CSIRO PUBLISHING
Crop & Pasture Science, 2012, **63**, 555–569
http://dx.doi.org/10.1071/CP12129

The extent and cost of mallee–crop competition in unharvested carbon sequestration and harvested mallee biomass agroforestry systems

R. A. Sudmeyer[A,D], *T. Daniels*[B], *H. Jones*[B], *and D. Huxtable*[C]

[A]Department of Agriculture and Food Western Australia, Melijinup Rd, Esperance, WA 6450, Australia.
[B]Formerly Department of Agriculture and Food Western Australia, Melijinup Rd, Esperance, WA 6450, Australia.
[C]Equinox Environmental Pty Ltd, 6 Craigie Crescent, Manning, WA 6152, Australia.
[D]Corresponding author. Email: rsudmeyer@agric.wa.gov.au

Abstract. Mallee-based agroforestry has potential to provide farmers with new income sources derived from biofuels, biofeedstocks, and carbon sequestration. Although mallees are planted on >12 700 ha across the south-west of Western Australia, very little commercial harvesting of mallee has occurred to date. The development of biomass processing industries is constrained by lack of robust information regarding the productivity of integrated mallee and agricultural systems. This study addresses this constraint by quantifying the productivity and economics of agricultural crops and pastures growing in the competition zone adjacent to mallee belts at 15 sites across the Western Australian wheatbelt. The sites covered a range of climate and edaphic conditions, three mallee species (*Eucalyptus polybractea* R Baker, *E. loxophleba* ssp. *lissophloia* LAS Johnson and KD Hill, or *E. kochii* ssp. *plenissima* (CA Gardner) Brooker), various crop and pasture rotations, and various mallee harvest-management treatments.

Mallee–crop competition was negatively correlated with rainfall and positively correlated with mallee age and size, and greater for crops than pasture. Consequently, extent and magnitude of competition were highly variable across sites and years. On average, mallee–crop competition extended 11.3 m from unharvested belts and reduced crop and pasture yields by 36% within 2–20 m of the mallee belts relative to open paddock yields. This is similar to what has been reported for taller tree species. Harvesting mallees reduced competition such that crop and pasture yield was reduced by 22 or 27% relative to open paddock yields for mallees harvested at 3- or 6+-year intervals, respectively.

The economic cost of mallee–crop competition on agricultural enterprises was also highly variable between sites, and between years within individual sites. Averaged across all site-years, the opportunity cost of competition was equivalent to forgoing agricultural production for 14.4 m on each side of unharvested mallee belts, or 9–10 m on each side of harvested belts.

Farmers with mallee agroforestry systems will need to manage the economic impacts of competition by reducing agricultural input costs in the competition zone, timing crop-grazing rotations with mallee harvests, ensuring that the width of alleys is at least 25 times the height of the mature trees, and possibly root-pruning mallees in unharvested or long harvest interval systems.

This research has shown that mallee–crop competition presents a significant cost to farmers and must be considered when designing mallee agroforestry systems. The findings have relevance for the development of appropriate biomass and carbon sequestration pricing benchmarks for mallee plantings.

Additional keywords: biofuel, competition zone, *E. polybractea*, *E. loxophleba* subsp. *lissophloia*, *E. kochii* subsp. *Plenissima*, opportunity cost, tree–crop competition.

Received 3 April 2012, accepted 23 July 2012, published online 18 September 2012

Introduction

New industries based on integrating mallees (*Eucalyptus* spp.) into dryland cropping systems hold promise for providing farmers with new income sources derived from biofuels, biofeedstocks, and carbon sequestration and for ameliorating some of the environmental concerns associated with conventional farming systems (URS 2009; Bartle and Abadi 2010). Mallees are planted on >12 700 ha of farmland across the south-west of Western Australia (URS 2009). This constitutes a potential resource for biomass processing industries. However, to date, little commercial harvesting has occurred. The area planted is set to expand under federally mandated, renewable energy targets and cap-and-trade legislation for greenhouse gas emissions, and could result in large areas of permanent (i.e. not for harvest) plantings.

In southern Australia, best mallee growth is achieved when mallees are planted as two-row belts in alley systems (Cooper *et al*. 2005; URS 2009; Bartle and Abadi 2010). Growing the mallees in this way maximises the mallee–agriculture interface and the ability of the mallees to capture resources from the competition zone alongside the belts. However, this increased mallee growth comes at the cost of competition with adjacent crop and pasture (Sudmeyer 2001; Sudmeyer and Flugge 2005).

Australian research has shown that competition for water is the primary cause of reduced agricultural yields in the competition zone and that the economic impacts of competition are generally not offset by the productivity benefits of wind-speed reductions and associated micrometeorological changes (George-Jaeggli *et al*. 1998; Jones and Sudmeyer 2002; Sudmeyer *et al*. 2002*a*, 2002*b*; Unkovich *et al*. 2003; Oliver *et al*. 2005; Sudmeyer and Flugge 2005; Bennell and Verbyla 2008; Huth *et al*. 2010).

Harvesting mallees on a 1–2-year interval and root-pruning of unharvested mallees have been shown to improve agricultural production in the competition zone at a limited number of sites (Sudmeyer 2001; Sudmeyer and Flugge 2005). However, more recent analysis has suggested that harvest intervals significantly longer than 2 years are necessary to achieve commercially attractive mallee biomass yields (Bartle and Abadi 2010). It is unclear what the agricultural competition response will be in this case.

Lack of robust information regarding agricultural production in mallee agroforestry systems constrains their development. Economic uncertainty hinders decision making by land managers and investors (Pannell 2001), and at the wider policy level, it is necessary to account for the effects of direct and indirect land-use change in estimating the climate change benefits of biofuels and the implications for food security and equity (IEA 2009; Berndes *et al*. 2010; Marshall *et al*. 2011).

To overcome this constraint, we tested the following hypotheses regarding agricultural productivity in the competition zone: (*i*) reducing mallee water use by harvesting the belts will reduce the extent and magnitude of competition with adjacent crop and pasture; (*ii*) season of mallee harvest and time between harvests will influence how water is partitioned in the competition zone and subsequent crop and pasture growth; (*iii*) root-pruning of coppicing mallees will further reduce mallee water use and competition extent and magnitude; (*iv*) site edaphic characteristics influence competition, allowing site selection to be used to manipulate competition magnitude and extent; (*v*) economic impacts of competition can be reduced by manipulating agricultural inputs in the competition zone.

The information gained in this trial will be used to better understand the economics of mallee agroforestry systems and guide the selection of appropriate mallee biomass and carbon sequestration pricing benchmarks.

Methods

Sites

In 2005, 15 trial sites were established in pre-existing mallee plantings across the wheatbelt of Western Australian (Table 1). All of the sites were on privately owned farms. Site selection was based on the criteria that the mallees were at least 5 years old, planted in linear belts with at least 48 m between belts, and the species, growth, and survival were representative of better plantings in the locality. For the purposes of this study, distances from belts were measured at right angles from the outermost row of mallees.

Site characterisation

Climate

Annual rainfall (P) (Table 1) and potential evaporation (E) and growing season rainfall (GSP) and evaporation (GSE) data were obtained from the Silo Data Drill (Queensland Government 2011), with growing season defined as the period from April 1 to October 31 each year. Annual and growing season climate moisture index (CWI and GSCWI, respectively) were calculated as (P/E – 1) or (GSP/GSE – 1), respectively (Thornthwaite 1948).

Soil

The soil at each site was classified according to the Australian Soil Classification (Isbell 1996) (Table 1). Soil cores were collected 20 m from the mallee belts in the centre of each control plot at each site. Sites 1, 2, 5, and 6 were sampled in 2008; sites 3, 4, 7, 8, 11, 13, and 14 in 2009; and sites 9, 10, 12, and 15 in 2010. Cores were collected using an EVH Rhino 2100 drill rig (EVH Drill Engineering Pty Ltd, Canning Vale, WA). The cores were 44 mm in diameter and were collected to a maximum depth of 10 m or where bedrock, groundwater, or a hardpan too hard to drill through (e.g. silcrete or ferricrete) was intersected. Where free water was detected in the core, the core hole was left open for 1–2 h after drilling to allow a better measurement of watertable depth. On a few occasions, holes collapsed and it was not possible to re-measure watertable depth. This method may have overestimated watertable depth where the saturated layer conductivity was low. Cores were sampled according to visually identifiable horizons, and where the horizon thickness exceeded 0.75 m into 0.75-m-long samples. Each sample was dried to stable weight at 110°C in 2008 and 2009 and at 45°C in 2010. The >2-mm-diameter faction was determined and the <2-mm-diameter fraction analysed by CSBP Soil and Plant Analysis Laboratory (CSBP Ltd, Bibra Lake, WA).

The amount of each nutrient stored in the soil profile between the surface and 0.5 m depth was estimated using representative bulk densities (g m^{-2}) for the various soil horizons (sand 1.55, loam 1.75, clay 1.85). Mallee rooting depth was estimating using three sets of criteria: CL1, the minimum depth to watertable, bedrock, hardpan, or electrical conductivity of saturated paste extract (ECe) $\geq$8 dS m^{-1}; CL2, the minimum depth to watertable, bedrock, hardpan, pH($CaCl_2$) $\leq$4.5, or ECe $\geq$8 dS m^{-1}; CL3, the minimum of depth to watertable, bedrock, hardpan, or ECe $\geq$16 dS m^{-1}. A pH($CaCl_2$) $\leq$4.5 is considered very strongly acid (Peverill *et al*. 1999); ECe $\geq$8 dS m^{-1} is considered highly saline; and ECe $\geq$16 dS m^{-1} is considered severely saline (Saltlandgenie 2011).

Treatments

The treatments applied to the mallee belts related to timing of harvest (autumn or spring), harvest interval (3, 4, and 6+ years), and harvest with root-pruning. The control (C) was unharvested mallees. In 2006, three control, six autumn, and nine spring harvest treatment plots were established at each site. We intended to split the autumn harvest plots into 3- and 4-year harvest interval treatments (A3 and A4, respectively) and to split

Table 1. Site location, mean annual rainfall (mm, 1970–2011), soil types, mallee species, year planted, number of mallee rows in belt, and width of alley between belts

Mallee species: *E. polybractea* (Epb), *E. loxophleba* subsp. *lissophloia* (Ell), *E. kochii* subsp. *plenissima* (Ekp). Alley width expressed as m and multiples of belt height (H) in 2006 and 2011 (2009 where marked with asterisk)

Site	Nearest town	Lat.	Long.	Annual rainfall	Australian soil classification	Mallee species	Planting year	Rows in belt	Alley width (m)	H (2006)	H (2011)
1	Narrogin	–32.87	117.25	432	Brown Tenosol; brown Chromosol	Epb	1996	2	70	12	11
2	Wickepin	–32.85	117.59	353	Brown Kandosol	Ell	2000	3	50	13	10
3	Kalannie	–30.29	117.43	303	Acidic-mottled mesotrophic red Kandosol; sodic hypercalcic red Kandosol; mesotrophic subnatric red Sodosol; supracalcic subnatric red Sodosol	Ell	1999	3	95	21	15
4	Tincurrin	–32.98	117.74	368	Yellow Chromosol; grey Chromosol; brown Kandosol	Epb	1998	4	125–250	>24	>20
5	Kulin	–32.67	118.24	326	Red Tenosol	Ell	1997	2	48	12	10
6	Kalannie	–30.17	117.37	321	Acidic regolithic brown-orthic Tenosol; acidic-mottled mesotrophic brown Kandosol	Ekp	1994	2	95	23	21*
7	Kirwan	–30.60	117.39	296	Mottled-sodic eutrophic brown Dermosol	Ell	1999	2	50	13	9
8	Esperance	–33.62	121.78	539	Ferric-sodic mesotrophic brown Sodosol; ferric mottled-mesonatric brown Sodosol; bleached-ferric mesotrophic brown Sodosol; ferric mottled-subnatric brown Sodosol	Epb	2001	6	90–100	22	13
9	Esperance	–33.63	121.76	539	Ferric-sodic mesotrophic brown Chromosol	Epb	2001	6	120–140	>34	>21
10	Buntine	–29.97	116.48	327	Ferric subnatric yellow Sodosol; haplic mesotrophic yellow Kandosol; basic arenic yellow-orthic Tenosol	Ell	1998	4	>250	–	–
11	Koorda	–30.78	117.61	297	Eutrophic, mottled-hypernatric brown Sodosol	Ekp	1999	2	60–>250	>17	>21
12	Dumbleyung	–33.49	117.79	370	Red Chromosol	Ell	2000	6	55	17	14
13	Wongan Hills	–31.00	116.92	337	Mesotrophic petroferric grey Sodosol; ferric mottled-subnatric yellow Sodosol	Ell	2000	4	48–120	>14	>11*
14	Kalannie	–30.21	117.36	321	Hypercalcic subnatric red Sodosol; sodic supracalcic red Kandosol	Ell	1998	2	95	34	26
15	Esperance	–33.52	122.15	457	Mesotrophic petrocalcic brown Sodosol; vertic pedal hypercalcic Calcarosol; supracalcic petrocalcic brown Sodosol; ferric, sesquic aeric Podosol	Ell	2001	6	150–250	>50	>29

the spring harvest plots into 3- and 4-year harvest interval and root-pruned on a 2-year interval with 3-year harvest interval treatments (S3, S4, and RP3, respectively), but these harvest intervals had to be increased at sites with slower coppice growth rates. Consequently, the following treatments were applied at sites 1–9: C, S3, S4, A3, A4, and RP3. Treatments at Site 10 were C, S4, and A4. Treatments at sites 11–15 were C, spring harvest at 6+-year interval (S6+), autumn harvest at 6+-year interval (A6+), and root-pruned at 2-year interval with spring harvest at 6+-year interval (RP6+).

Each treatment was applied along either 40 m (sites 1–5 and 10–13) or 45 m (sites 6–9, 14, and 15) of mallee belt, and plots extended 24–30 m into the agricultural area adjacent to the belts to form a rectangular treatment plot. Treatment plots included 10-m-wide buffers on each side. Each treatment was replicated three times in a randomised block design.

From 2006 to 2008, agricultural productivity was measured on four treatments at each site (except for three at site 10). The treatment sets were {C, S3, A3, RP3} and {C, S6+, A6+, RP6+}, although to 2008, both treatment sets were effectively equivalent. From 2009 to 2011, treatments S4 and A4 were also measured at sites 1–9, as these were no longer equivalent to treatments S3 and A3.

Mallees were harvested by cutting stems at ground level using chainsaws or hand-pruning equipment, removing all of the above-ground biomass, and allowing the mallees to coppice from the stump. Mallee growth rates and above-ground biomass are reported in Huxtable *et al*. (2012). Sheep grazed coppicing mallees at some sites, so the tree lines were progressively fenced between 2006 and 2009.

At sites 3, 13, and 14, some of the treatment replicates showed poor mallee survival or growth after being harvested in 2006. Consequently, coppice growth was considered less than would be acceptable in a commercial enterprise and mallee–crop competition was minimal. Therefore, data from the following treatment replicates were removed from the subsequent analysis of mallee–crop competition: site 3—all replicates of S3 and one replicate each of A3, A4, S4, and RP3; site 13—one replicate of

A6+ and two replicates each of S6+ and RP6+; and site 14—one replicate each of S6+ and RP6+.

Root-pruning treatments RP3 and RP6+ to sever lateral mallee roots commenced in 2006 with farmers using their own rippers. The ripping depth ranged between 0.3 and 0.7 m depending on available machinery and depth to subsoil clay. The timing of root pruning ranged between spring and autumn and the distance from the belts ranged between 2 and 5 m. In autumn 2008, a trailed ripper was used at all sites to achieve a uniform ripping depth of 0.6 m, at a distance of 2.5 m from the belts. In autumn 2010, a three-point linkage mounted ripper was used 2.5 m from the belts, with ripping depth ranging between 0.3 and 0.6 m depending on subsoil clay depth. Ripping is expected to have cut most of the lateral roots where the subsoil clay was within 0.5 m of the soil surface, but to have left lateral roots uncut below the depth of the ripper at sites with deep sands (Sudmeyer *et al*. 2004).

The benefits of root-pruning unharvested trees led to farmers root-pruning three of the sites during the trial. Site 7 was root-pruned to a depth of 0.2 m in 2008 and 2009 using an agro-plough. In 2009, site 6 was root-pruned to 0.65 m at 2 and 4 m from the belts, and site 8 to a depth of 0.25 m at 2 m from the belts. The depth of pruning at sites 7 and 8 was not considered sufficient to sever all lateral mallee roots, so measurements were continued. The depth of pruning at site 6 was considered sufficient to significantly affect mallee–crop competition, and measurements were discontinued.

Crop and pasture growth

Crop or pasture growth was measured between 2006 and 2011, although not all sites or treatments were measured each year, due to drought conditions, agronomic manipulations (e.g. chemically fallowed pastures were not measured), or other reasons.

Crop and pasture growth was determined from measurement strips running parallel to the belt at centreline distances of 2, 4, 6, 8, 12, 16, 20, 24, and 30 m from the belt in each treatment plot. The measurement strips were 20 m long at sites 1–5 and 10–13, and 25 m long at sites 6–9, 14, and 15. Measurements at 30 m were only made at sites with taller belts (sites 1, 4, 6, and 10 in all years, and Sites 3, 8, 9, and 15 from 2009).

Grain yield was measured by machine-harvesting 1.7- or 1.8-m-wide strips centred on each distance. At sites 8, 9, and 15, canola yield was determined from hand-harvested samples taken just before the crop was swathed. This involved the measurement of total above-ground green biomass (weighed in the field) determined from five 0.5 m^2 quadrats cut at each distance. At each site, samples from each distance in the three replicates of treatment C were subsequently dried at 70°C, and the grain weight and harvest index determined. The harvest index at each site was used to estimate grain weight using the green above-ground biomass data determined in the field.

Pasture above-ground biomass was determined once in September each year using the calibrated visual assessment technique of Campbell and Arnold (1973). Assessments were made at 20 points along each measurement strip (10 assessments by two persons in 2006–09 and 10 assessments by one person in 2010 and 2011) and average above-ground biomass was determined for each distance in each treatment replicate.

Open yields in this study were assumed to be equal to the average yield ≥20 m from the belts for all treatments. The distance of 20 m from unharvested belts ranged between 2.6 and 13.5 times the height of the unharvested mallees (H) and averaged 5.4 H. Sudmeyer *et al.* (2002*a*) showed that where crops were unaffected by sandblasting, crop yield between 4 and 20 H was not significantly different from yield at ≥20 H. Belt heights from our sites (Huxtable *et al.* 2012) and data from Sudmeyer *et al*. (2002*a*) were used to express yields at 20, 24, and 30 m relative to yield at ≥20 H for each site and year. This analysis suggests that average yield at 20–30 m from unharvested belts would have ranged between 90 and 104% and averaged 99% of yield at ≥20 H. Where belts had been harvested, shelter and competition would have been reduced, and it could be assumed that average yield at 20–30 m was equivalent to yield at ≥20 H.

The lateral extent of mallee–crop competition (competition extent) in each treatment was estimated by consecutively comparing yield at each measurement distance with yield at distances further from the belt. Competition extent was taken to be where yield first exceeded 80% of the mean of yield at all distances further from the belt.

For the purposes of comparing crop and pasture yields in the competition zone (competition zone yield) among sites and years, crop or pasture yield at each measurement distance was normalised by expressing it as a percentage of open yield for that particular treatment plot. As the first 2 m on either side of mallee belts is usually assumed to be left uncropped and competition extent was variable, competition zone yield was calculated as the mean normalised yield between 2 and 20 m from the belts. Where the uncropped distance next to the trees was >2 m wide, yield from 2 m to the crop edge was assumed to be zero. As crop measurement swathes were 1.7 or 1.8 m wide, the relationship between yield and distance from the belt is represented by a step function defined by the measured yields at the set distances extrapolated to the area defined by the midpoints between the preceding and succeeding measurement distances. This has the effect of weighting the distance increments, and gives similar (but not the same) results as linear weighting and averaging methods. The magnitude of competition is expressed as the difference between open yield (100%) and competition zone yield.

The spatially complex crop–pasture yield responses in the competition zone were simplified to a single step function, i.e. an area next to the belt where yield was effectively zero (the zero-yield distance) and the remaining area where yield was equivalent to open values. This approach has been taken with crop yield or drainage below the root-zone in several other studies (Lefroy *et al.* 2001; Knight *et al.*2002; Ellis *et al*. 2005; Oliver *et al*. 2005; Robinson *et al*. 2006; Crosbie *et al*. 2008). The zero-yield distance was calculated using Eqn 1:

$$\text{Zero} - \text{yield distance} = \left(\sum \text{yield}_{0-22\,\text{m}} - 22\text{open yield}\right) / \text{open yield} \qquad (1)$$

where open yield is the mean crop or pasture yield for each particular treatment replicate at distances ≥20 m from the belt (t ha^{-1}) and $\sum \text{yield}_{0-22\,\text{m}}$ is the cumulative yield in a transect stretching from the belt out to a distance of 22 m (the midpoint between the 20- and 24-m measurements.

A positive zero-yield distance indicated a net increase in yield in the competition zone, while a negative result indicated a loss, with the amount expressed as the width (m) of land from which agricultural production was effectively gained or lost along one side of the belt.

Statistical analyses

Treatment effects on competition extent and yield in the competition zone were compared for each site and year combination using analysis of variance. Analysis of variance was also used to do combined analyses across sites for each year. Treatment × site interactions were also assessed at this time. Only sites with the same treatments were compared for each year, i.e. sites 1–10 (treatments C, S3, S4, A3, A4, and RP3) and sites 11–15 (treatments C, S6+, A6+, and RP6+).

The correlations between edaphic and climatic conditions and competition extent and competition zone yield adjacent to harvested and unharvested mallees were investigated using all-subsets multiple regression. Two analyses were conducted:

(1) The first analysis used treatment averages for either harvested or unharvested belts at each site each year with the following variables tested: CWI, P, GSCWI, GSP, crop or pasture, CL1, CL2, CL3, depth to clay subsoil (m), mallee belt mean annual above-ground biomass increment (MAI, green t ha^{-1} $year^{-1}$), mallee belt biomass (green t ha^{-1}), mallee leaf biomass (dry t ha^{-1}), mallee age (years), mallee height (m), and, for harvested trees only, years since mallee harvest and years since ripping.
(2) The second analysis used only data from the control treatment. For each site, competition extent or competition zone yield was averaged across all years. In addition to testing the variables described above, the following variables were also tested: the percentage of years the site was in crop, nitrogen (N) present as ammonium or nitrate, organic carbon, available sulfur, and Colwell phosphorous (Colwell P) or potassium (Colwell K), with soil nutrients expressed as the amount present in the top 50 cm of the soil profile (g m^{-2}).

Optimal models were selected on the basis of providing the greatest explanatory power with the least variables and all of the variables being significant ($P < 0.05$).

Economic analysis

The gross margin (GM) or annualised return (AU$ ha^{-1}) from crops and pastures growing adjacent to the mallee belts was estimated for each distance that measurements were made using treatment averages for each site and year. These values were used to calculate the break-even distance (where costs of production were equal to returns) and the opportunity-cost distance, i.e. the width of the area alongside the belts over which agricultural income was effectively forgone. Opportunity-cost distance was calculated in a similar way to zero-yield distance using Eqn 2:

$$\text{Opportunity} - \text{cost distance} = \left(\sum \text{GM}_{0-22\,\text{m}} - 22\text{open GM}\right)/\text{open GM} \quad (2)$$

where open GM (\$ m^{-2}) is the mean gross margin for each particular treatment replicate at distances ≥20 m from the belt and $\sum \text{GM}_{0-22\,\text{m}}$ is the cumulative GM in a transect stretching from the belt out to a distance of 22 m. A positive result indicated a net increase in returns from the competition zone, while a negative result indicated a loss, with the amount expressed as the width (m) of land from which agricultural income is effectively gained or lost alongside one side of the belt.

It was not possible to calculate opportunity-cost distance for years when open GM was negative. To be able to include data from those years in the analysis, average opportunity cost distance was calculated for each site using Eqn 2 where open GM and $\sum \text{GM}_{0-22\,\text{m}}$ were the sum for all of the years that data were available at that site. These values were used in turn to calculate the average for each treatment across all sites.

Grain prices were taken from quoted prices (Co-operative Bulk Handling Ltd, West Perth, WA; and Emerald Group Australia Pty Ltd, Richmond, Vic.), cash prices (pers. comm. from local farmers), and the Australian Bureau of Agricultural and Resource Economics (ABARE) index of prices received (ABARE 2009; ABARES 2011) and were at the 'farm gate', i.e. after transport costs and fees. Wheat prices were for Australian Premium White grade equivalent, and barley price was the average of feed and malt grades. Costs of production were based on published gross margins (DAFWA 2005), unpublished farm survey data, information published in the Farm Budget Guides for 2006–2010 (Farm Weekly 2006, 2007, 2008, 2009, 2010) and ABARE's index of prices paid (ABARES 2011). Sheep income was derived from average productivity of wool and sheep enterprises for the various regions as given in Bankwest (2006, 2008) and updated according to the indexes of prices paid and received (ABARES 2011). The cost of root-pruning was assumed to be \$15 km^{-1} for each side of the belt (Sudmeyer and Flugge 2005) and was indexed according to ABARE's index of prices paid (ABARES 2011). Input costs for pasture were applied for all distances ≥2 m from the belt, but only where crop had actually been sown for a particular site-year.

It should be noted that this analysis gives an indication of gross margins based on district averages each year rather than site-specific values.

Results

Crop and pasture growth

Crop and pasture yields typically were least nearest the belts and increased with distance from the belts, to reach a plateau outside the competition zone (open yield) (see, for example, Fig. 1*a*). The considerable variation in competition extent and magnitude among sites, years, and treatments is shown in Tables 2 and 3. Six sites had unacceptably high variance due to poor and patchy pasture or crop growth. This was attributed to abnormally dry seasons at sites 3, 5, 7, and 13 and poor weed control at site 9 (Tables 2 and 3). As the variability could not be attributed solely to treatment effects, data from these sites and years were omitted from further analysis.

Averaged across all the sites and years for which data are available, competition next to unharvested mallees extended for 11.3 m and reduced yield between 2 and 20 m by 36%. Zero-yield distance was 8.8 m. Harvesting mallees generally reduced competition extent and magnitude compared with unharvested

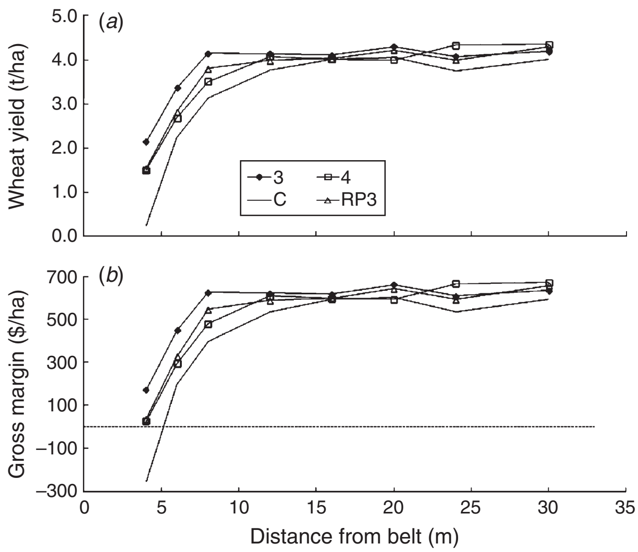

Fig. 1. Example of (*a*) wheat yield and (*b*) gross margin (AU$) at various distances from mallee belts that were: unharvested (C); harvested on a 3-year (3) or 4-year (4) interval or a 3-year interval and root-pruned biennially (RP3). Data are from site 9 in 2009, values for 3- and 4-year harvests are means of treatments harvested in spring and autumn.

mallees. Mean competition extent differed significantly among treatments at one, five, two, four, four, and two sites in years 2006–2011, respectively (Tables 2 and 3), and mean competition magnitude differed significantly among treatments at four, three, four, two, four, and six sites in years 2006–2011, respectively (Tables 2 and 3).

Competition magnitude and extent were most strongly correlated with mallee age, years since harvest, MAI, height, GSP, and GSCWI (Tables 4 and 5). Competition magnitude and extent increased with mallee age, years since harvest, MAI, and height, and decreased with increasing GSP or decreasing GSCWI, and were greater for crop than pasture for harvested mallees. Unharvested mallee biomass was negatively correlated with competition extent and magnitude but not enough to offset the positive correlation between MAI and competition extent and magnitude (Table 4). Mallee age or years since harvest, height, MAI, and biomass were all correlated and were somewhat interchangeable as explanatory variables, as were P, GSP, CWI, and GSCWI (data not presented). Although the resultant linear equations were statistically significant, they explained only 44 and 45% of the variability in competition extent and magnitude, respectively, for unharvested mallees (Table 4) and 31 and 27%, respectively, for harvested mallees (Table 5).

For unharvested mallees and across all years, analysis showed that site mean competition extent and magnitude were weakly correlated with, and increased with, mallee age and Colwell P (Table 6). Variables such as depth to clay subsoil, mallee rooting depth, and other soil fertility parameters were either non-significant or less significant.

While competition extent tended to increase with mallee height, it was generally >4 m even for harvested mallees (Fig. 2). Consequently, the proportion of the sheltered zone subject to competition increased as mallee height decreased. Competition extent averaged 2.6 H for unharvested mallees (range 1.0–5.7 H), and 5.2 H for harvested mallees.

Broad temporal trends in competition response to harvesting were evident across sites each year (excluding sites 7, 10, 11, and 14 in 2010 when only treatment C was measured). Competition magnitude and extent were only decreased in the year the mallees were harvested in autumn (Fig. 3). Competition magnitude and extent subsequently decreased compared with the control in the first and second years after mallee harvest for both autumn and spring harvest treatments. By 3 years after harvest, competition extent and magnitude were still less than for the control, but only significantly less for treatments S6+ and RP6+. In a dry year, 4 years after harvest (2010), competition extent and magnitude were similar for control and harvested mallees, but in a comparatively wet year, 5 years after harvest (2011), competition extent and magnitude were significantly reduced. Root-pruning of harvested mallees did not significantly reduce competition extent or magnitude compared with just harvesting at the same interval and season.

Averaged over 6 years, compared with unharvested mallees, harvesting mallees on 3-, 4-, and 6+-year intervals increased agricultural yields within 20 m by 15, 10, and 8% of open yield, respectively, decreased competition extent by 3.7, 2.4, and 1.6 m, and decreased zero-yield distance by 2.3, 1.9, and 1.9 m (Table 7). Note that these analyses did not include data from harvested treatments at sites 7, 10, 11, and 14 in 2010 as these sites were not fully measured in that year. If those data were available, competition extent and magnitude and zero-yield distance adjacent to harvested mallee belts would likely be slightly greater than indicated in Table 7, as rainfall was below average in 2010. Removing data for treatment C for these sites in 2010 reduced the mean competition magnitude by 2–3% and extent by 0.4–0.5 m.

Economic analysis

District average values for input costs and crop and sheep returns, together with measured productivity data, suggest that open GM was less than zero for 11 of the 74 field years for which data were collected (data not presented). This is in addition to the four field years when data were not collected because the crop or pasture was considered too drought-affected to warrant measurement (Tables 2 and 3). The GM followed similar trends to crop yield, so was generally least near the belts and increased with distance to reach open values outside the extent of competition (Fig. 1*b*). Where yield was particularly low, GM dropped below zero (i.e. treatment C in Fig. 1*b*).

Break-even distance ranged from 2 m (the closest distance to the belt at which measurements were made) to 18.1 m (data not presented). Mean break-even distance was similar for harvested and unharvested mallees in the year the mallees were first harvested, then declined for harvested mallees relative to unharvested mallees and remained less for at least 5 years (Fig. 4*c*, *d*).

The mean break-even distance for unharvested mallees over 6 years was 7.5 m (all sites-years). Harvesting mallees on 3-, 4-, and 6+-year intervals reduced the mean break-even distance by 1.8, 1.6, and 1.6 m, respectively (Table 7). Root-pruning of

Table 2. Crop or pasture grown each year, open yield (grain yield or pasture food-on-offer, t ha^{-1}), competition extent (m), and yield in the competition zone from 2 to 20 m (expressed as % of open yield) at sites 1–10

Treatments: unharvested mallees (C); mallees harvested in autumn (A) or spring (S) at 3- and 4-year harvest intervals; RP, root-pruning. Also shown are significance of differences between treatments (*P*-values, bold are significant) and least significant differences (l.s.d.) at $P = 0.05$. Where measurements were not taken, the reason is indicated: dry conditions (D), poor mallee growth (PG), other reasons (O). Shading indicates the years that mallees were harvested. †, Site-years marked thus showed high variability

Site	Year	Crop/ pasture	Open yield	Competition extent								Yield from 2 m to 20 m							
				C	S3	S4	A3	A4	RP3	*P*	l.s.d.	C	S3	S4	A3	A4	RP3	*P*	l.s.d.
1	2006	Wheat	2.1	11.9	14.0	–	9.6	–	12.3	0.310	5.0	58	55	–	77	–	61	0.096	18
	2007	Pasture	3.0	10.0	6.6	–	5.2	–	4.6	0.189	5.5	75	89	–	90	–	100	0.136	22
	2008	Wheat	1.8	6.7	4.7	–	7.0	–	4.8	0.184	2.8	91	84	–	84	–	89	0.744	18
	2009	Pasture	2.1	8.8	6.5	10.2	6.1	5.4	5.7	0.329	5.2	73	80	75	93	88	93	0.178	20
	2010	Pasture	1.3	10.2	4.5	6.1	4.0	6.3	4.0	**0.001**	2.2	71	97	90	106	88	100	**0.003**	14
	2011	Oats	3.9	8.0	7.6	6.5	7.4	5.0	6.7	0.212	2.6	85	77	89	81	95	87	0.791	32
2	2006	Barley	3.0	7.3	6.2	–	6.3		7.2	0.479	2.0	79	81	–	85	–	77	0.547	14
	2007	Pasture	7.5	8.2	4.0	–	7.9	–	7.1	0.083	3.5	82	97	–	90	–	81	0.170	16
	2008	Pasture	6.4	5.2	4.4	–	5.5	–	4.6	0.611	2.0	84	93	–	87	–	85	0.194	10
	2009	Pasture	3.3	8.8	6.5	10.2	6.1	5.4	5.7	0.329	5.2	92	89	93	92	88	91	0.939	13
	2010	Pasture	0.9	6.2	7.6	9.5	4.5	6.7	4.0	0.087	5.0	95	99	70	103	79	100	**0.042**	23
	2011	Pasture	1.6	7.6	5.2	5.3	5.4	4.8	4.5	0.062	2.0	81	93	90	91	96	91	**0.046**	9
3	2006	Pasture	–	D	PG	–	D	–	D	–	–	D	PG	–	D	–	D	–	–
	2007	Barley	2.4	17.3	PG	–	6.6	–	7.5	**0.032**	7.3	42	–	–	89	–	75	0.073	41
	2008†	Pasture	1.0	11.3	PG	–	5.7	–	10.7	0.447	16.7	60	–	–	97	–	77	0.428	98
	2009	Wheat	1.6	12.0	PG	9.7	5.3	7.1	5.8	**0.001**	1.5	56	–	76	102	85	86	**0.005**	15
	2010	Wheat	–	D	PG	D	D	D	D	–	–	D	PG	D	D	D	D	–	–
	2011	Pasture	–	O	O	O	O	O	O	–	–	O	O	O	O	O	O	–	–
4	2006	Wheat	1.0	21.0	15.1	–	14.5	–	13.9	0.533	13.9	36	47	–	69	–	51	0.183	31
	2007	Lupins	2.2	10.1	5.7	–	5.3	–	6.8	**0.042**	3.3	69	78	–	92	–	78	0.231	23
	2008	Wheat	–	O	O	O	O	–	O	–	–	O	O	O	O	–	O	–	–
	2009	Canola	0.7	14.7	15.7	15.4	13.3	14.1	9.7	0.376	6.3	49	58	48	65	52	48	0.816	31
	2010	Wheat	0.4	17.8	15.7	18.4	13.3	12.0	13.2	0.071	4.9	39	46	30	59	65	60	**0.036**	23
	2011	Wheat	3.4	13.3	10.4	10.2	10.4	9.4	12.8	0.542	5.3	61	67	68	66	71	59	0.600	17
5	2006	Wheat	0.6	17.8	15.8	–	10.1	–	11.8	0.086	6.5	35	40	–	69	–	55	**0.021**	21
	2007†	Pasture	1.5	6.9	5.2	–	8.9	–	4.0	0.177	4.9	71	97	–	98	–	102	0.478	50
	2008	Wheat	2.4	12.7	12.1	–	10.3	–	9.2	0.594	6.4	56	65	–	67	–	75	0.381	24
	2009†	Pasture	0.9	8.7	6.4	6.0	5.0	7.3	4.0	**0.002**	1.8	70	124	93	114	106	150	**0.022**	41
	2010	Wheat	–	D	D	D	D	D	D	–	–	D	D	D	D	D	D	–	–
	2011	Wheat	2.1	11.8	11.2	12.0	10.3	7.5	10.9	0.497	5.4	55	65	58	68	70	68	**0.012**	8
6	2006	Wheat	0.5	13.6	14.9		9.3		11.3	0.137	5.4	52	46	–	65	–	54	**0.035**	11
	2007	Pasture	0.5	15.8	4.9		4.0		7.4	**0.020**	6.9	35	71	–	73	–	72	**0.005**	20
	2008	Wheat	1.4	14.9	7.6		8.6		7.8	**<0.001**	1.2	50	82	–	65	–	69	**0.028**	19
	2009	Measurements discontinued																	
7	2006†	Pasture	0.4	12.9	10.9	–	5.0	–	11.1	0.172	7.9	66	71	–	209	–	66	**0.013**	83
	2007	Barley	–	D	D	–	D	–	D	–	–	D	D	–	D	–	D	–	–
	2008	Pasture	2.7	15.2	7.9	–	6.4	–	6.1	0.054	7.0	54	68	–	79	–	77	**0.002**	9
	2009	Canola	–	O	O	–	O	–	O	–	–	O	O	–	O	–	O	–	–
	2010	Barley	0.3	19.0	O	O	O	O	O	–	–	16	O	O	O	O	O	–	–
	2011	Wheat	–	O	O	O	O	O	O	–	–	O	O	O	O	O	O	–	–
8	2006	Pasture	4.36	4.0	4.0	–	4.0	–	4.0	0.441	–0	89	94	–	90	–	85	0.213	9
	2007	Pasture	3.8	6.9	5.0	–	4.4	–	11.2	0.138	6.4	81	80	–	87	–	67	0.192	19
	2008	Pasture	2.6	6.5	5.0		5.5		5.0	0.105	1.4	81	87	–	86	–	88	0.518	11
	2009	Canola	1.5	13.3	8.5	12.0	11.2	14.9	11.5	0.637	5.4	61	64	68	68	55	64	0.444	12
	2010	Wheat	3.3	8.9	5.8	7.8	5.7	5.6	4.6	**0.036**	2.7	74	79	77	80	78	91	0.104	11
	2011	Pasture	1.6	8.8	6.6	6.1	6.7	5.2	6.4	0.212	2.8	67	93	84	86	88	81	0.661	34
9	2006	Canola	1.8	7.1	5.3	–	4.0	–	5.7	0.328	3.6	80	96	–	92	–	87	**0.007**	7
	2007	Wheat	4.8	6.7	4.0	–	4.0	–	4.0	0.079	2.4	90	92	–	88	–	88	0.941	21
	2008	Pasture	3.8	8.3	6.3	–	5.6	–	6.7	0.191	2.6	78	95	–	88	–	85	0.119	14

Table 2. (*continued*)

Site	Year	Crop/ pasture	Open yield	Competition extent								Yield from 2 m to 20 m							
				C	S3	S4	A3	A4	RP3	*P*	l.s.d.	C	S3	S4	A3	A4	RP3	*P*	l.s.d.
	2009	Wheat	4.2	8.2	6.3	7.4	4.8	7.5	6.9	**0.024**	**1.8**	76	85	77	88	79	81	0.061	10
	2010†	Canola	1.1	9.4	4.4	6.3	4.2	4.0	4.5	**0.003**	2.5	84	107	88	84	102	101	0.742	44
	2011	Wheat	4.0	12.7	8.7	12.0	10.1	7.9	9.9	0.138	4.0	56	72	65	73	75	67	**0.046**	12
10	2006	Wheat	1.7	13.7	–	18.7	–	16.6	–	0.432	9.31	44	–	29	–	48	–	0.192	30.3
	2007	Wheat	1.0	19.1	–	5.0	–	17.3	–	**0.024**	4.70	26	–	75	–	50	–	**0.023**	26.9
	2008	Wheat	1.9	12.2	–	4.0	–	4.0	–	0.314	16.67	83	–	128	–	114	–	0.081	40.46
	2009	Wheat	1.6	12.9	–	6.4	–	8.0	–	0.070	5.37	57	–	82	–	76	–	0.177	32.6
	2010	Canola	0.7	20.3	–	O	–	O	–	–	–	20	–	O	–	O	–	–	–
	2011	Wheat	3.1	18.1	–	6.0	–	5.1	–	**0.002**	4.6	48	–	79	–	76	–	**<0.001**	7.11

Table 3. Crop or pasture grown each year, open yield (grain yield or pasture food-on-offer, t ha^{-1}), competition extent (m), and yield in the competition zone from 2 to 20 m (expressed as % of open yield) at sites 11–15

Treatments: unharvested mallees (C); mallees harvested in autumn (A) or spring (S) at 6+ year harvest interval; RP, root-pruning. Also shown are significance of differences between treatments (*P*-values, bold are significant) and least significant differences (l.s.d.) at $P = 0.05$. Where measurements were not taken, the reason is indicated: poor weed control (W), other reasons (O). Shading indicates the years that mallees were harvested. †, Site-year marked thus showed high variability

Site	Year	Crop/ pasture	Open yield	Competition extent						Yield from 2 m to 20 m					
				C	S6+	A6+	RP6+	*P*	l.s.d.	C	S6+	A6+	RP6+	*P*	l.s.d.
11	2006	Wheat	1.9	7.5	6.3	6.8	6.6	0.129	1.1	79	86	80	86	0.199	9
	2007	Pasture	0.6	7.5	7.3	7.8	7.7	0.999	9.9	83	88	87	89	0.974	33
	2008	Wheat		W	W	W	W	–	–	W	W	W	W	–	–
	2009	Pasture		W	W	W	W	–	–	W	W	W	W	–	–
	2010	Wheat	0.8	12.1	O	O	O	–	–	49	O	O	O	–	–
	2011	Lupins	1.2	12.3	11.9	9.3	7.5	0.212	5.5	59	60	72	64	0.491	11
12	2006	Pasture	1.6	4.3	8.3	10.2	8.4	**0.003**	2.4	78	67	93	81	**0.014**	14
	2007	Pasture	5.0	11.3	6.9	7.1	9.7	0.365	6.2	73	78	77	77	0.912	18
	2008	Oats	1.0	9.5	9.7	7.9	6.7	0.402	4.5	69	78	84	92	0.147	21
	2009	Pasture	1.5	10.4	9.7	11.2	7.4	0.377	5.2	72	77	58	73	0.318	25
	2010	Pasture	2.6	12.9	14.9	13.9	13.8	0.780	4.4	61	52	58	61	0.664	19
	2011	Pasture	6.1	10.6	11.0	11.0	9.4	0.937	4.0	70	68	71	76	0.512	11
13	2006	Wheat	1.4	4.0	4.0	4.0	4.0	0.441	–	93	89	105	96	0.219	18
	2007	Pasture	3.2	4.9	2.9	3.6	4.2	0.564	1.8	95	109	79	79	**0.016**	14
	2008†	Pasture	1.9	5.1	4.3	5.5	5.5	0.434	6.6	107	88	106	109	0.846	84
	2009	Wheat		O	O	O	O	–	–	O	O	O	O	–	–
	2010	Measurements discontinued													
14	2006	Pasture	0.6	9.5	11.7	11.5	14.1	0.575	8.6	79	54	60	46	0.131	29
	2007	Wheat	1.0	13.4	6.7	8.8	6.7	**0.021**	3.7	31	79	76	73		
	2008	Wheat	3.0	14.8	4.0	8.7	4.0	**0.004**	4.6	51	88	82	88	**0.006**	15
	2009	Wheat	1.6	11.9	4.0	5.8	4.0	**0.002**	2.8	64	102	82	109	**0.001**	12
	2010	Wheat	0.9	19.6	O	O	O	–	–	29	O	O	O	**–**	–
	2011	Canola	0.7	14.7	11.6	10.4	8.0	0.160	6.7	34	58	63	75	**0.049**	28
15	2006	Wheat	2.6	8.2	6.9	5.8	6.2	0.196	2.5	77	82	86	85	0.743	20
	2007	Barley	2.6	8.1	7.5	6.2	6.2	0.329	2.8	82	81	85	88	0.728	16
	2008	Pasture	3.1	12.2	8.6	8.5	5.0	0.438	9.8	56	85	72	86	**0.030**	20
	2009	Canola	1.6	10.7	9.0	10.7	9.5	0.196	2.1	70	76	73	73	0.812	14
	2010	Wheat	3.7	11.2	9.8	12.0	10.0	**0.009**	1.1	69	78	65	77	**0.011**	7
	2011	Barley	2.3	14.0	10.5	13.1	11.5	**0.002**	1.0	48	64	53	57	**0.050**	10

mallees further decreased mean break-even distance by 0.3 and 0.7 m for the 3- and 6+-year harvest intervals, respectively.

The opportunity-cost distance ranged between +4.1 and 43.5 m for unharvested mallees and +6.8 and 32.9 m for harvested mallees (where + indicates a benefit or effective increase in GM) (data not presented). Annual treatment means of opportunity-cost distance showed similar trends over time to break-even distance (Fig. 4*a*, *b*).

The mean opportunity-cost distance for unharvested mallees over 6 years was 14.4 m (all sites-years). If site averages were used so that site-years with open GM <0 could be included in the analysis, the opportunity-cost distance was 14.1 m for

Table 4. Regression coefficients for the 1–4-variable models that best explained annual competition extent and magnitude adjacent to unharvested mallee belts

Explanatory variable parameters: mallee age (years); GSP, growing season rainfall (mm); GSCWI, growing season climate wetness index; mallee height (m); MAI, mallee mean annual increment (t ha^{-1} $year^{-1}$); mallee aboveground biomass (t ha^{-1}). The *t* probabilities of parameters are in parentheses

Constant	Explanatory variable parameter						r^2
	Mallee age	GSP	GSCWI	Mallee height	Mallee MAI	Mallee biomass	
			Yield from 2 to 20 m (% of open yield)				
97.1	–3.441 (<0.001)						0.17
129.3	–3.799 (<0.001)		49.8 (<0.001)				0.33
141.0	–3.179 (0.001)		59.0 (<0.001)	–2.69 (0.191)			0.34
142.3	–10.13 (<0.001)	0.121 (<0.001)			–9.720 (<0.001)	0.861 (<0.001)	0.45
			Competition extent (m)				
4.05	0.763 (<0.001)						0.19
8.58	0.796 (<0.001)	–0.021 (<0.001)					0.34
8.12	0.612 (0.002)	–0.027 (<0.001)		0.753 (0.076)			0.36
–4.36	2.031 (<0.001)	–0.025 (<0.001)			1.898 (<0.001)	–0.166 (<0.001)	0.44

Table 5. Regression coefficients for the 1–4-variable models that best explained annual competition extent and magnitude adjacent to harvested mallee belts

Explanatory variable parameters: mallee aboveground biomass (t ha^{-1}); GSP, growing season rainfall (mm); crop or pasture (crop = 0, pasture = 1); GSCWI, growing season climate wetness index. The *t* probabilities of parameters are in parentheses

Constant	Explanatory variable parameter				r^2
	Mallee biomass	GSP	Crop/pasture	GSCWI	
		Yield from 2 to 20 m (% of open yield)			
83.4	–0.269 (<0.001)				0.18
80.2	–0.247 (<0.001)		7.59 (<0.001)		0.23
70.0	–0.242 (<0.001)	0.046 (<0.001)	7.42 (<0.001)		0.27
		Competition extent (m)			
7.06	0.047 (<0.001)				0.13
10.03	0.045 (<0.001)	–0.003 (<0.001)			0.20
10.67	0.041 (<0.001)	–0.012 (<0.001)	–1.66 (<0.001)		0.25
23.29	0.041 (<0.001)	–0.036 (<0.001)	–1.80 (<0.001)	12.38 (<0.001)	0.31

Table 6. Regression coefficients for the 1- and 2-variable models that best explained site mean competition extent and magnitude adjacent to unharvested mallee belts

The *t* probabilities of parameters are in parentheses

Constant	Explanatory variable parameter		r^2
	Mallee age (years)	Colwell P (g m^{-2})	
	Yield from 2 to 20 m (% of open yield)		
115.8	–5.58 (0.019)		0.31
141.2	–6.20 (0.003)	–2.796 (0.011)	0.57
	Competition extent (m)		
0.32	1.187 (0.018)		0.31
–5.46	1.328 (0.002)	0.636 (0.005)	0.62

unharvested mallees. Harvesting the mallees on 3-, 4-, and 6+-year intervals reduced the opportunity-cost distance by 3.9, 3.3, and 3.9 m, respectively (Table 7). Root-pruning of mallees further decreased the opportunity cost by 0.2 and 1.0 m for the 3- and 6+-year harvest intervals, respectively.

Opportunity-cost distances were calculated for sites-years when the actual width of the uncropped area next to the mallees varied from 2 to 9 m and averaged 3.6 m (data not presented). It was possible to reduce the opportunity-cost distance for sites and years with a wide break-even distance. For example, for treatment C at site 10 in 2007, opportunity-cost distance was reduced from 36 to 19 m by increasing the uncropped distance from 3 to 18 m (Fig. 5). However, where the break-even distance was relatively small (e.g. for treatment S3 at Site 10 in 2007 or harvested and unharvested mallees at Site 9 in 2009), there was no advantage in leaving >5 m uncropped. The costs of inputs and prices received for agricultural products did not alter the optimum uncropped distance in a particular year but did affect the opportunity-cost distance (Fig. 6). Opportunity-cost distance generally increased with increasing input costs and declined with increasing prices paid for agricultural produce. Consequently, opportunity-cost distance was generally less for pasture than for crop, averaging 12.9 and 15.8 m, respectively, adjacent to unharvested mallees.

Discussion

The extent and magnitude of tree–crop competition varied widely among sites and years but for unharvested mallee belts were broadly similar to what has been reported for various agroforestry systems in southern Australia. The economic impact of this

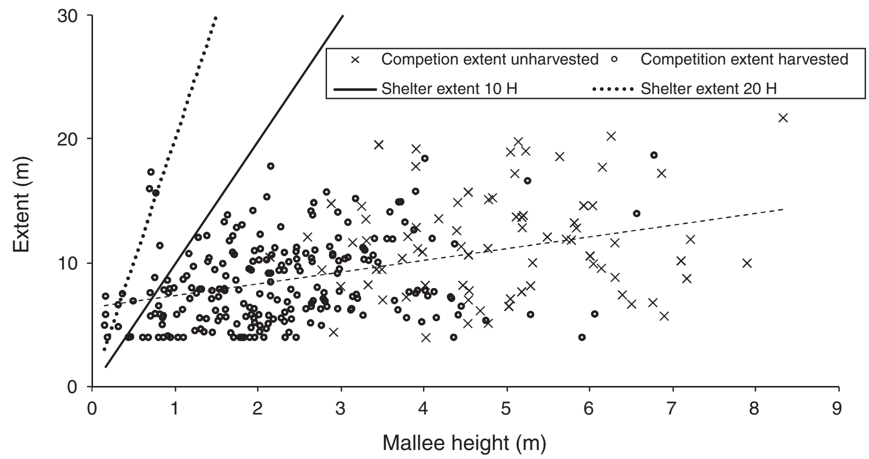

Fig. 2. Lateral extent of competition zone and sheltered zones of widths 10 and 20 times the height of the unharvested mallees (10 H, 20 H), for harvested and unharvested mallee belts of differing height. Also shown is the line that best describes the relationship between tree height and competition extent: competition extent (m) = 0.949 × tree height (m) + 6.448, $r^2 = 0.17$.

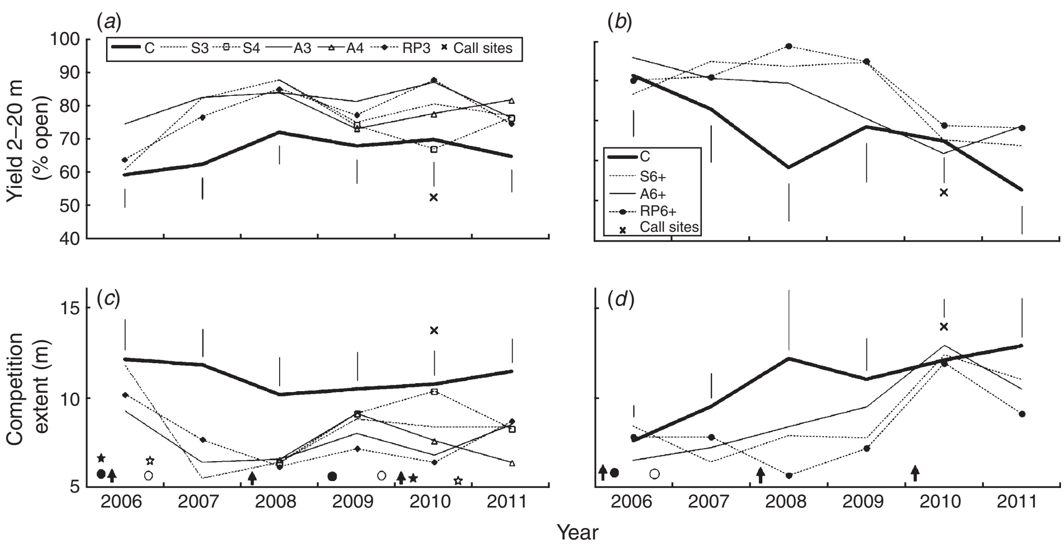

Fig. 3. Mean yield at 2–20 m from mallee belts and lateral extent of competition for crops and pasture adjacent to mallee belts at sites that were unharvested (C), or harvested on: (*a*, *c*) a 3- and 4-year interval, or (*b*, *d*) a 6+-year interval. Closed circles show when autumn (A) and open circles when spring (S) harvests were made on 3- or 6+-year intervals; closed stars show when autumn and open stars when spring harvests were made on 4-year intervals. Arrows indicate when treatments RP3 and RP6+ were root-pruned. Vertical bars are l.s.d. ($P = 0.05$). Two values for treatment C are shown for 2010: the average value for sites where all treatments were measured (i.e. excluding sites 7, 10, 11, and 14), and the average including sites 7, 10, 11, and 14 (C all sites).

competition on agricultural production was considerable. Harvesting mallee belts reduced competition adjacent to the belts for up to 5 years. These findings, along with some of the economic implications, are discussed below.

The average extent of tree–crop competition adjacent to unharvested mallees (11.3 m, or 2.6 H) was within the range reported for mallees (Sudmeyer and Flugge 2005; Sudmeyer and Daniels 2010) and for various exotic and native tree species in southern Australia (Bird *et al.* 2002; Sudmeyer *et al.* 2002*a*; Woodall and Ward 2002; Unkovich *et al.* 2003; Oliver *et al.* 2005; Sudmeyer and Flugge 2005; Bennell and Verbyla 2008; Sudmeyer and Daniels 2010; Huth *et al.* 2010) and temperate areas elsewhere in the world (e.g. Brandle *et al.* 2009). It is also within the measured root extent of mallees (Sudmeyer *et al.* 2004) or extent inferred from reduced soil water content (Robinson *et al.* 2006; Brooksbank *et al.* 2011).

This competition from unharvested mallees resulted in an average reduction in crop and pasture yield between 2 and 20 m from the belts of 36% and a zero-yield distance of 8.8 m, which are also within the range of values reported for various tree species in southern Australia (Bird *et al.* 2002; Sudmeyer *et al.* 2002*a*; Woodall and Ward 2002; Unkovich *et al.* 2003; Oliver *et al.* 2005;

Table 7. Mean yield from 2 to 20 m from mallees (% of open yield), competition extent (m), zero-yield distance (m), and opportunity-cost and break-even distances (m) averaged over 6 years for unharvested mallees at sites 1–10 (C3–4) and sites 11–15 (C6+) and mallees harvested on 3-, 4-, and 6+-year intervals with (+RP) and without (–RP) root pruning

Yield and gross margin (GM) adjacent to mallees harvested every 4 years was assumed to be the same as adjacent to mallees harvested every 3 years for 3 years after the first harvest. Values are means from sites where all treatments were measured (i.e. excluding sites 7, 10, 11 and 14 in 2010) and when open GM >AU\$0 ha^{-1}

	C3–4	C6+	Harvest interval				
			3 years		4 years	6+ years	
			–RP	+RP	–RP	–RP	+RP
Yield 2–20 m	65	68	80	77	75	76	79
Competition extent	11.3	10.2	7.6	7.6	8.9	8.6	7.8
Zero-yield distance	8.6	7.8	6.3	6.6	6.7	5.9	5.8
Break-even distance	6.7	7.7	4.9	4.6	5.1	6.1	5.4
Opportunity-cost distance	12.8	13.7	8.9	8.7	9.5	9.8	8.8

Bennell and Verbyla 2008) and mallee belts in Western Australia (Sudmeyer and Flugge 2005; Sudmeyer and Daniels 2010).

Competition was positively correlated with mallee height and MAI, and harvesting the mallees reduced both the extent and magnitude of competition, supporting hypothesis (*i*). The greatest reductions were seen in the first and second years after harvest, with reduced competition still evident 5 years after harvest at sites with slower growing mallees and longer harvest intervals. Competition was not reduced 4 years after harvest, which may have reflected the very dry conditions in that year and negative correlation between rainfall and competition.

Crop yield generally increased and zero-yield distance declined with increasing frequency of mallee harvest, so crop and pasture yield increased by 14–9% (of open yield) and zero-yield distance decreased by 2.4–2.0 m for harvest intervals of 3–6+ years, respectively, supporting hypothesis (*ii*). Season of harvest also influenced competition response, probably as a result of both immediate reductions in mallee water use and subsequent differences in coppice growth rates; this also supports hypothesis (*ii*). In the year mallees were harvested, competition was only reduced when harvest was before the onset of growing season rainfall (autumn harvest), with spring harvest having little effect. This was evident for both the first and second harvests. Autumn harvest stopped mallee water use at a time when rainfall generally exceeded potential evaporation, reducing soil-water deficits and partitioning more water to crop or pasture growth in the early part of their growing season. In contrast, when mallees were harvested in spring, crop or pasture had established and completed vegetative growth phases under conditions of high soil-water deficit. Mallee water use then ceased when potential evaporation generally exceeded rainfall and there was less potential for reducing soil-water deficits.

Mallee coppice regrowth 3 and 4 years after harvest was 23% greater for autumn than for spring harvest ($P = 0.003$ and $P = 0.030$, respectively; data for our sites only in Huxtable *et al.* 2012). At the sites with 6+-year rotation lengths, this resulted in greater competition extent and magnitude adjacent to autumn-harvested mallees at 2 and 3 years after harvest compared with spring-harvested mallees (Fig. 2*b*, *d*). At sites with 3- and 4-year harvest intervals, the water-saving benefits of autumn harvest offset any additional competitiveness afforded by greater coppice growth.

Root-pruning had little effect on competition when mallees were harvested on a 3-year interval, and only reduced mean opportunity-cost distance by 1 m when mallees were harvested on a 6+-year interval, suggesting that hypothesis (*iii*) should be

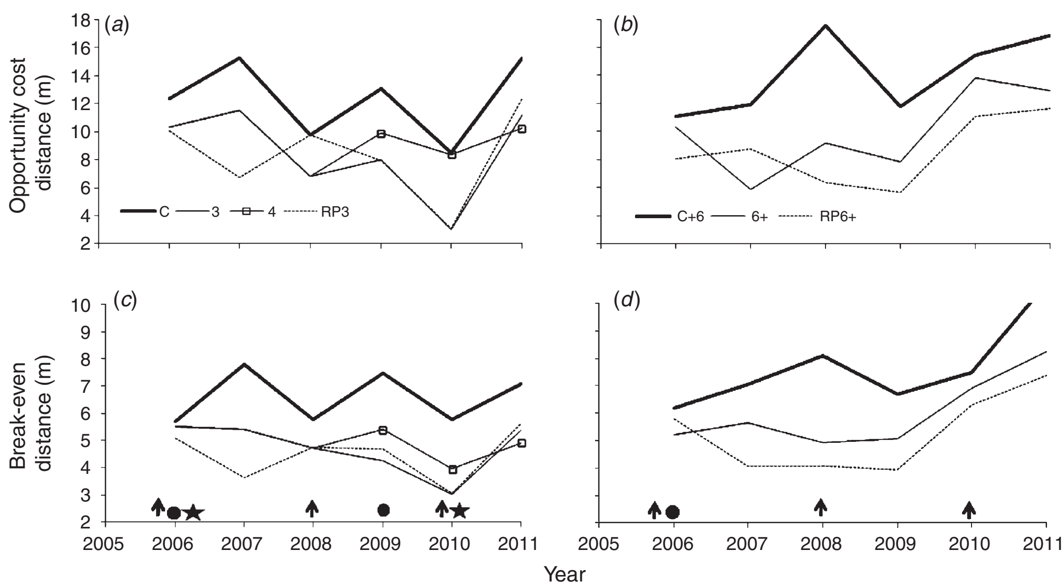

Fig. 4. Mean opportunity-cost distance and mean break-even distance for crops and pasture adjacent to mallee belts at sites that were unharvested (C), or harvested on: (*a*, *c*) a 3- and 4-year interval, or (*b*, *d*) a 6+-year interval. Closed circles show when treatments were harvested on a 3- or 6+-year interval, closed stars when treatments were harvested on a 4 year interval. Arrows indicate when treatments RP3 and RP 6+ were root-pruned. Values are means of both spring- and autumn-harvested treatments.

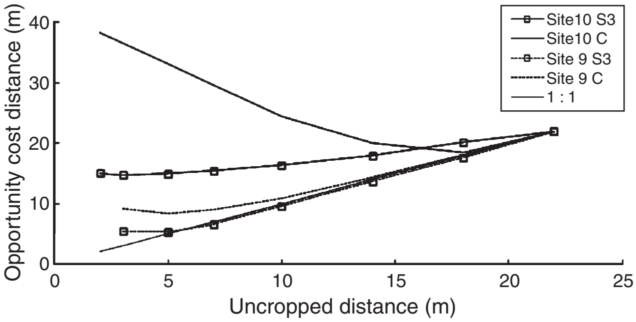

Fig. 5. Change in opportunity-cost distance with distance uncropped next to belts. Calculated using data for unharvested mallees (C) and mallees spring-harvested on a 3-year interval (S3) at sites 10 (2007) and 9 (2009).

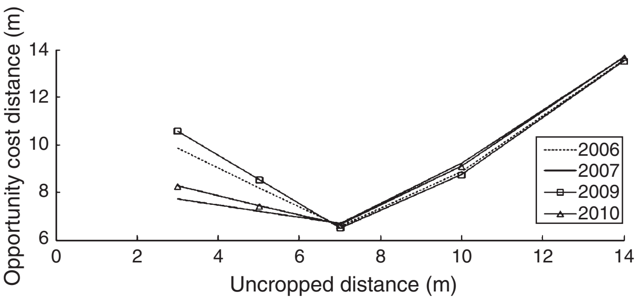

Fig. 6. Change in opportunity-cost distance next to unharvested mallees with various uncropped distances and open gross margin. Calculated using data from site 15 in 2006 and input costs and farm-gate wheat prices for 2006 (AU\$230 ha^{-1} and \$182 t^{-1}, respectively), 2007 (\$280 ha^{-1} and \$368 t^{-1}, respectively), 2009 (\$308 ha^{-1} and \$225 t^{-1}, respectively) and 2010 (\$270 ha^{-1} and \$290 t^{-1}, respectively).

rejected. This result differs from that reported by Sudmeyer and Flugge (2005), who found that root-pruning decreased competition adjacent to mallees harvested on a 1–2-year interval and was associated with a statistically significant decline in mallee growth rates. While root pruning in the present study did not statistically reduce mallee growth, there was a general trend for less growth of root-pruned belts at sites with 6+-year harvest intervals (Huxtable *et al.* 2012). There is good evidence of root-pruning reducing tree–crop competition adjacent to unharvested tree lines (Sudmeyer *et al.* 2002*b*; Woodall and Ward 2002; Sudmeyer and Flugge 2005), but the effectiveness of root-pruning in longer harvest cycles and unharvested mallee systems needs further investigation. It is particularly important to understand what effect root-pruning has on mallee growth and subsequent income from biomass production or carbon sequestration.

There appears to be little scope for using site selection to minimise competition, suggesting that hypothesis (*iv*) should be rejected. In order for harvested mallee agroforestry systems to be economically competitive with conventional agriculture, they have to be located in medium- and high-rainfall areas where high mallee growth rates can be achieved (Bartle *et al.* 2012). Competition extent and magnitude were negatively correlated with growing season rainfall, a trend also observed in other studies (Sudmeyer *et al.* 2002*a*; Woodall and Ward 2002; Unkovich *et al.* 2003; Oliver *et al.* 2005; Sudmeyer and Daniels 2010; Huth *et al.* 2010); however, this is offset by greater mallee growth in higher rainfall environments. In terms of site edaphic conditions, competition was positively correlated with soil Colwell P, but this is also linked to a positive correlation between Colwell P and tree growth (Huxtable *et al.* 2012).

The economic consequences of competition in terms of agricultural income foregone were greater than could be inferred from yield reductions alone. While there was considerable variability among sites and years, the average opportunity-cost distance was 14 m on each side of unharvested mallee belts. This included an average uncropped distance of 4 m and amounted to ~39% of mean alley width. Average opportunity-cost distances adjacent to harvested mallees of 9–10 m, while less, are still significantly greater than the 2 m on either side of mallee belts that is commonly assumed to be left uncropped. These opportunity costs will have a significant impact on the economics of mallee agroforestry systems, particularly carbon sequestration schemes utilising integrated belts of unharvested mallees.

Foregoing agricultural production from 14 m or even 9 m on either side of mallee belts poses a cost to farmers that will be a significant factor in farmers' perceptions and decisions regarding mallee agroforestry systems (Pannell 2001; Ong *et al.* 2002; Brandle *et al.* 2009). Financial benefits tend to be the most highly rated motivation for farmers adopting changes to production systems, followed by environmental and personal considerations, respectively (Ecker *et al.* 2011). For mallee agroforestry systems to be broadly acceptable, the cost of foregone agricultural production will have to be offset by direct returns from mallee biomass, sequestered carbon, or indirect benefits such as shelter or environmental amelioration. In all cases, mallee agroforestry systems will be more profitable and acceptable to land managers if competition can be minimised.

There is scope for reducing the opportunity-cost distance by reducing the cost of agricultural inputs such as fertilisers, herbicides, and pesticides applied to the competition zone, particularly in years when costs rise or prices for products fall, or in dry years when competition can be expected to increase, supporting hypothesis (*v*). This could be achieved by maintaining pasture rather than cropping, using variable-rate technologies, or increasing the width of the uncropped area immediately adjacent to the belt.

While harvesting in commercial mallee biomass production systems would operate year-round, farmers would benefit financially from flexibility in scheduling mallee harvests and crop rotations. Although the variable response of different crop types to shelter provided by tree windbreaks has been widely reported (Sudmeyer *et al.* 2002*a*; Bennell and Verbyla 2008; Brandle *et al.* 2009), it is not possible to recommend crops that are more competitive with mallees. Consequently, agricultural crops that require greater input costs and are less competitive than pasture should be scheduled for years when mallees are least competitive, i.e. when mallees are harvested in the preceding summer–autumn and for 2 years after harvest. Pastures and stock grazing would be best scheduled for years before mallee harvest when the mallees are most competitive and large enough to resist grazing damage.

The uncropped distance was quite variable in this study, ranging from <2 m to 9 m. As costs exceed returns inside the break-even distance, there is a good case for routinely increasing the uncropped distance to 7 m or 4–5 m next to unharvested or harvested mallees, respectively. These wider alley margins would still require management to ensure that vegetative cover was maintained to prevent wind erosion and the margins did not become reservoirs for pest and diseases or the source of herbicide resistance from poorly controlled weeds (GRDC 2010). Further work is required to quantify the economics of doing this and to investigate whether reducing the application of fertilisers affects mallee growth.

The potential for direct returns from mallee agroforestry has most recently been explored by Bartle *et al*. (2012), using mallee growth and competition data from the sites in this study. They found that mallee agroforestry producing biomass for electricity generation was economically competitive with conventional agriculture in areas of the Western Australian wheatbelt receiving >450 mm rainfall. Their analysis included payment for sequestered carbon and avoided greenhouse gas emissions but did not include payment for other environmental services. The value of environmental services is often difficult to quantify, and currently there are no mechanisms for farmers to receive payment. However, this may change; for example, Garnaut (2011) suggested that carbon offset schemes that provided additional environmental services may attract a price premium.

Much of the initial interest in mallee agroforestry research and development was based on the potential to reduce groundwater recharge and so mitigate secondary salinisation. Bennett *et al*. (2011) showed that while unharvested mallee belts spaced <30 m apart can reduce the area affected by secondary salinity in the wheatbelt of Western Australia, belts spaced >50 m apart have little effect in the absence of other land-use changes. Our study suggests that alley widths <30 m are functionally similar to block plantings, given agricultural production would be severely compromised by mallee–crop competition. For farmers who want to continue cropping, alley widths must be designed to accommodate wider uncropped distances than are currently the norm. Also, increasingly large agricultural machinery and a move towards controlled traffic operations favour wide, straight alleys. The study by Bennett *et al*. (2011) suggests that the valuation of salinity mitigation benefits from wide-spaced mallee agroforestry systems is subject to uncertainties and remains problematic.

Similar uncertainties relate to the provision of habitat services by mallee plantings. Smith (2009) investigated the habitat value of 48 mallee planting sites in Western Australia, stratified by planting configuration (block or belt) and proximity to remnant vegetation. The mallee plantings were found to provide some structural habitat values, but less than half the predicted habitat value of good-quality remnant vegetation, due to a lack structural and floristic diversity. Re-colonisation of mallee sites by native species (which would increase habitat value) was greater in plantings adjacent to woodland, which may also be linked to the exclusion of stock.

The shelter benefits of unharvested mallee belts offer more economic promise. Shelter in southern Australia has been shown increase crop yield by 7% within a sheltered zone of width 10 H (Bennell and Verbyla 2008) or 2–4% in a sheltered zone of width 20 H (Sudmeyer *et al*. 2002*a*; Oliver *et al*. 2005) (both excluding the competition zone). If the greatest shelter benefit; i.e. a 4% yield increase to 20 H, is assumed for the sites in this study, the mean opportunity-cost distance is reduced by 2 m. If the alleys had been >25 H wide, so that the ratio of sheltered zone to competition zone was maximised, the opportunity-cost distance would have been reduced by 4 m. It should be noted that the shelter benefit will be <4% where crops are not subject to occasional sandblasting (Sudmeyer *et al*. 2002*a*), belts are not oriented to protect against damaging winds, or for 1–3 years after harvest when the sheltered zone is small in relation to the competition zone.

The preferred two-row mallee-belt layout (Cooper *et al*. 2005; URS 2009; Bartle and Abadi 2010) directly displaces agricultural production from a strip 2–3 m wide (two rows with 2–3 m between rows). Accounting for the zero-yield distance increases effective unharvested or harvested belt width to 17–20 m or 14–16 m, respectively. Clearly, this has land-use change implications that need to be considered when accounting for the greenhouse gas benefits of mallee biofuels (Berndes *et al*. 2010; Marshall *et al*. 2011).

Mallee–crop competition will be an unavoidable feature of mallee agroforestry systems. Consequently, for mallee systems to be widely acceptable, they will have to be designed and managed to minimise competition losses and offset the remaining losses with direct income from the mallees.

Conclusions

This research has shown mallee–crop competition presents a significant cost to farmers which must be considered when estimating the economics of mallee agroforestry with either unharvested mallees for carbon sequestration or harvested mallees for biomass production.

Agricultural production adjacent to mallee belts is positively correlated with growing season rainfall and inversely correlated with mallee age and size. Consequently, the economic cost of mallee–crop competition on agricultural enterprises is variable. Averaged across all site-years, the opportunity cost of competition was equivalent to forgoing agricultural production for 14 m or 9–10 m on each side of unharvested and harvested belts, respectively.

Farmers with mallee agroforestry systems will need to manage the economic costs of competition by reducing agricultural input costs in the competition zone, timing pasture rotations with mallee harvests, ensuring that alley widths are at least 25 times the height of unharvested mature trees, and possibly root-pruning mallees in unharvested or long harvest interval systems.

Acknowledgments

The following landowners are thanked for their generosity in allowing us to make measurements on their farms: Don Alexander, Gaye and Meryl Armstrong, the Bird Family, Gordon and John McDougall, Michael and Narelle Dodd, Carl Fuchbichler, Neil Gillies, Trevor Johnson, the Morrell family, Harry and Bernadine Mullan, Gerry Pauley, John Pepal, Norm Quicke, Ashley and Megan Reichstein, the Saddler family, the Stanley family, and the Sullivan family. Andrew Van Burgel is thanks for his advice and assistance with analysing the data and improving the manuscript. Angela Stuart-Street, Paul Galloway, and Claire Robertson are thanked for describing and naming the soils at various sites. Tim Pope and Ben Cohen are thanked for assisting with collecting soil cores at each site. Dave Mills is thanked for ripping the sites, and Vince Lambert, Chris Mills, and Shari Dougall are thanked for harvesting crops at various sites. Don Bennett, Kim Brooksbank, and Daniel Mendham are thanked for reviewing drafts of this paper. Funding for this project has been provided by the Western Australian Department of Agriculture and Food, the Department of Environment and Conservation, Rural Industries Research and Development Corporation, Avon Catchment Council, National Heritage Trust, and Department of Resources Energy and Tourism.

References

ABARE (2009) 'Australian commodity statistics 2009.' (Australian Bureau of Agricultural and Resource Economics: Canberra)

ABARES (2011) 'Agricultural commodities: December quarter 2011. Vol. 1. No. 2.' (Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra)

Bankwest (2006) 'BankWest benchmarks: 2005–2006 season.' (BankWest Agribusiness Centre: Perth, W. Aust.)

Bankwest (2008) 'Planfarm BankWest benchmarks: 2007–2008 season.' (Planfarm, BankWest Agribusiness Centre: Perth, W. Aust.)

Bartle JR, Abadi A (2010) Towards sustainable production of second generation bioenergy feedstocks. *Energy & Fuels* **24**, 2–9. doi:10.1021/ef9006438

Bartle J, Abadi A and Thomas Q (2012) Economic analysis. In 'Productivity of mallee agroforestry systems. The effect of harvest and competition management regimes'. RIRDC Publication No. 11/162. (Eds A Peck, R Sudmeyer, D Huxtable, J Bartle, D Mendham) pp. 98–124. (Rural Industries Research and Development Corporation: Canberra)

Bennell MR, Verbyla AP (2008) Quantifying the response of crops to shelter in the agricultural regions of South Australia. *Australian Journal of Agricultural Research* **59**, 950–957. doi:10.1071/AR08188

Bennett D, Simons J, Speed R (2011) Hydrological impacts of integrated oil mallee farming systems. Department of Agriculture and Food, Resource Management Technical Report 377, Perth, W. Aust.

Berndes G, Bird N, Cowie A (2010) Bioenergy, land use change and climate change mitigation – Background Technical Report. IEA Bioenergy: ExCo:2010 : 03. Available at: www.ieabioenergy.com/LibItem.aspx?id=6927

Bird PR, Jackson TT, Kearney GA, Williams KW (2002) Effect of two tree windbreaks on adjacent pastures in south-western Victoria, Australia. *Australian Journal of Experimental Agriculture* **42**, 809–829. doi:10.1071/EA02016

Brandle JR, Hodges L, Tyndall J, Sudmeyer RA (2009) Windbreak practices. In 'North American agroforestry: an integrated science and practice'. 2nd edn (Ed. HE Garrett) pp. 75–104. (America Society of Agronomy Inc.: Madison, WI)

Brooksbank K, White DA, Veneklaas EJ, Carter JL (2011) Hydraulic redistribution in *Eucalyptus kochii* subsp. *borealis* with variable access to fresh groundwater. *Trees.* doi:10.1007/s00468-011-0551-0

Campbell NA, Arnold GW (1973) The visual assessment of pasture yield. *Australian Journal of Experimental Agriculture and Animal Husbandry* **13**, 263–267. doi:10.1071/EA9730263

Cooper D, Olsen G, Bartle J (2005) Capture of agricultural surplus water determines the productivity and scale of new low-rainfall woody crop industries. *Australian Journal of Experimental Agriculture* **45**, 1369–1388. doi:10.1071/EA04152

Crosbie RS, Wilson B, Hughes JD, McCulloch C (2008) The upscaling of transpiration from individual trees to areal transpiration in tree belts. *Plant and Soil* **305**, 25–34. doi:10.1007/s11104-007-9420-4

Department of Agriculture and Food Western Australia (2005) 'Gross margins guide 2005 Western Australia: representative gross margins for crop and livestock enterprises of the agricultural regions of Western Australia.' (Department of Agriculture and Food: Perth, W. Aust.)

Ecker S, Kancans R, Thompson L (2011) Drivers of practice change in land management in Australian agriculture: preliminary national survey results. Science and Economics Insights, Issue 2.1. Australian Bureau of Agricultural and Resource Economics-Bureau of Rural Sciences, Canberra.

Ellis T, Hatton T, Nuberg I (2005) An ecological optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments. *Agricultural Water Management* **75**, 92–116. doi:10.1016/j.agwat.2004.12.004

Farm Weekly (2006) Farm budget guide 2006. Farm Weekly, Perth, W. Aust.

Farm Weekly (2007) Farm budget guide 2007. Farm Weekly, Perth, W. Aust.

Farm Weekly (2008) Farm budget guide 2008. Farm Weekly, Perth, W. Aust.

Farm Weekly (2009) Farm budget guide 2009. Farm Weekly, Perth, W. Aust.

Farm Weekly (2010) Farm budget guide 2010. Farm Weekly, Perth, W. Aust.

Garnaut R (2011) Garnaut Climate Change Review—Update 2011. Update Paper 4: Transforming rural land use. www.garnautreview.org.au/update-2011/update-papers/up4-key-points.html

George-Jaeggli B, Meinke H, Carberry PS, de HN Maia A, Voller P (1998) Variations in wheat yield behind windbreaks in southern Queensland. In 'Agronomy, growing a greener future? Proceedings of the 9th Australian Agronomy Conference'. 20–23 July 1998, Wagga Wagga, NSW. (Eds DL Michalk, JE Pratley)

GRDC (2010) Managing resistance on fencelines and crop margins. Glyphosate Resistance Fact Sheet. Grains Research and Development Corporation, Canberra.

Huth NI, Robertson MJ, Poulton PA (2010) Regional differences in tree–crop competition due to soil, climate and management. *Crop & Pasture Science* **61**, 763–770. doi:10.1071/CP09254

Huxtable D, Peck A, Bartle J, Sudmeyer R (2012) Tree biomass. In 'Productivity of mallee agroforestry systems. The effect of harvest and competition management regimes'. RIRDC Publication No. 11/162. (Eds A Peck, R Sudmeyer, D Huxtable, J Bartle, D Mendham) pp. 5–58. (Rural Industries Research and Development Corporation: Canberra)

IEA (2009) Bioenergy—the impact of indirect land use change. Summary and Conclusions from the IEA Bioenergy ExCo63 Workshop. IEA Bioenergy: ExCo:2009 : 04. Available at: www.ieabioenergy.com/DocSet.aspx?id=6214&ret=lib

Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Melbourne)

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

Knight A, Blott K, Portelli M, Hignett C (2002) Use of shrub belts to control leakage in three dryland cropping environments. *Australian Journal of Agricultural Research* **53**, 571–589. doi:10.1071/AR01089

Lefroy EC, Stirzaker RJ, Pate JS (2001) The influence of tagastaste (*Chamaecytisus proliferus* Link.) trees on the water balance of an alley cropping system on deep sand in south-western Australia. *Australian Journal of Agricultural Research* **52**, 235–246. doi:10.1071/AR00035

Marshall E, Weinberg M, Wunder S, Kaphengst T (2011) EuroChoices. *The Agricultural Economics Society and the European Association of Agricultural Economists* **10**, 43–49.

Oliver YM, Lefroy EC, Stirzaker R, Davies CL (2005) Deep-drainage control and yield: the trade-off between trees and crops in agroforestry systems in the medium and low rainfall areas of Australia. *Australian Journal of Agricultural Research* **56**, 1011–1026. doi:10.1071/AR04213

Ong CK, Wilson J, Deans JD, Mulayta J, Raussen T, Wajja-Musukwe N (2002) Tree-crop interactions; manipulations of water use and root function. *Agricultural Water Management* **53**, 171–186. doi:10.1016/S0378-3774(01)00163-9

Pannell DJ (2001) Explaining non-adoption of practices to prevent dryland salinity in Western Australia: Implications for policy. In 'Land degradation'. (Ed. A Conacher) (Kluwer: Dordrecht)

Peverill KI, Sparrow LA and Reuter DJ (1999) 'Soil analysis: an interpretation manual.' (CSIRO Publishing: Melbourne)

Queensland Government (2011) Silo Data Drill. Available at: www.longpaddock.qld.gov.au/silo/

Robinson N, Harper RJ, Smettem KRJ (2006) Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. *Plant and Soil* **286**, 141–151. doi:10.1007/s11104-006-9032-4

Saltlandgenie (2011) Unit 7 Saltland Toolbox – salinity indicators. Available at: www.saltlandgenie.org.au/all-about-saltland/unit-7-toolbox/measuring-salinity-and-waterlogging.htm

Smith FP (2009) Assessing the habitat quality of oil mallees and other planted farmland vegetation with reference to natural woodland. *Ecological Management & Restoration* **10**, 217–227. doi:10.1111/j.1442-8903.2009.00491.x

Sudmeyer RA (2001) Tree and crop growth in an oil mallee alley system: the effect of soil type and competition management. In 'Proceedings of Vegetation Recovery in Degraded Land Areas Workshop'. Kalgoorlie, Western Australia, 27 October–3 November 2001. (Promoco Conventions Pty Ltd: Perth, W. Aust.)

Sudmeyer RA, Daniels T (2010) 'The golden wreath wattle as an alternative to the mallee eucalypt for alley systems; comparative growth, water use, nutrient use and competitiveness of *Acacia saligna* and *Eucalyptus polybractea*.' RIRDC Publication No. 10/071. (Rural Industries Research and Development Corporation: Canberra)

Sudmeyer R, Flugge F (2005) The economics of managing tree-crop competition in windbreak and alley systems. *Australian Journal of Experimental Agriculture* **45**, 1403–1414. doi:10.1071/EA04155

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**, 1333–1346. doi:10.1093/treephys/24.12.1333

Thornthwaite CW (1948) An approach toward a rational classification of climate. *Geographical Review* **38**, 55–94. doi:10.2307/210739

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

URS (2009) 'Oil Mallee industry development plan for Western Australia.' (Oil Mallee Association: Perth, W. Aust.) Available at: www.fpc.wa.gov.au/content_migration/_assets/documents/plantations/industry_plans/oil_mallee_idp.pdf

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