CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar *Australian Journal of Agricultural Research*, 2005, **56**, 1011–1026

Deep-drainage control and yield: the trade-off between trees and crops in agroforestry systems in the medium to low rainfall areas of Australia

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Abstract. In the dryland cropping areas of southern Australia, at risk from dryland salinity, tree belts can improve water management by taking up water unused by crops, with the risk that crop yield will be reduced through competition. As there are few direct markets for tree products grown in the medium to low rainfall areas, the design of agroforestry systems becomes important in reducing the trade-off in crop yield.

This study examined some factors that influence the trade-off between crop yield and deep-drainage control in order to develop design guidelines for medium to low rainfall agroforestry. Twenty-one sites in the grain-growing region of Western Australia and southern New South Wales were surveyed over 2 years for crop yields, tree leaf area index, and estimated recharge, providing data from 32 tree–crop interfaces on the relative influence of environmental factors and farming system characteristics on the trade-off between water management and crop yield.

The factors most strongly correlated with higher yields were water-gaining sites, orientation that provided shelter from southerly to north-westerly (S, SW, W, NW) winds, and tree age (<10 years). The factors most strongly correlated with the area of cropped land protected against deep drainage were tree age (>10 years), lighter soil types, and low rainfall (<400 mm). Economic analysis of the trade-off required to produce a particular deep-drainage reduction target produced 3 groups of sites: (*1*) those where trees resulted in a gross margin increase of \$15/ha and an estimated deep-drainage reduction of 52% ($n = 3$), (*2*) those with a gross margin loss of \$49/ha and estimated deep-drainage reduction of 47% ($n = 11$), and (*3*) those with a gross margin loss of \$163/ha and a deep-drainage reduction of 37% ($n = 18$). None of the 3 sites in the first group were in the most favourable class in both years, highlighting the vulnerability of a relatively fixed farming system to climate variability.

Additional keywords: no-recharge-zone, no-yield-zone, complementarity, alley farming.

Introduction

The greatest opportunity for agroforestry exists where trees capture resources under-utilised by crops without compromising crop yield (Sanchez 1995; Cannell *et al*. 1996; Ong and Leakey 1999). If such complementarity can be reliably demonstrated under Australian conditions, it has 2 potential benefits for the sustainability of our farming systems: improved crop yield through a more favourable microclimate and more complete water use resulting in better management of dryland salinity and erosion.

Stirzaker *et al*. (1999) proposed the theoretical conditions under which trees would be best integrated, segregated, or rotated with crops. Ideally, trees in spaced belts would reduce deep drainage and salinity risk while allowing crops to be grown profitably in the alleys between. The challenge is to identify whether there is likely to be a trade-off or benefit in crop yield, and to determine the extent of any reduction in deep drainage.

The degree of trade-off between water management and production goals in a tree–crop system can be determined from the relative size of the no-yield-zone (NYZ) and the no-recharge-zone (NRZ) (Fig. 1) (Ellis *et al*. 1999; Lefroy *et al*. 2001; Stirzaker *et al*. 2002). The NYZ is defined as the lateral distance from the trees over which they effectively reduce yield to zero, and the NRZ is the distance from the trees over which they effectively reduce deep drainage to zero or to a level similar to native vegetation. The NRZ is the terminology used by Lefroy *et al*. (2001) but is used here to explain a reduction in drainage below the root-zone, which may not necessarily relate to a reduction in recharge.

In water-limiting environments, successful design of agroforestry systems for salinity management (such as windbreaks and alley cropping) depends on managing the interface between the trees and crops to optimise the value of the trees, minimise competition, and reduce deep drainage

 10.1071/AR04213 0004-9409/05/101011

(Lefroy and Stirzaker 1999). The potential impact of trees on deep drainage and yield suggests the following 5 possible scenarios for tree–crop combinations; however, there may be additional trade-offs in farm production through displacing land from crop production.

- Lose–win (positive trade-off). Yield loss with reduction in deep drainage, where the area of influence over drainage is larger than that over which yield is affected (i.e. NRZ > NYZ). In such circumstances, less area would be required under trees in belts than in plantations to meet a deep-drainage reduction target. Under this scenario a closely integrated system such as alley farming would be the preferred design as it maximises the length of the tree–crop interface.
- Lose–win (negative trade-off). Yield loss with reduction in deep drainage, where the area of influence over deep drainage is less than that over which yield is affected (i.e. NRZ < NYZ). A segregated or rotated agroforestry system such as block plantations or phase forestry would be the preferred design as it minimises the length of the tree–crop interface.
- Win–win. Yield enhancement, with reduction in deep drainage.
- Win–lose. Yield enhancement with little change to deep drainage.
- Lose–lose. Yield loss and the deep drainage is increased.

The crop response to competition with trees could potentially range from yield enhancement (due to microclimate and seasonal influences) to yield loss. The reduction in deep drainage due to trees can occur under the trees and at some distance from the trees. Optimal agroforestry design requires an understanding of the site and system features that increase the probability of win–win or positive trade-off scenarios.

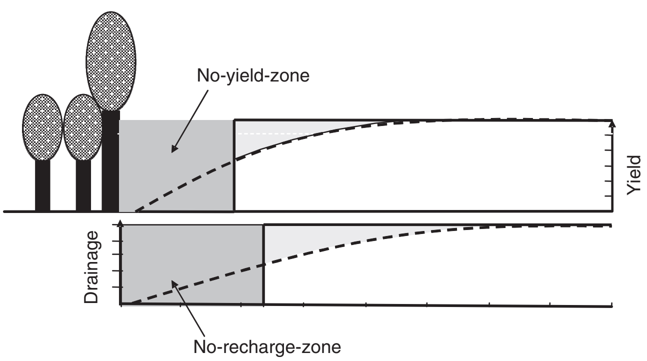

Fig. 1. Yield and deep drainage are both zero at the base of the tree and increase with distance from the belt to levels characteristic of a sole crop. This is reduced to a step function to facilitate easy comparison of the magnitude of above- and below-ground effects. Adapted from Stirzaker *et al*. (2002).

Australian and international tree–crop experiments have characterised the effect of shelter in the form of a windbreak signature (Fig. 2) consisting of 3 distinct zones: a zone of competition extending from 0 to 3 tree heights; a sheltered zone with increased or unchanged yield extending from 3 to 15 tree heights; and an open paddock or open field zone outside the influence of the trees extending from ~20 tree heights, in which yield returns to levels experienced in the unsheltered state (Marshall 1967; Bird 1998; Nuberg *et al*. 2002).

Reduced yield in the competition zone in temperate alley cropping systems has been attributed primarily to competition for soil water (Ong *et al*. 1991) with some contribution from shading and nutrient competition (Jose *et al*. 2000; Miller and Pallardy 2001; Sudmeyer and Scott 2002*b*), whereas increased yields in the sheltered zone have been attributed primarily to the microclimate effect and protection from damaging winds (Sudmeyer and Scott 2002*b*).

Research in Australia in the 1980s and 1990s identified some beneficial interactions between trees and crops (Lynch and Donnelly 1980; Bicknell 1991; Burke 1991; Sun and Dickinson 1994). More comprehensive studies carried out through the RIRDC National Windbreak Program (1994–97) indicated only very modest net gains in yield over the whole paddock despite significant yield increases at 3–5 tree heights from the trees (Cleugh *et al*. 2002).

Most research on tree–crop interaction has been in-depth studies on a particular agroforestry system or a particular issue such as the microclimate effect of windbreaks and alleys (Cleugh 1998; Nuberg *et al*. 2002; Sudmeyer and Scott 2002*a*), tree root morphology (Jonsson *et al*. 1988; Gregory 1996; Sudmeyer *et al*. 2002), hydrological impact (Lefroy *et al*. 2001; Hall *et al*. 2002), and crop yield (Nuberg and Mylius 2002; Sudmeyer and Scott 2002*b*). The complex interactions among environmental conditions make it difficult to predict their effect on yield (Sudmeyer and Scott 2002*b*), and variation in crop yield due to other factors such as soil depth and soil type can swamp the subtle effects of tree belts (Nuberg and Mylius 2002).

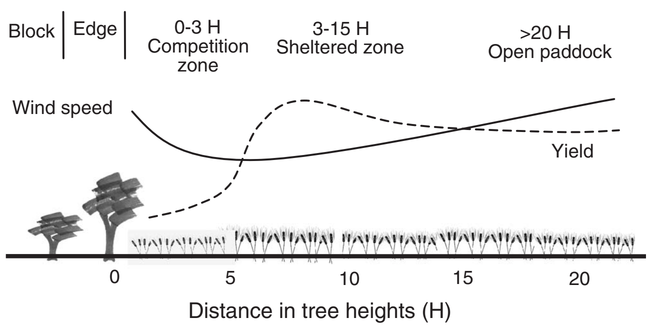

Fig. 2. The typical windbreak signature, adapted from Huth *et al*. (2002).

Because of this difficulty, very few studies have looked at the combined effects of trees on yield and deep drainage to produce specifications for agroforestry aimed at water and salinity management.

Australian and international research therefore suggests a need to understand how agroforestry design could achieve natural resource management outcomes at minimal cost to short-term productivity. To do this requires an understanding of the above-ground and below-ground effects of adding trees to a cropping system, and the trade-off that occurs between the yield and deep-drainage control.

This study set out to identify the relative importance of 4 farming system characteristics (tree species, tree age, tree height, and crop type) and 5 environmental factors (orientation, soil type, rainfall, landscape position, and hydrology) of tree belts on the trade-off between crop yield and deep-drainage reduction at 5 sites in eastern Australian and 16 sites in Western Australia over 2 years. Ultimately, design decisions will depend on the relative value to the landholder of crop production and deep-drainage management. Our aim was to identify the more influential site and system features that could be manipulated through design and modified through more targetted research.

Methods

Site

Twenty-one sites in the 300–600 mm rainfall zone in the grain-producing areas of Western Australia and New South Wales were selected to provide a range of site and system characteristics (Fig. 3).

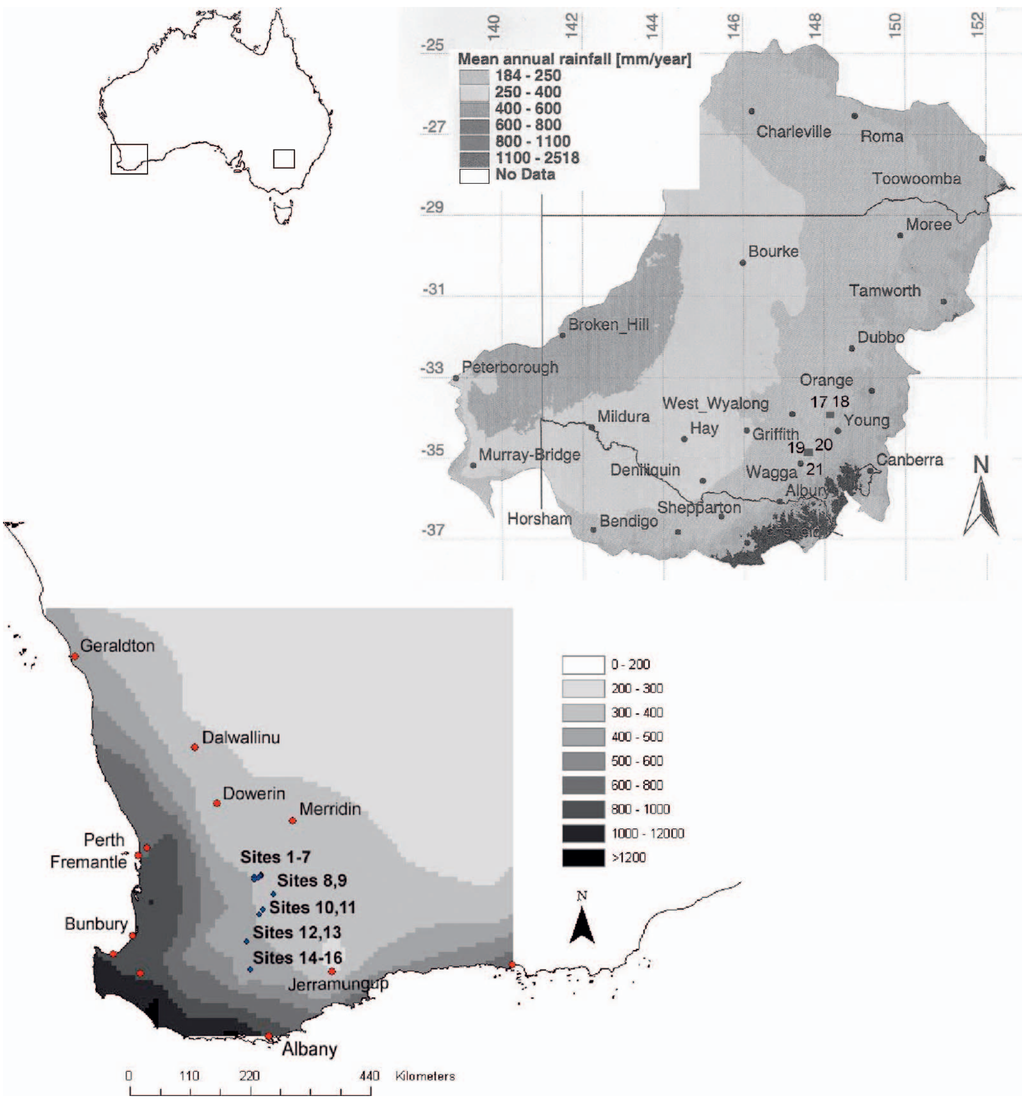

Fig. 3. Site location and annual average rainfall for Sites 1–16 in south-western WA and Sites 17–21 in the Murray–Darling Basin.

The percentage silt and clay, measured by the pipette method (Gee and Bauder 1979) was used to determine soil texture for soil sampled at depth intervals of 0–0.1 m, 0.5–0.6 m, and 1.0–1.1 m. The soil textures in each layer were then used to classify the soil profile to 1 m, grouping the layers as light and heavy soils. The light soil type included the deep sands, sandy loam, sand over sandy clay and sandy clay loam, and loamy sand over clay loam. The heavy soil type included sand over clay, loamy sand over clay, sandy clay over clay and loam over a medium clay.

The orientation of the tree belts covered all points of the compass and was grouped as (*a*) north to south-east (N, NE, E, SE), and (*b*) south to north-west (S, SW, W, NW) (Table 1). The prevailing winds during winter (June–August) in both WA and NSW are predominantly from the west, north-west and south-west (Bureau of Meteorology).

Five crop types were represented (wheat, lupins, barley, canola, and peas), with the first row of crop ranging from 2 to 10 m from the trees, depending on the presence of fences and firebreaks. The trees included 8 eucalyptus species, 1 pine species (*Pinus radiata*), and tagasaste (*Chamaecytisus proliferus)*. The trees ranged in age from 6 to 16 years and had an outer tree height of 3–23 m. The tree belts had 1–24 rows (median 4 rows) of trees, which were spaced 2–8 m apart (median 3 m) with 2–16 m between the trees within a row (median 4), and low to medium porosity (estimated from photographs). At all sites the tree belts were fenced and had little or no understorey growth.

The climate in the WA region is of Mediterranean type with cool, wet winters and hot, dry summers. Annual average rainfall at the WA sites over the 2 years of the study (2001, 2002) ranged from 375 to 461 mm. The May–October rainfall in 2001 was slightly lower than average (81–90% of long-term average) at most sites, and significantly lower at Kulin (54% of long-term average). In 2002, Kulin received only 35% of May–October long-term average rainfall and the other sites had 64–80% of the long-term average.

The annual average rainfall at the NSW sites ranged from 528 to 649 mm. The NSW sites experience more evenly distributed long-term average monthly rainfall and lack the pronounced seasonality of the WA sites. The monthly rainfall was lower than average (60–80%) in 2001 and 2002 except for a few storm events in February 2002 at all sites and in June 2001 at Grenfell.

Measuring the no-yield-zone (NYZ)

Crop biomass and yield were determined from triplicate quadrats (0.5 m by 0.5 m) cut at 4, 8, 16, 32, 64, and 128 m from the tree

Table 1. Site location and environment

Site no.	Location	Latitude (S)	Longitude (E)	Ave. annual rainfall	Orientation	Position	Soil	WG site[A]	Tree species	Age	No. rows	Belt width (m)	Tree height (m)
						SE Western Australia							
1	Corrigin	32°22′21.6″	117°45′1.0″	375	NE	Valley	Loamy sand over clay loam	N	*E. sideroxylon*	14	6	19.0	5.3
2	Corrigin	32°22′20.5″	117°45′0.3″	375	NE	Valley	Sand over clay	Y	*E. populnea*	14	6	19.8	5.9
3	Corrigin	32°22′21.6″	117°45′0.0″	375	SW	Valley	Loamy sand over clay loam	N	*E. sideroxylon*	14	6	19.0	7.0
4	Corrigin	32°22′21.3″	117°44′59.3″	375	SW	Valley	Sand over clay	Y	*E. populnea*	14	6	19.8	6.2
5	Corrigin	32°24′35.2″	117°42′19.1″	375	W	Mid-slope	Deep sand	–	*Chamaecytisus proliferus*	6	Hedge	10.0	4.7
6	Corrigin	32°24′4.8″	117°39′45.2″	375	SE	Valley	Sand over sandy loam	Y	*Pinus radiata*	8	8	36.6	8.2
7	Corrigin	32°26′34.4″	117°39′37.6″	375	E	Mid-slope	Sand over sandy loam	Y	*Chamaecytisus proliferus*	6	5	23.1	3.7
8	Kulin	32°41′15.7″	117°58′23.5″	359	NE	Mid-slope	Sand over sandy clay	N	*E. leucoxylon*	15	10	44.3	6.7
9	Kulin	32°41′15.7″	117°58′23.5″	359	SW	Mid-slope	Sand over sandy clay	N	*E. leucoxylon*	15	13	68.1	6.5
10	Harrismith	32°55′35.5″	117°47′20.3″	390	N	Low slope	Sand over clay	Y	*E. polybractea*	7	24	300.0	5.5
11	Harrismith	33°01′5.6″	117°43′44.3″	401	W	Low slope	Sand over sandy clay	–	*Eucalyptus* spp.	7	2	10.0	6.8
12	Woodanilling	33°27′9.0″	117°31′36.0″	461	W	Mid-slope	Loamy sand over clay	Y	*E. polybractea*	6	4	9.4	6.0
13	Woodanilling	33°26′59.6″	117°31′26.3″	461	S	Mid-slope	Loamy sand over clay	Y	*E.polybractea*	6	4	8.2	6.4
14	Broomehill	33°55′3.0″	117°35′42.8″	444	N	Mid-slope	Sand over clay	Y	*E.wandoo*	16	5	20.0	7.3
15	Broomehill	33°55′4.7″	117°35′50.6″	444	N	Mid-slope	Loamy sand over clay	Y	*E. camaldulensis*	16	4	18.0	6.3
16	Broomehill	33°55′12.4″	117°35′53.5″	444	SE	Low slope	Sand over sandy clay loam	–	*E. camaldulensis*	16	4	25.0	7.6
						NSW							
17	Cowra	33°46′43.5″	148°47′38.5″	540	NE	Valley	Sandy clay loam over clay	N	*E. microcarpa*		5	29.0	22.7
18	Grenfell	33°42′34.2″	148°5′59.8″	649	E	Valley	Sandy clay over a clay	–	Eucalyptus spp.	12	3	10.9	9.0
19	Junee	34°43′44.5″	147°32′47.8″	528	E	Valley	Loam over a medium clay	Y	*Pinus radiata*	13	3	9.7	10.7
20	Junee	34°43′44.7″	147°32′49.1″	528	E	Low slope	Loam over a medium clay	Y	*Pinus radiata.*	13	3	9.3	9.0
21	Junee	34°43′34.5″	147°32′45.9″	528	E	Low slope	Loam over a medium clay	N	*E. sideroxylon*	10	3	7.9	12.6

[A] Water-gaining sites.

base, perpendicular to the tree line. In 2001, crop biomass and yield were monitored at 16 sites in WA and at 5 in NSW. Due to crop rotations and drought, only 9 sites in WA and 2 in NSW were cropped in 2002.

The open paddock yield was determined from the average of the triplicate measurements of the yield at 64 m and 128 m, because for most sites (30 out of 32) there was no significant difference between the average yield at 64 m and 128 m. The yield at each distance was converted to relative yield by dividing by the open paddock yield. Relative yields were used to enable comparison among different states, tree species, and orientation by removing the variation in crop yields due to crop species, rainfall zone, soil, and agronomic practices. Distance was also converted to tree heights for each site by dividing the distance by the height of the outer tree row.

Percentage change in crop yield was calculated from the difference in the measured paddock yield (including yield loss and enhancement over the transect) and the open paddock yield (Fig. 4 and Eqn 1). The yield change is calculated from the base of the outer tree as the belt width differs at all sites.

$$\%\,\text{Yield change} = 100 \times \frac{\text{Yield enhancement area} - \text{Yield loss area}}{\text{Transect length} \times \text{Open paddock yield}} \quad (1)$$

$$\text{NYZ} = \text{Transect length} \times \text{Yield change} \quad (2)$$

The NYZ is the distance over which the yield is effectively reduced to zero and is calculated as the yield change over the transect length of 128 m (Eqn 2), which takes into account both the yield enhancement and yield loss.

Measuring the no-recharge-zone (NRZ)

Ellis *et al*. (1999, 2001) proposed a method using leaf area as a surrogate measure of water use and hence drainage management by eucalypt tree belts. It is based on the assumption that the enhanced growth commonly observed in trees on outside rows (edge trees) is proportional to the additional stored soil water they take up from beneath adjacent crops or pasture in medium to low rainfall zones.

The tree belts were characterised by measuring orientation, width of belt, diameter at breast height, tree height, canopy widths of trees, distance between trees, distance between row, and leaf area (Table 1). For multi-stemmed trees, the diameter at breast height was calculated from the square root of the sum of the square of each breast height diameter of all leaf-bearing stems.

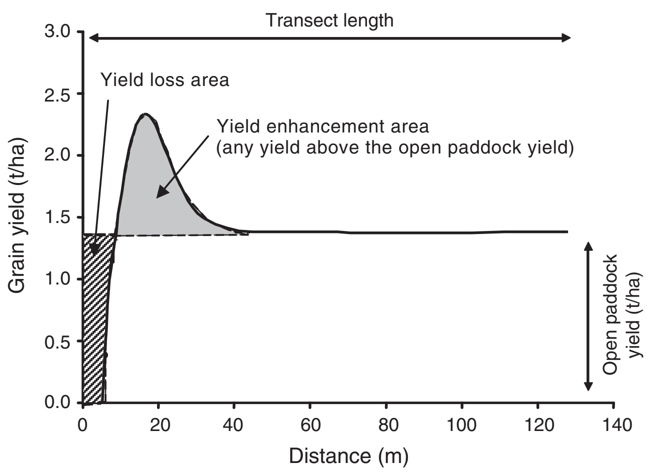

Fig. 4. Grain yield at distances from the trees, indicating the yield loss, the yield enhancement, and the open paddock yield.

The leaf area index (LAI) was measured using the Adelaide (module) technique (Andrew *et al*. 1979). Three edge trees and 3 inner trees were chosen to represent the belt. For each tree, a representative module branch was sampled, and the number of these modules on each tree was determined as the average of 2 recorders' estimates. The leaf area of the representative module was then measured using an electronic planimeter and the leaf area of the tree determined from the module leaf area multiplied by the number of modules in the tree. The LAI was determined from the leaf area of 3 trees divided by the area deemed to be occupied by the 3 trees (determined from the spacing within and between rows).

The NRZ is taken to be the lateral distance from the belt over which edge trees are taking up water, and is derived from the ratio of the LAI of the outer trees (LAI_{outer}) to the LAI of the inner trees (LAI_{inner}) and the row spacing of the belt, termed $NRZ_{outer/inner}$ (Eqn 3) (Ellis *et al*. 1999, 2001):

$$\text{NRZ}_{outer/inner} = \left(\frac{\text{LAI}_{outer}}{\text{LAI}_{inner}} \times \text{row spacing}\right) - \frac{1}{2}\,\text{row spacing} \quad (3)$$

where NRZ is the no recharge zone calculated from the edge of one side of the tree belt and LAI is the leaf area index.

If there is no edge effect (as in a 2-row tree belt) then the ratio of the LAI of the outer tree (LAI_{outer}) to the LAI of a native stand (LAI_{native}) is used, termed $NRZ_{outer/native}$ (Eqn 4). This method assumes that as outer trees in the belts can take up water under the crops, they will be larger than the native vegetation. For eucalypts, Ellis *et al*. (1999) showed that the native LAI can be estimated from rainfall and pan evaporation (Eqn 5).

$$\text{NRZ}_{outer/native} = \left(\frac{\text{LAI}_{outer}}{\text{LAI}_{inner}} \times \text{row spacing}\right) - \frac{1}{2}\,\text{row spacing} \quad (4)$$

$$\text{LAI}_{native} = 2.9\,\frac{\text{Annual rainfall}}{\text{Annual evaporation}} \quad (5)$$

Defining water-gaining sites

The $NRZ_{outer/inner}$ is assumed to reflect the relative water use of outer and inner trees and the access they have to water in the adjacent cropped zone under the same site, nutrient, and soil conditions. The $NRZ_{outer/inner}$ therefore compares local-scale processes. The $NRZ_{outer/native}$, on the other hand, represents the extra growth of the planted outer trees compared with native vegetation, which is assumed to survive on rainfall alone, and includes differences due to access to water under crops, as well as access to groundwater and run-on.

Comparing the LAI_{outer}, LAI_{inner}, and LAI_{native} gives some insight into the water use by the trees, in particular whether they are taking up additional groundwater or runoff. There are 3 distinct categories based on the LAI of belt trees and the predicted LAI of native trees. These categories can be used to describe the following 3 plausible scenarios for the effect of planted belts of trees on soil water management.

(1) $LAI_{outer} > LAI_{inner} < LAI_{native}$. These are sites with poor tree growth but still featuring an edge effect. The outer trees obtain extra water from under crops and out-compete inner trees, but the LAI of the inner trees compared with native trees suggests that they are not reaching the environmental potential of the site. In this case, the No-Recharge-Zone calculated from the ratio of LAI_{outer} to LAI_{native} is likely to overestimate the impact of the trees on water management.

(2) $LAI_{outer} > LAI_{inner} \approx LAI_{native}$. This is the classic case where the outer trees experience enhanced growth over inner trees due to better

access to resources, and the growth of inner trees approximates that of native vegetation. The NRZ calculated from either the ratio of LAI_{outer} to LAI_{inner} or the ratio of LAI_{outer} to LAI_{native} should equally describe the influence of the trees on soil water under the crops.

(3) $LAI_{outer} > LAI_{inner} > LAI_{native}$. This indicates enhanced tree growth, with an edge effect. Both inner and outer trees take up additional water (groundwater, near-surface aquifers, or run-on), with the outer trees also taking up water under the crops. The $NRZ_{outer/inner}$ may be high but does not include the groundwater transpired. The $NRZ_{outer/native}$ includes both groundwater and the water under the crops. The inner trees may also have been shaded by the outer trees, which would cause the $NRZ_{outer/inner}$ to be high. For this analysis we have assumed that the trees, which are 6 years old and greater, have used any water that accumulated at depth since the original vegetation was removed. However, it is possible that both inner and outer trees are taking up stored soil water, but this is more likely to occur at sites with young and newly planted trees.

Sites in Category 3 are referred to from here on as water-gaining sites, as the trees obtain more water than is available from rainfall in addition to stored soil water under adjacent crops.

Statistical analysis

To understand the relative influences of environmental and farming system characteristics the data were separated to compare 2 features at a time. The groups were: (*a*) all sites, (*b*) WA *v.* NSW sites, (*c*) Eucalypt *v.* non-Eucalypt, (*d*) cereal *v.* non-cereal crops, (*e*) orientation that protected crops from north to south-east winds (N, NE, E, SE) *v.* south to north-west winds (S, SW, W, NW), (*f*) high landscape position (mid-slope to high) *v.* low landscape position (lower slope to valley), (*g*) heavy soils (sand over clay and loam over clay) *v.* light soils (deep sands and sand over sandy loam/sandy clay/sandy clay loam), (*h*) water gaining sites, (*i*) tree height (<8 m *v.* >8 m), (*j*) age of tree (<10 years *v.* >10 years) and (*k*) rainfall (>400 mm *v.* <400 mm).

The relative yield at 4 m, 8 m, 16 m, and 32 m was averaged for all replicates and all sites for each grouping. The average relative yield at each distance was compared between the groupings using ANOVA statistics. For example, the average relative yield at 4 m for all the NSW sites was statistically compared with the average relative yield at 4 m for the WA sites. The NYZ was calculated using the average yield at each distance for each grouping and also compared statistically. The average NRZ for each site was similarly grouped and then compared.

Gross margin analysis

The assumptions used in calculating gross margins and deep drainage reduction were as follows. Tree belts were assumed to be part of a uniform alley system, with belts 15 m wide and spaced 100 m apart, leaving 85 m of arable land between belts. The gross margin calculations used on-farm prices of \$180/t for barley, \$190/t for wheat, \$195/t for lupins, \$210/t for peas, and \$385/t for canola, with variable costs of \$180/ha. Deep drainage reduction and net yield were based on Eqns 6 and 7. The NYZ and NRZ were doubled to incorporate the effect of trees on both sides of a belt.

$$\text{\% Recharge reduction} = \frac{(2 \times \text{NRZ} + \text{Belt width})}{\text{Tree spacing}} \qquad (6)$$

$$\text{Adjusted yield} = \frac{[\text{Tree spacing} - (2 \times \text{NYZ} + \text{Belt width})] \times \text{Open paddock yield}}{\text{Tree spacing}} \qquad (7)$$

$$\text{Gross margin of alley system (\$)} = \text{Adjusted yield} \times \text{\$Crop value} - (0.85 \times \text{\$Cost}) \qquad (8)$$

The costs were multiplied by 0.85 because only 85 m out of 100 m would have incurred cropping cost.

Results and discussion

The effect of trees on the crop yield

To examine the influence of the tree belts on crop yield, the relative yield was plotted against distance from the tree belts in metres and tree heights (H) for the 2001 and 2002 replicate data (Fig. 5*a* and *b*). The yields in 2002 were generally lower than in 2001, reflecting generally lower rainfall in that year (Table 2).

The typical windbreak signature with an area of low yield in the competition zone (within the first 0–16 m) and yield enhancement in the sheltered zone (14–50 m) occurred at 15 out of 21 sites in 2001 and 6 out of 11 sites in 2002 (Table 2). The remaining sites exhibited some yield loss in the sheltered zone. The open paddock yield, used to

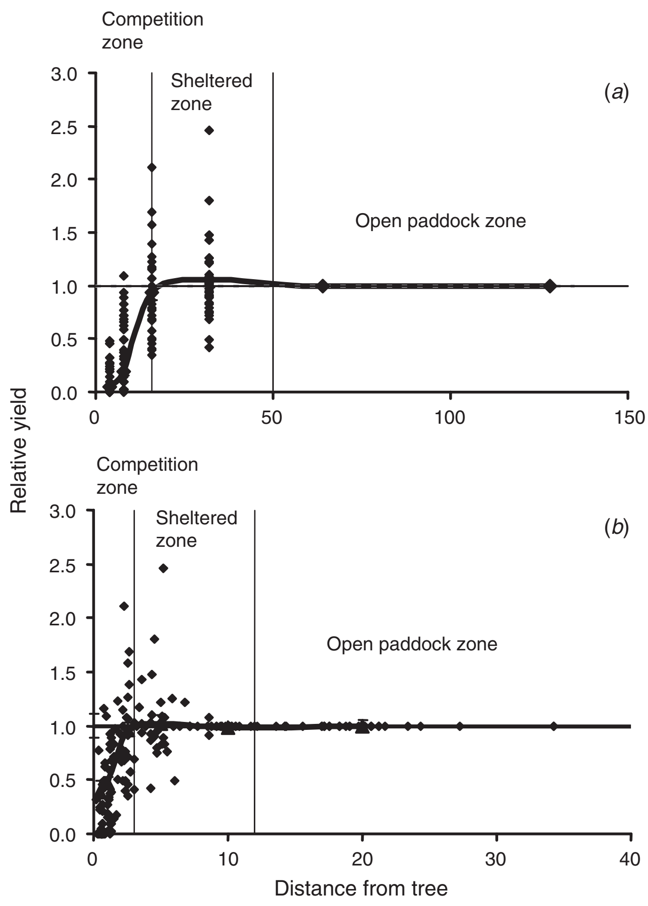

Fig. 5. The relative yield (yield/yield at 128 m) for 32 tree–crop interfaces in NSW and WA in 2001 and 2002, expressed as the measured distance from the tree (*a*) in metres and (*b*) in tree heights (m/height of tree) (H).

Table 2. Open paddock crop yield (t/ha), percentage yield enhancement, and percentage yield loss over the whole transect area, net yield change, no-yield-zone (NYZ) in metres (m) and tree heights (H)

See Fig. 4 for an explanation of yield enhancement and yield loss areas used to calculate the percentage over the whole transect. Note: Negative NYZ = effective gain in cropped land at open paddock yield

Site no.	Year	Crop species	Open paddock yield	% Yield change over 128 m transect			NYZ	
				Enhancement	Loss	Net change	m	H
1	2001	Wheat	3.47	0.0	−23.8	−23.8	30.46	5.8
2	2001	Wheat	3.34	0.0	−17.5	−17.5	22.35	3.8
3	2001	Lupins	1.33	0.0	−13.4	−13.4	17.22	2.5
4	2001	Lupins	1.25	3.8	−8.0	−4.2	5.38	0.9
5	2001	Barley	0.89	5.2	−8.0	−2.8	3.59	0.8
6	2001	Wheat	2.12	5.0	−9.5	−4.5	5.72	0.7
7	2001	Wheat	2.10	1.5	−6.3	−4.8	6.19	1.7
8	2001	Lupins	1.75	1.4	−14.8	−13.4	17.13	2.5
9	2001	Barley	2.00	1.5	−4.9	−3.5	4.46	0.7
10	2001	Wheat	1.92	4.8	−5.1	−0.3	0.35	0.1
11	2001	Wheat	2.12	0.0	−17.3	−17.3	22.12	3.2
12	2001	Canola	1.38	7.9	−4.6	3.3	−4.19	−0.7
13	2001	Canola	1.45	6.4	−4.4	2.0	−2.62	−0.4
14	2001	Wheat	2.67	10.0	−7.4	2.5	−3.24	−0.4
15	2001	Wheat	3.73	0.0	−18.6	−18.6	23.86	3.8
16	2001	Wheat	2.85	1.4	−10.9	−9.6	12.25	1.6
17	2001	Canola	0.39	4.5	−8.7	−4.2	5.40	0.3
18	2001	Wheat	1.65	1.4	−11.2	−9.8	12.58	1.4
19	2001	Peas	0.40	1.1	−11.5	−10.4	13.38	1.3
20	2001	Wheat	0.57	9.8	−5.9	3.9	−5.00	−0.6
21	2001	Canola	0.10	0.0	−16.3	−16.3	20.84	1.6
3	2002	Wheat	0.69	22.4	−6.2	16.2	−20.74	−3.0
4	2002	Wheat	0.88	26.8	−9.5	17.3	−22.15	−3.6
7	2002	Wheat	0.94	0.4	−10.0	−9.6	12.33	3.3
8	2002	Wheat	1.41	0.0	−16.2	−16.2	20.77	3.1
12	2002	Wheat	2.87	1.7	−6.8	−5.1	6.58	1.1
13	2002	Wheat	3.10	1.2	−7.0	−5.8	7.37	1.2
14	2002	Barley	1.90	2.2	−9.5	−7.3	9.40	1.3
15	2002	Barley	1.86	1.6	−14.0	−12.4	15.87	2.5
16	2002	Barley	2.56	0.0	−23.2	−23.2	29.72	3.9
18	2002	Wheat	1.05	0.0	−13.7	−13.7	17.49	2.0
19	2002	Canola	0.41	0.0	−15.9	−15.9	20.33	1.9

calculate the relative yield, was the average of the replicates at 64 m and 128 m to reduce any errors associated with the variability in the open paddock yield. For the calculation of NYZ, relative yield at both 64 m and 128 m distances was set to 1 (Fig. 5*a*).

When the distance from the tree belts in metres was converted to tree heights, some of the variation in the windbreak signature between the sites was removed (Fig. 5*b*). The yield losses occurred more often in the competition zone and the yield enhancement occurred more often in the sheltered zone. The remaining scatter is most likely due to other site factors such as soil type, crop type, tree species, orientation, wind direction, and rainfall, and the relatively small sample size and limited replication (discussed below).

The percentage yield change over the 128 m transect ranged from a 17.0% yield enhancement to a 23.0% yield loss with an average 7.4% yield loss (Table 2). This percentage yield change takes into account both the yield loss and the yield enhancement across the paddock (Fig. 4).

For all sites, the average NYZ extended 9.5 m or 1.4 H into the paddock and ranged from a loss of 30.5 m of arable land to an equivalent gain of 22.2 m due to the beneficial influences of the trees. Although some yield enhancement occurred at 22 of the 32 sites, at only 6 sites was percentage yield enhancement greater than percentage yield loss, resulting in a net yield gain (and thus a negative NYZ). The negative value for the NYZ in these cases (ranging from –2.6 to –22.2 m or –0.4 to –3.6 H) indicates the equivalent extra crop land gained with this tree–crop combination in that season. At the other 16 sites, the percentage yield enhancement was less than the percentage yield loss, resulting in a positive NYZ. However, the net yield gain was seasonally dependent, with no sites showing a gain in both years.

The influence of the trees on the NRZ

The NRZ is the distance from the base of the outer tree over which deep drainage is assumed to be effectively reduced to zero, or similar to the deep drainage occurring under native vegetation in the region. The predicted $NRZ_{outer/inner}$ ranged from 0.6 to 25 m (0.1–3.8 H) and the $NRZ_{outer/native}$ ranged from 2.0 to 30.4 m (0.1–4.9 H) (Table 3). The $NRZ_{outer/inner}$ was generally lower than the $NRZ_{outer/native}$, reflecting the fact that the inner belt trees in this study had higher LAI than that expected for native trees, with only 4 exceptions where the trees appear to have been poorly adapted to those sites. A low $NRZ_{outer/native}$ indicates that the trees do not provide much additional deep drainage control over the area that the trees occupy as they are performing much like the native vegetation and are surviving on rainfall alone.

For *Eucalyptus* spp., Ellis *et al*. (1999, 2001) found the NRZ inferred from soil chloride profiles ranged from 25 to 60 m compared with a predicted NRZ of 10–60 m. Robinson *et al*. (2002) found that the measured soil water depletion for 5 sites planted to mallee Eucalypts ranged from 7 to 12 m (2.4–5 H) compared with the predicted NRZ of 8–15 m (2–7 H). This provides some confidence in the predicted NRZ based on leaf area as used in this study.

Influence of environmental and farming system characteristics on the NRZ and NYZ

In this study we have assumed uniform soil and chemical properties across the paddock and under the trees. However, it is likely that there are some differences in soil type, fertility, depth to rock, and weed management across the paddock. Some of the variation in yield, both across the paddock and within replicates, may be caused by these factors. Therefore more replicates are required to determine relationships between site and system features. To overcome the small number of sites and replicates, average NYZ for 2 features were compared.

The NYZ was significantly lower when the crops were protected from winds from the south to north-west compared with the north to south-east (i.e. crop yields in lee of tree belts were higher). Crops next to trees planted on water-gaining sites or adjacent to younger trees (<10 years) also had a significantly lower NYZ (Table 4). Due to the highly variable yield response, site and system characteristics were not always significantly related to differences in the NYZ using ANOVA statistics.

However, there were differences in the relative yield in the competition zone (0–16 m) in response to site (hydrology, soil type, orientation, and region) and system (tree species) characteristics (Table 4). Most of the influence on the crop

Table 3. No-recharge-zone (NRZ) estimated from the edge tree effect and predicted LAI of the native vegetation

Site	Average LAI (m^2/m^2) Outer	Average LAI (m^2/m^2) Inner	Predicted LAI (m^2/m^2) Native	$NRZ_{outer/inner}$ (m)	$NRZ_{outer/native}$ (m)	$NRZ_{outer/inner}$ (H)	$NRZ_{outer/native}$ (H)
1	2.8	0.6	0.60	17.3	16.6	3.3	3.2
2	3.7	2.6	0.60	3.8	22.7	0.6	3.9
3	2.6	0.6	0.60	14.2	15.5	2.0	2.2
4	4.9	1.7	0.60	9.5	30.4	1.5	4.9
5	2.7	A	0.60	A	14.2		3.0
6	3.8	2.5	0.60	4.8	26.5	0.6	3.2
7	3.5	4.8	0.60	0.8	18.4	0.2	4.9
8	1.3	0.5	0.55	9.3	8.5	1.4	1.3
9	2.3	0.4	0.55	24.9	16.4	3.8	2.5
10	4.2	1.8	0.70	3.7	11.0	0.7	2.0
11	4.4	A	0.70	A	24.7		3.6
12	2.8	1.6	0.90	1.8	3.9	0.3	0.6
13	4.0	1.7	0.90	2.7	6.0	0.4	0.9
14	3.3	2.1	0.90	3.6	11.0	0.5	1.5
15	4.7	1.9	0.90	7.1	16.7	1.1	2.6
16	3.8	B	0.90	B	24.3		3.2
17	1.4	0.2	1.00	24.4	2.0	1.1	0.1
18	0.4	0.2	1.00	5.3	C	0.6	C
19	6.1	6.2	1.10	1.2	10.0	0.1	0.9
20	5.8	7.8	1.10	0.6	9.4	0.1	1.0
21	0.4	0.5	1.10	0.8	C	0.1	C

[A]The tree belt had only 2 rows (no inner row).
[B]Inner trees were 2 years younger than outer trees.
[C]$LAI_{outer} < LAI_{native}$.

Table 4. Average no-yield-zone (NYZ) for sites grouped by region, tree species, crop type, orientation, soil type, landscape position, access to water, tree height (H), and tree age (standard errors in parentheses)
Light soils = (sand and sandy clays), Heavy soils = (heavy duplex clays)

	Sites	NYZ (m)	Relative yield at: 8 m	16 m	NRZ (m) (outer/inner)	(outer/native)
All	32	10.0 (2.1)	0.38 (0.04)	0.92 (0.08)	7.3 (1.3)	12.7 (1.6)
State						
WA	25	8.8 (1.6)	0.38 (0.08)	0.95 (0.05)	5.5 (2.8)	4.3 (2.8)***
NSW	7	12.2 (3.1)	0.38 (0.04)	0.84 (0.09)	7.7 (1.6)	16.0 (1.5)***
Tree species						
Eucalypts	26	9.9 (1.6)	0.34 (0.04)*	0.92 (0.05)	8.4 (1.5)	12.9 (1.7)
Non-eucalypts	6	8.1 (3.1)	0.52 (0.08)*	0.95 (0.1)	1.6 (3.1)	16.1 (3.6)
Crop type						
Cereal	23	9.2 (1.7)	0.34 (0.04)	0.88 (0.06)	n.a.	n.a.
Non-cereal	9	10.3 (2.7)	0.46 (0.06)	1.02 (0.06)	n.a.	n.a.
Orientation						
N, NE, E, SE	16	13.4 (1.8)***	0.31 (0.05)*	0.77 (0.05)***	5.9 (1.8)	10.1 (2.1)*
S, SW, W, NW	16	4.6 (2.1)***	0.46 (0.05)*	1.1 (0.06)***	8.9 (2.1)	16.8 (2.1)*
Soil type						
Light soils	14	12.9 (2.3)	0.33 (0.06)	0.86 (0.06)	10.8 (1.6)*	17.3 (2.2)*
Heavy soils	18	7.5 (1.8)	0.41 (0.05)	0.96 (0.07)	5.1 (2.2)*	10.5 (2.1)*
Landscape position						
High in landscape	18	8.4 (2.2)	0.44 (0.05)	0.98 (0.07)	5.8 (1.8)	11.4 (2.4)
Low in landscape	14	10.4 (1.9)	0.33 (0.05)	0.89 (0.06)	7.9 (1.7)	14.5 (2.2)
Access to water						
Water-gaining sites[A]	18	6.2 (2.0)*	0.46 (0.05)*	0.99 (0.06)	n.a.	n.a.
Non-water-gaining sites	11	13.9 (2.8)*	0.27 (0.07)*	0.91 (0.09)	n.a.	n.a.
Tree height						
Short trees <8 m	21	8.9 (1.7)	0.35 (0.07)	0.95 (0.05)	8.2 (1.7)	14.5 (1.9)
Tall trees >8 m	11	11.3 (2.9)	0.47 (0.04)	0.85 (0.09)	5.0 (2.4)	11.6 (2.7)
Tree age						
Young trees <10 years	10	5.7 (2.6)*	0.66 (0.06)***	1.07 (0.08)*	3.5 (2.4)*	12.3 (2.9)
Old trees >10 years	22	11.3 (1.7)*	0.25 (0.04)***	0.86 (0.05)*	9.1 (1.6)*	13.8 (2.0)
Rainfall						
>400 mm	18	11.2 (1.9)	0.38 (0.05)	0.90 (0.06)	4.6 (1.8)*	n.a.
<400 mm	14	7.4 (2.2)	0.38 (0.05)	0.96 (0.07)	10.1 (1.9)*	n.a.

n.a., Not able to use statistic for comparison due to co-dependence of the parameters and the grouping.
*$P < 0.05$; ***$P < 0.005$.
[A]Statistical analysis does not include Sites 5, 11, and 16 as they only had 2 rows of trees (i.e. no inner row).

yield occurred within 16 m as there were no significant differences in the relative yield at distances from the tree of 32 m or greater.

Crops that were protected from south, south-west, west, and north-west winds had a higher relative yield in the sheltered zone at 8 m and 16 m (~1–2 H) (Table 4). This represents the microclimate influence of the tree belt on yield in the sheltered zone (Sudmeyer and Scott 2002*a*). Albertsen *et al*. (2000) similarly found that orientation was significant in influencing pasture loss adjacent to bluegum (*Eucalyptus globulus*) plantations.

Older trees were more likely to reduce the yield in the competition zone, with significantly lower relative yield at 8 m and 16 m compared with younger trees of less than 10 years. The younger trees may be competing less with the crops as they may be taking up stored water from under the trees and crops, which would have already been used by the older trees, and have less extensive lateral roots.

Where trees were planted on water-gaining sites such as over groundwater, shallow surface aquifers, or with access to run-on (as suggested by $LAI_{outer} > LAI_{inner} > LAI_{native}$), the relative yield in the competition zone at 8 m (~1 H) was significantly higher than at sites that were not classified as water gaining (Table 4). Three sites were excluded from this analysis as they did not have inner tree rows (Sites 5, 11, and 16).

The relative yield at 8 m was lower for eucalypt than for non-eucalypt species (Table 4), which may indicate greater competition for resources by eucalypts, but although this was statistically significant there were only a small number of sites with non-eucalypts. Sudmeyer *et al*. (2002) suggested that *P. pinaster*, *P. radiata*, and *E. globulus* might have similar potential to compete with crops, given that the lateral extent of their roots was found to be similar on a duplex soil, with all 3 having their greatest root density within 0.5 m of the soil surface where crop and pasture roots are concentrated.

The yield benefit of shelter reported for non-cereals such as lupins, peas, and canola in the Northern Hemisphere literature (Kort 1988; Brandle *et al*. 1992) was not observed at 8 or 16 m from the trees for the non-cereal crops in this study. This may reflect the absence of deleterious climatic events to which these crops are more sensitive than cereals at critical stages of growth in either year of the study.

The effect of season on the NYZ was evident at 11 sites measured in both 2001 and 2002. The NYZ was wider in 2002 than in 2001 for 8 of these sites (7, 8, 12, 13, 14, 16 18, and 19), reflecting lower rainfall in 2002 and greater potential for competition between the trees and crops for available water (Ssekabembe *et al*. 1994; Jose *et al*. 2000).

Carberry *et al*. (2002*a*) found a strong relationship between their visually determined NYZ and tree height for eucalypts on the Darling Downs ($r^2 = 0.86$, $n = 23$). However, in this study there was no clear relationship between tree height (m) and the width of the NYZ (Fig. 6). Normalising the distance data by expressing it in units of tree height (H) removes some of the scatter in the yield (Fig. 5*b*) but it was insufficient to base any prediction of the NYZ.

Lighter soils had a greater $NRZ_{outer/inner}$ than heavier soils ($P = 0.045$), suggesting a greater lateral exploration of the roots in sandier soils. The soil description was based on samples from the top metre where most of the tree roots occur; however, the depth to clay may also be a factor for tree water use. The $NRZ_{outer/inner}$ was higher for old trees ($P = 0.026$). The $NRZ_{outer/native}$ was significantly lower on the western side of a tree belt than on the eastern side ($P = 0.028$) but it is difficult to explain why recharge should be affected by the wind direction, unless there is a link between above- and below-ground morphology in response to environmental variables.

The high rainfall sites had the lowest $NRZ_{outer/inner}$ and $NRZ_{outer/native}$ ($P = 0.046$, 0.001, respectively). The likely cause for this was less competition between the inner and outer trees for water due to high rainfall. The $NRZ_{outer/native}$ was significantly lower in WA than in NSW ($P < 0.001$), whereas the position in the landscape did not have a significant influence on the NRZ.

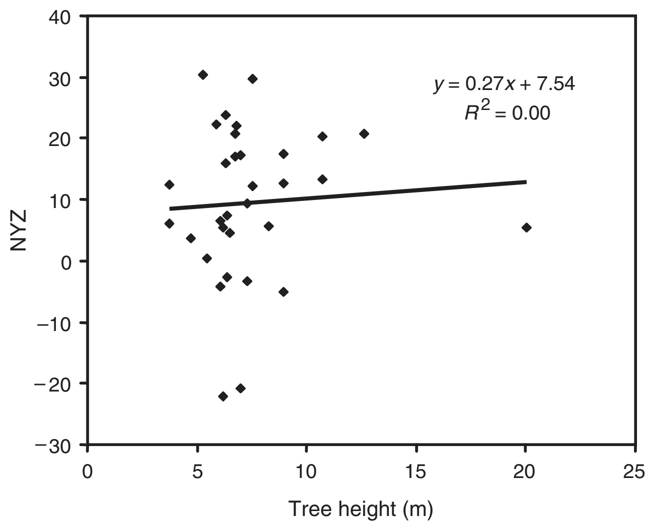

Fig. 6. The relationship between no-yield-zone (NYZ) and tree height (m).

While the NYZ is easily measured, it is more difficult to obtain a direct measurement of the NRZ. Empirical measurement of deep drainage in agroforestry systems has been attempted by Lefroy *et al*. (2001) and others (Hall *et al*. 2002; White *et al*. 2002). These studies required a large amount of costly and time-consuming data collection to quantify the components of the water balance but were still only able to achieve an estimate of deep drainage. As such work cannot be repeated over a wide range of tree, crop, soil, and climate combinations, a simplified approach is required.

The NRZ calculated from LAI in this way was shown to adequately describe NRZ measured for eucalypts using soil chloride profiles (Ellis *et al*. 1999, 2001) and gravimetric water content (Robinson *et al*. 2002) in the medium rainfall zone of Australia. This method appears to work best when applied to eucalypts >6 years old in equilibrium with rainfall between 300–700 mm. When the Ellis approach was applied to younger trees, the NRZ predicted from LAI_{native} was greater than that based on measurement of soil water content adjacent to young trees (Knight *et al*. 2002). This may reflect young trees taking up stored water in their immediate vicinity, resulting in fast initial growth and high leaf area, which then reduces as the trees adapt to surviving on rainfall alone and venture out into the adjacent cropped zone in search of water. This theory may require more validation for young eucalypts and additional calibration for other tree species.

Given the difficulty of measuring LAI, this study examined surrogate measures that could be used to make a more rapid prediction of NRZ. However, no relationship was found between the diameter at breast height and LAI or the ratio of the outer and inner diameter at breast height and the ratio of the outer and inner LAI. Similarly, tree basal area, which is simply measured and often found to be a good predictor of leaf area within a species, was a poor predictor of leaf area across the wide range of species involved in this study, suggesting that the search for simply measured integrals of system functioning still has some way to go.

In summary, the site and system features most strongly correlated with reduced competition or yield enhancement as reflected by a greater relative yield in the sheltered zone (0–16 m) were: (*1*) crops protected from the south through to the north-west, (*2*) young trees, and (*3*) water-gaining sites. Those features most strongly correlated with greater reduction in deep drainage were: (*1*) lighter soils, (*2*) older trees, (*3*) low rainfall areas, and (*4*) crops protected from the south, south-west, west, and north-west.

Trade-off

The NYZ and NRZ were used to determine the degree of trade-off between yield and deep-drainage control, classed as win–win, positive trade-off, and negative trade-off (Table 5). The chance of obtaining a win–win or positive trade-off scenario may be increased by planting trees with certain site and system features (Table 5).

Table 5. The site class by trade-off type showing genotypic (tree species and crop type) and environmental influences (soil type, landscape position, orientation and water gaining potential) for 2001 and 2002

Site	Year	Genotype		State	Environment						
		Tree	Crop		Orientation	Position[A]	Soil type[B]	Water gaining	Tree height (m)	Tree age (years)	Rainfall (mm)
					Win–win						
14	2001	Euc	Cereal	WA	N–SE	High	Heavy	Y	<8	>10	>400
13	2001	Euc	Non-cereal	WA	S–NW	High	Heavy	Y	<8	<10	>400
20	2001	Non-Euc	Cereal	NSW	N–SE	Low	Heavy	Y	>8	>10	>400
4	2002	Euc	Cereal	WA	S–NW	Low	Heavy	Y	<8	>10	<400
12	2001	Euc	Non-cereal	WA	S–NW	High	Heavy	Y	<8	<10	>400
3	2002	Euc	Cereal	WA	S–NW	Low	Light	N	<8	>10	<400
					Positive trade-off						
10	2001	Euc	Cereal	WA	N–SE	Low	Heavy	Y	<8	<10	<400
4	2001	Euc	Non-cereal	WA	S–NW	Low	Heavy	Y	<8	>10	<400
6	2001	Non-Euc	Cereal	WA	S–NW	Low	Light	Y	>8	<10	<400
5	2001	Non-Euc	Cereal	WA	S–NW	High	Light	[A]	<8	<10	<400
9	2001	Euc	Cereal	WA	S–NW	High	Light	N	<8	>10	<400
7	2001	Non-Euc	Cereal	WA	N–SE	High	Light	Y	<8	<10	<400
16	2001	Euc	Cereal	WA	S–NW	Low	Light	[B]	<8	>10	>400
7	2002	Non-Euc	Cereal	WA	N–SE	High	Light	Y	<8	<10	<400
14	2002	Euc	Cereal	WA	N–SE	High	Heavy	Y	<8	>10	>400
11	2001	Euc	Cereal	WA	S–NW	Low	Light	[A]	<8	<10	>400
15	2002	Euc	Cereal	WA	N–SE	High	Heavy	Y	<8	>10	>400
2	2001	Euc	Cereal	WA	N–SE	Low	Heavy	Y	<8	>10	<400
					Negative trade-off						
3	2001	Euc	Non-cereal	WA	S–NW	Low	Light	N	<8	>10	<400
16	2002	Euc	Cereal	WA	S–NW	Low	Light	[B]	<8	>10	>400
13	2002	Euc	Cereal	WA	S–NW	High	Heavy	Y	<8	<10	>400
19	2002	Non-Euc	Non-cereal	NSW	N–SE	Low	Heavy	Y	>8	>10	>400
15	2001	Euc	Cereal	WA	N–SE	High	Heavy	Y	<8	>10	>400
12	2002	Euc	Cereal	WA	S–NW	High	Heavy	Y	<8	<10	>400
1	2001	Euc	Cereal	WA	N–SE	Low	Light	N	<8	>10	<400
8	2001	Euc	Non-cereal	WA	N–SE	High	Light	N	<8	>10	<400
19	2001	Non-Euc	Non-cereal	NSW	N–SE	Low	Heavy	Y	>8	>10	>400
8	2002	Euc	Cereal	WA	N–SE	High	Light	N	<8	>10	<400
17	2001	Euc	Non-cereal	NSW	N–SE	Low	Heavy	N	>8	>10	>400
21	2001	Euc	Non-cereal	NSW	N–SE	Low	Heavy	N	>8	>10	>400
18	2002	Euc	Cereal	NSW	N–SE	Low	Heavy	N	>8	>10	>400
18	2001	Euc	Cereal	NSW	N–SE	Low	Heavy	N	>8	>10	>400

[A]Landscape position: low, valley and lower slope; high, high and mid-slope in landscape.

[B]Light soil type: deep sand, sand with increasing to sandy loam, sand over a sandy clay/sandy clay loam, loamy sand over clay loam. Heavy soil type, sand over clay, loamy sand over clay, sandy clay over clay and loam over a medium clay.

The win–win scenario occurs when the tree-crop combination produces a yield enhancement; however, this does not guarantee improved deep-drainage control. This occurred at 6 sites, with a significant effect on deep drainage estimated to be likely only at 3 of these 6. Alley farming would be the most favourable strategy at these sites in terms of crop production, whereas the effect on the management of deep drainage will vary, depending on environmental and genotypic factors. For win–win scenarios the common traits were water-gaining sites, trees <8 m tall, trees older than 10 years, and heavy soils.

The positive trade-off scenario occurs where the area of land over which trees reduce crop yield is less than the area over which they reduce drainage, i.e. NYZ < NRZ. At 12 of the 32 sites where this occurred, alley cropping may be a viable strategy for water management and crop production. More sites were in positive trade-off with the following grouped features: in 2001 than in 2002, with cereals than with non-cereal, in WA than in NSW, on light soils than on heavier soils, on water-gaining sites, with trees <8 m tall than with trees >8 m tall, and rainfall <400 mm than rainfall >400 mm.

The negative trade-off scenario occurs when the area of yield loss is greater than the area over which deep drainage is reduced, i.e. NYZ > NRZ. At the 14 of the 32 sites where this occurred, segregated use of trees in block plantations is more likely to be the optimal strategy for water management and crop production. Features common to these sites were non-water-gaining sites and older trees.

The NRZ and NYZ, however, reflect effects of trees that are valued quite differently. Whereas the effect of trees on crop yield is fairly easily determined, it is very difficult to place a value on their role in managing deep drainage. Apart from a few case studies in NSW and Victoria testing payment for ecosystem services (MBI Working Group 2002; Stoneham *et al.* 2002), landholders are not rewarded for managing deep drainage. Although the NRZ and NYZ express the relative influence of trees on crops and soil water, landholders making decisions about agroforestry will be influenced to a far greater extent by the absolute impact of trees on their income.

Opportunity cost

To give an indication of the opportunity cost of using trees for water management, this section presents estimated change in gross margin and deep-drainage reduction for the 32 sites. The results are presented in 3 groups based on the degree of trade-off in crop yield required to achieve a particular deep-drainage reduction target (Fig. 7 and Table 6). The first group (Group A) consists of the 3 sites at which the gross margin increased in the presence of trees *and* deep drainage was estimated to be reduced by more than 30%. The average for these sites was a 52% reduction in estimated deep drainage with a gross margin increase of $53/ha.

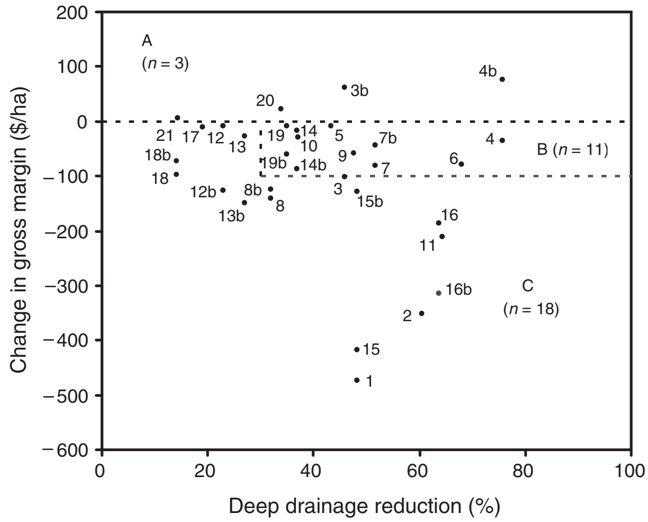

Fig. 7. Change in crop gross margin ($/ha) for a given level of deep drainage reduction (%) for 32 tree–crop interfaces. Group A is those sites with a gross margin increase *and* greater than 30% reduction in deep drainage; Group B is those sites with a gross margin loss of less than $120/ha *and* greater than 30% reduction in deep drainage; Group C are those sites with a gross margin loss of greater than $100/ha *or* less than 30% reduction in deep drainage. Percentage deep drainage reduction is based on the size of the no-recharge-zone in relation to the total area under crop.

The second group (Group B) consisted of 11 sites at which the gross margin fell by less than $100 *and* deep drainage was estimated to be reduced by more than 30%. The average for these sites was a 47% reduction in deep drainage at an opportunity cost of $47/ha, varying from $40 in 2001 to $64 in 2002. Most sites (18) fell into the least favourable group (Group C) where either the gross margin fell by more than $100 or deep drainage was estimated to be reduced by less than 30%. The average for these sites was a 37% reduction in deep drainage at a cost of $163/ha.

Across all sites, the average trade-off was a $102/ha reduction in gross margin for a 42% reduction in deep drainage, with the opportunity cost proving relatively insensitive to changes in variable costs. This analysis does not take into account other longer term and indirect benefits such as protection against water and wind erosion, aesthetics and enhanced biodiversity values. Although these may influence the adoption of agroforestry systems, the primary driver is likely to remain the effect on farm income.

Although some environmental factors were found to increase the NRZ or decrease the NYZ, it was difficult to relate them to increased profitability from integrating trees into cropping systems for water management. Features more common in the more profitable systems were trees planted on water-gaining sites in low rainfall areas (<400 mm) and

Table 6. Sites ranked by gross margin ($) and percentage recharge reduction (%) showing their status with respect to the five factors most likely to produce a favourable yield–deep drainage relationship (water-gaining sites, S–NW orientation, and low rainfall)
Sites measured in 2002 are labelled b

Site	Gross margin difference	Deep-drainage reduction	Water-gaining sites	S–NW orientation	Low rainfall
		Gross margin increase and >30% deep-drainage reduction			
4b[A]	76.3	75.8	√	√	√
3b[B]	61.6	45.9		√	
20	21.6	33.8	√		√
Average	53.2	51.8			
		Gross margin loss <$100 and >30% deep-drainage reduction			
19	−8.0	35.0			
5[B]	−8.5	43.3	–	√	√
14	−16.3	37.0	√		
10[B]	−30.4	37.0	√		√
4[A]	−35.7	75.8	√	√	√
7b[B]	−44.1	51.8			√
9[B]	−59.0	47.7	√	√	√
19b	−60.2	35.0			
6[A]	−79.5	67.9	√	√	√
7[A]	−82.0	51.8	√		√
14b	−88.3	37.0	√		
Average	−46.6	47.2			
		Gross margin loss >$100 or <30% deep-drainage reduction			
21	+5.5	14.3	√		
12[B]	−8.2	22.9	√	√	
17	−11.3	19.0			
13[B]	−27.3	26.9	√	√	
18	−72.7	14.1			
18b	−98.6	14.1			
3[B]	−101.7	45.9		√	√
8b	−124.8	32.0			√
12b[B]	−126.7	22.9	√	√	
15b	−129.4	48.4	√		
8	−140.8	32.0			√
13b[B]	−148.4	26.9	√	√	
16	−186.6	63.7	–	√	
11	−211.3	64.4	–	√	
16b	−315.5	63.7	–	√	
2[B]	−352.2	60.4	√		√
15	−417.1	48.4	√		
1	−473.7	48.2			√
Average	163.4	37.1			

−, Could not determine the water-gaining site attribute as no inner tree row.
[A]Two out of 3 attributes.
[B]Three out of 3 attributes.

orientation of tree belts to protect crops from the south to north-westerly winds.

Although this study examined a range of tree–crop interfaces over a wide geographical area, the data only cover 2 years, one of which was a drought at virtually all sites. When making decisions about the adoption of agroforestry, however, it is important to have some idea of the likely effect of trees over a range of seasonal conditions given the inflexible nature of the technology. Carberry *et al*. (2002*b*) modelled grain yield and gross margin for 11 sites over 30 years based on experimental data on crop production in the lee of windbreaks from a smaller number of experimental sites around Australia. In comparison with this study, their modelling suggested a far narrower range in gross margin change as a result of adding trees to a cropping paddock (±$20/ha) with a mean change of –$2.50/ha.

This was primarily due to the assumptions involved in their modelling. As only one side of a tree belt was considered to a distance of 100 m, this equated to having tree belts 200 m apart. In addition the belts were assumed to occupy only one tree height of arable land (equivalent to 7–10 m for our sites, compared with 15 m used in our economic analysis). Competition was also set at 20% yield loss in the first 3.5 H (compared with 40% yield loss extending over a larger distance in this study), and yield gain set at 4.6% at 5 H for all sites in all years (compared with a mean 2% yield loss in this study). These assumptions result in more favourable crop yield and a smaller hydrological effect due to the wider spacing between belts.

Variability

As the relatively small sample size and limited replication may have lead to some outlying data points, the data were re-analysed with some outliers removed. Relative yields of <0.5 at 32 m (5 H) were set to 0.5 as yield reductions of greater then 50% were considered unlikely to be caused by the presence of trees. This affected 4 sites (Sites 1, 6, 16b, and 21), but had only a marginal effect on their NYZ and gross margin difference and did not affect their trade-off class.

Relative yields greater than 1.5 were reset to 1.5, as yield enhancement of >50% in the sheltered zone (16–32 m) was also considered unlikely to be related to the influence of trees. This reduced the yield enhancement at 5 sites (Sites 3b, 4b, 12, 14, and 20) but these sites still had a net yield gain, indicated by negative NYZs; however, these were reduced by 50–80%. These sites still fell in the win–win trade-off class (Table 5) but their gross margins were reduced. The gross margin for 3 sites in Group A (gross margin increase and >30% deep-drainage reduction) was smaller with an average of \$14.6/ha compared with \$53.2/ha. Removing these outliers reduced yield enhancement, resulting in a narrower range in gross margin improvements from tree–crop systems.

In summary, when outlying data points were removed, the economic analysis showed that of the 32 tree–crop interfaces studied, the win–win situation of a gross margin increase *and* a reduction in deep drainage still occurred at only 3 sites, with a gross margin increase ranging from \$1 to 16/ha. At a further 11 sites, a better than 30% reduction in deep drainage was achieved at a cost of a gross margin loss of under \$100/ha, with an average gross margin loss of \$49/ha. Most sites (18) there was an average of 37% reduction in deep drainage at the cost of a gross margin loss of over \$162/ha.

Seasonal conditions had a strong influence on the complementarity between water management and yield, with some sites being in positive trade-off in one year and negative trade-off in the other. As agroforestry systems are long lived and therefore relatively inflexible to management, modelling would be required to produce a probabilistic prediction of trade-off over time. Removing outlying data points had very little effect on the average NYZ for sites grouped by sites or system features (Table 4). The combination of factors found to be most strongly correlated with profitable tree–crop systems, positive trade-off scenario and win–win trade-off scenario were: (*1*) protection of crops from the south, south-west, west, or north-west; (*2*) water gaining sites (access to perched watertables or run-on water); and (*3*) lower rainfall (<400 mm).

Conclusions

Competition was found to be the norm for the 32 tree–crop interfaces studied, with an average 7.4% yield loss equivalent to 9.5 m of land lost to production. Although some yield enhancement in the sheltered zone was measured at 22 of the sites, a net yield gain occurred at only 6 sites.

Trees were able to protect on average 12.7 m of cropped land from deep drainage but this ranged from a very small predicted lateral influence on deep drainage (0.6 m) to highly effective deep drainage control (30 m). The difference between the LAI_{outer}, LAI_{inner}, and LAI_{native} provided insight into the potential of water-gaining sites, which may influence the NYZ and NRZ.

In short, in water-limited environments, competition appears to rule and the trees tend to win. Where trees are of equal or higher value than the crops, this does not present a problem. However, at present, commercial products from trees grown in cropping environments are largely absent and fixed investment in trees involves a significant opportunity cost. This study suggests that locating trees with consideration for hydrology and aspect can offset this opportunity cost.

Acknowledgments

This project was a collaboration between the Joint Venture Agroforestry Project (JVAP) and the Grains Research and Development Corporation (GRDC). JVAP is funded by three R&D Corporations — RIRDC, LWRRDC, and FWPRDC – and managed by RIRDC.

The authors acknowledge the generous assistance provided by the participating landholders: Laurie and Jenny Pitman, Kevin and Julie Ling, Richard and Chantal Guiness, Tim, Margaret and Robert Clayton, Gordon and Cameron McDougall, Peter and Wendy Bessell-Brown, Ian Cooley, Greg Parker, John and Fiona Johnson, Bill and Clemmence Matchett, Tony and Kerry Richens, and Ann and Bernard Hart.

We thank David Waugh (University of Western Australia) for his assistance with the data collection in WA, and Alan Reid (CSIRO Sustainable Ecosystems, Canberra) for his assistance with data collection in NSW.

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Manuscript received 14 September 2004, accepted 11 July 2005