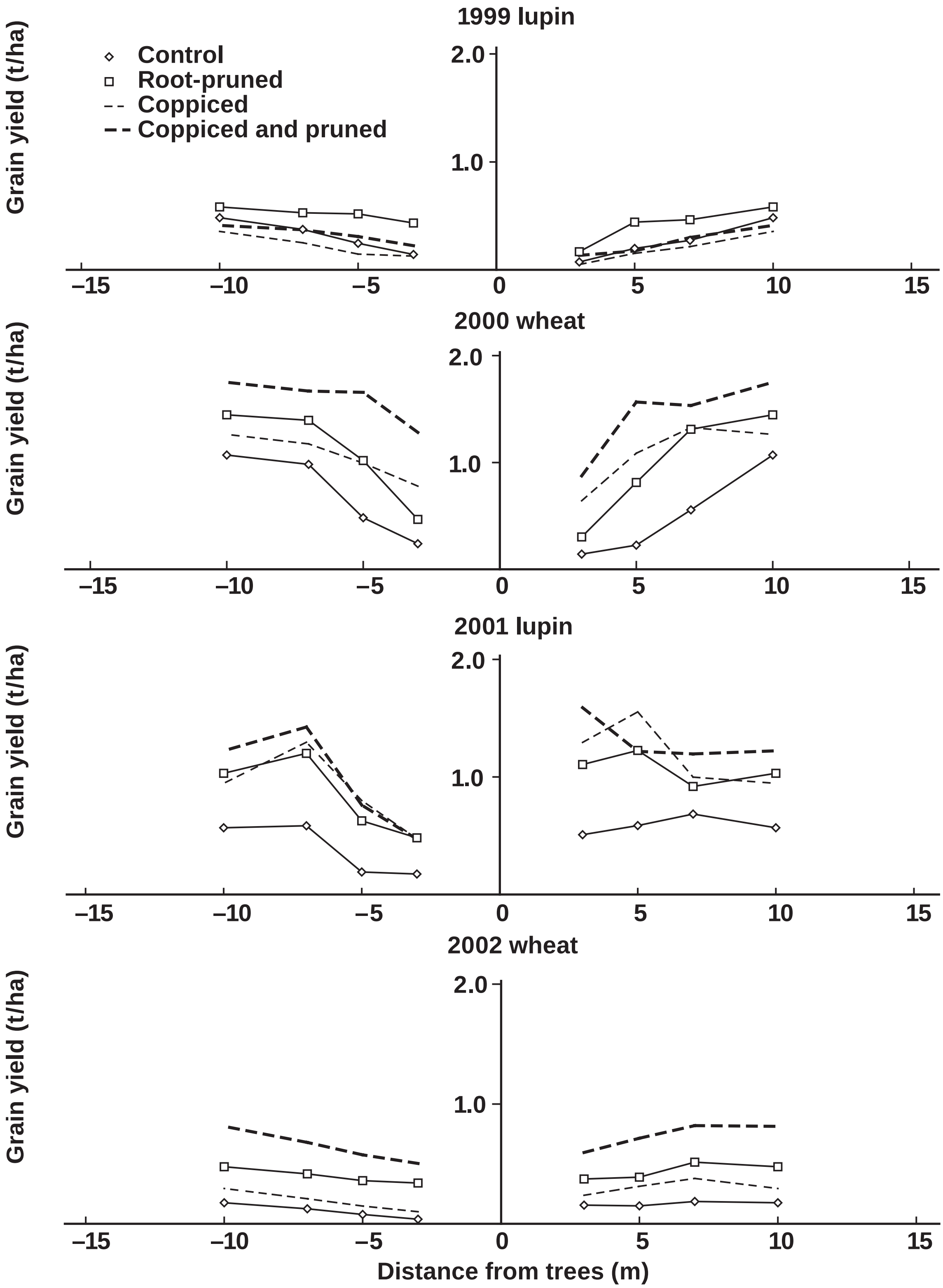

Figure 2. Esperance region 1999–2002. The lupin and wheat grain yield growing on the north (positive distance) and south (negative distance) sides of *E. kochii* hedges at site 6 with various competition management strategies. Values are means of all replicates, *i.e.* both soil types.

Table 12. Profitability and cash flow of a wheat–lupin rotation growing on duplex and deep sand soils (sole-crop duplex and sand, respectively), blocks of mallees growing on duplex and deep sand soils (mallee duplex and mallee sand, respectively) and mallee hedges that were either root-pruned or unpruned with wheat–lupin intercrops growing on duplex or deep sand soils (alley duplex and alley sand, respectively)

Scenario	NPV at 30 years ($/ha)	AER ($/ha)	No. of years to break-even	Peak debt ($/ha)	Years till peak debt
Sole-crop duplex	1201	97	1	172	0.5
Sole-crop sand	–729	–59	Not achieved	742	30
Mallee duplex	–617	–50	Not achieved	1546	1.5
Mallee sand	347	28	21	1546	1.5
Alley duplex unpruned	845	68	3	279	0.75
Alley duplex pruned	949	77	1, 3	279	0.75
Alley sand unpruned	–783	–63	Not achieved	795	28.5
Alley sand pruned	–793	–64	Not achieved	804	28.5

Given the relative profitability of sole-crop, block-planted mallees and the alley system, this analysis suggests that the deep sands were more suited for growing block-planted mallees and the duplex soils more suited to sole-crops. However, while a block-planted mallee enterprise may be profitable on deep sands, it would have a greater peak debt and longer pay back period compared with alley farming or sole-cropping (Table 12). Clearly, changing the cost–price assumptions used in the model would influence the relative profitability of the different systems. For example, putting a monetary value on the environmental services provided by the mallees (e.g. water use, wildlife habitat or carbon sequestration) would improve the economy of block-planting and alley cropping systems. Presently, however, only the shelter provided by mallee hedges or windbreaks can deliver an economic return directly to farmers.

Windbreak systems

The profitability of windbreak systems in southern Australia is generally dependant on the frequency of wind events that result in reduced crop or pasture yields. In the absence of damaging wind events, microclimate improvements in the sheltered zone are not great enough to offset competition losses in the Western Australian environment (Jones and Sudmeyer 2002; Sudmeyer *et al.* 2002*a*), even if windbreaks are root-pruned (Table 13).

However, with only 3 damaging wind events over the 35-year life of a windbreak system, the AER exceeds that of sole-crop by $1, even if competition is not managed (Table 13). When crop productivity in the competition zone is improved by root-pruning, without reducing tree height growth, the AER from the windbreak system is $4 more than that from sole-crop. If root-pruning reduces tree height growth by 25% (thus reducing the sheltered area which is proportional to tree height), the AER from the windbreak system is $1 more than that from sole-crop. As the number of damaging wind events increases, the AER from a windbreak system increases relative to the AER from sole-crop; however, there appears to be little benefit from root-pruning if it reduces tree growth.

Clearly, root-pruning windbreaks is of benefit in areas where severe wind damage events are unlikely. However, as the likelihood of damaging wind events increases, it is better to leave the lateral roots of windbreaks unpruned as returns from the additional shelter provided by the taller trees exceed the returns from reduced competition next to shorter root-pruned windbreaks.

As the protected area behind a windbreak is proportional to windbreak height, the shelter value of regularly harvested mallee hedges varies depending on the stage in the harvest cycle at which damaging wind events occur. Accordingly, damaging events that coincided with maximum hedge height

Table 13. Effect of root-pruning on annual equivalent return ($/ha) from sole-crop and windbreak systems with and without root-pruning affecting tree growth, and with and without damaging wind events

Scenario	Annual equivalent return ($/ha)
No severe wind damage events over 35 years	
Sole-crop	200
Unpruned windbreaks	187
Pruned windbreaks: tree growth unaffected	191
Pruned windbreaks: tree growth reduced 25%	192
Severe wind damage events in years 5, 10 and 20	
Sole-crop	169
Unpruned windbreaks	170
Pruned windbreaks: tree growth unaffected	173
Pruned windbreaks: tree growth reduced 25%	171
Severe wind damage events in years 5, 10, 15 and 20	
Sole-crop	162
Unpruned windbreaks	167
Pruned windbreaks: tree growth reduced 25%	167
Severe wind damage events in years 5, 10, 15, 20 and 25	
Sole-crop	158
Unpruned windbreaks	167
Pruned windbreaks: tree growth reduced 25%	165

on 6 or more occasions over 35 years increased the NPV of crops growing in the alleys between mallee hedges relative to sole-crops (data not shown). The NPV increased further if the mallee hedges grew taller between harvests. However, wind damage events occurring when hedges were at less than maximum height (i.e. 1–2 years after harvest), decreased the NPV of the alley crop, as the greater width of the competition zone at maximum tree height was not offset by shelter benefits. In addition, more frequent damaging events were required for the NPV of the alley crop to equal that of the sole-crop (break-even). In all cases, the NPV of crops in the alley was greater if the hedges were root-pruned, even if pruning reduced mallee growth.

For mallees, the combination of a comparatively wide competition zone (in terms of H) compared with taller tree species, and regular harvesting reduced their shelter value. This suggests that while increased crop yields due to shelter may contribute positively to the economy of mallee alley systems, root-pruning mallee hedges and high mallee yields will still be needed to offset crop losses in the competition zone.

This paper has not attempted to deal with the water-use benefits of alley or windbreak systems. However, it should be noted that competition management can reduce tree water use, increase soil water content and increase the incidence of waterlogging in the competition zone (R. Sudmeyer and D. Hall unpublished data). These issues will be dealt with in a later paper.

Conclusions

This research has shown that when trees are not commercially harvested, the use of root-pruning, coppicing, or thinning can improve the economic productivity of cropping and grazing enterprises in the competition zone. However, when trees provide commercial products or shelter from damaging winds, the benefits of reduced tree–crop competition may not offset consequent reductions in tree growth rates and shelter. For mallee alley systems on agriculturally productive soils, mallee growth rates must be great enough to compensate for crop losses in the competition zone. On relatively less productive soils, block-planted mallees may be more profitable than sole-crops or alley systems.

Competition management strategies can be used to manipulate the relative productivity of trees, crops and pasture at the tree–agriculture interface. The use of these strategies will depend on the relative economic value of tree and crop products and the value put on secondary tree benefits, such as shelter and reduced groundwater recharge.

Acknowledgments

The authors would like to thank the Grains Research and Development Corporation for funding this research, Rob Johnstone, Ken deGrussa, the Lewis family, Ewin Stewart and Brendan Freeman for making trial sites available on their farms. Micheal O'Connell is thanked for his excellent advice and assistance with the economic analysis. We also thank Shirley Milne and Dimphia McGuigan, for their technical assistance, the staff of EDRS; particularly Colin Boyd and Noel Rennie for sowing and harvesting trial crops and David Hall, Don Cooper and Alan Herbert for their comments on the manuscript.

References

Abadi A, Lefroy E, Cooper D, Hean R, Davies C (2003) Profitability of medium to low rainfall agroforestry in the cropping zone. RIRDC/Land & Water Australia/FWPRDC Joint Venture Agroforestry Program. Rural Industries Research and Development Corporation, Canberra.

Abadi A, Cooper D (2003) A case study of the economics of alley farming with oil mallees in Western Australia using the *Imagine* framework. In 'Proceedings of the 14th international farm management congress'. (CD ROM) (International Farm Management Association: Perth)

Anon. (2002) Gross Margins Guide 2003 Western Australia. WA Department of Agriculture, Miscellaneous Publication 18/2002, Perth.

Burnage T (Ed.) (1996) 'Esperance Regional Development Strategy for Farm Forestry.' (South-East Forest Foundation: Esperance, WA)

Enecon (2001) Integrated Tree Processing of Mallee Eucalypts. Rural Industries Research and Development Corporation, Publication No. 01/160, Canberra.

George R, McFarlane D, Nulsen RA (1997) Salinity threatens the viability of agriculture and ecosystems in Western Australia. *Hydrogeology Journal* **5**, 6–21.

George-Jaeggli B, Meinke H, Carberry PS, Maia AHN, Voller P (1998) Variations in wheat yields behind windbreaks in Southern Queensland — results from a survey. In 'Proceedings of the 9th Australian agronomy conference'. (Eds DL Michalk and JE Pratley) p. 683. (The Australian Agronomy Society Inc.: Parkville, Vic.)

Hatton TJ, Nulsen RA (1999) Towards achieving functional ecosystem mimicry with respect to water cycling on southern Australian agriculture. *Agroforestry Systems* **45**, 203–214. doi:10.1023/A:1006215620243

Huth NI, Carberry PS, Poulton PL, Brennan LE, Keating BA (2002) A framework for simulating agroforestry options for the low rainfall areas of Australia using APSIM. *European Journal of Agronomy* **18**, 171–185. doi:10.1016/S1161-0301(02)00103-X

Jones HK, Sudmeyer RA (2002) Economic assessment of windbreaks on the southeast coast of Western Australia. *Australian Journal of Experimental Agriculture* **42**, 751–762. doi:10.1071/EA02010

Short R, McConnell C (2001) Extent and Impacts of Dryland Salinity. Resource Management Technical Report 202, WA Department of Agriculture, Perth.

Sudmeyer RA, Adams M, Eastham J, Scott PR, Hawkins W, Rowland I (2002*a*) Broad-acre crop yield in the lee of windbreaks in the medium and low rainfall areas of south-western Australia. *Australian Journal of Experimental Agriculture* **42**, 739–750. doi:10.1071/EA02011

Sudmeyer RA, Hall DJM, Eastham J, Adams M (2002*b*) The tree-crop interface: The effects of root-pruning in south-western Australia. *Australian Journal of Experimental Agriculture* **42**, 763–772. doi:10.1071/EA02012

Sudmeyer RA, Speijers J, Nicholas BD (2004) Root distribution of *Pinus pinaster, P. radiata, Eucalyptus globulus* and *E. kochii* and associated soil chemistry in agricultural land adjacent to tree lines. *Tree Physiology* **24**, 1333–1345.

Unkovich M, Blott K, Knight A, Mock I, Rab A, Portelli M (2003) Water use, competition, and crop production in low rainfall, alley farming systems of south-eastern Australia. *Australian Journal of Agricultural Research* **54**, 751–762. doi:10.1071/AR03049

Woodall GS, Ward BH (2002) Soil water relations, crop production and root-pruning of a belt of trees. *Agricultural Water Management* **53**, 153–169. doi:10.1016/S0378-3774(01)00162-7

Zorzetto A, Chudleigh P (1999) Commercial Prospects for Low Rainfall Agroforestry. Rural Industries Research and Development Publication No. 99/152, Canberra.

Received 30 July 2004, accepted 3 December 2004