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Edward Lefroy, Stirzaker, RJ, Pate, JS

Bibliographic citation
Lefroy, Edward; Stirzaker, RJ; Pate, JS (2001). The influence of tagasaste (Chamaecytisus proliferus) trees on the water balance of an alley cropping system on deep sands in south western Australia. University Of Tasmania. Journal contribution.
https://figshare.utas.edu.au/articles/journal_contribution/The_influence_of_tagasaste_Chamaecytisus_proliferus

Is published in: 10.1071/AR00035

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Australian Journal of Agricultural Research

VOLUME 52, 2001
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Aust. J. Agric. Res., 2001, **52**, 235–246

The influence of tagasaste (*Chamaecytisus proliferus* Link.) trees on the water balance of an alley cropping system on deep sand in south-western Australia

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Abstract. Components of the water balance of an alley cropping system were measured to assess the extent to which tree rows 30 m apart with access to a fresh, perched watertable at 5 m depth were able to capture deep drainage from an inter-cropped cereal–legume rotation. Neutron probe data showed that the 4-year-old trees, cut back to 0.6-m high at the beginning of the experiment, depleted soil water to 2, 4, and 8 m laterally from the tree rows in their first, second, and third years of coppice regrowth, respectively. Combining data from soil water depletion in summer and comparisons of deuterium:hydrogen ratios of groundwater, xylem sap of trees, and herbaceous plants, it was shown that tagasaste trees drew on soil water for 80% of their transpiration in the first winter and 40% in the second, while switching to near total dependence on groundwater each summer and early autumn. Tree water use on a whole plot basis was 170 mm in 1997 (68% from groundwater) *v.* 167 mm in 1998 (73% from groundwater). Recharge to the perched watertable was estimated to be 193 mm under sole crop in 1998 (52% of rainfall), reducing to 32 mm when uptake of groundwater by trees was included. The degree of complementarity between tagasaste trees and crops in alley cropping used for water management is quantified for 1998 by calculating the ratio of the distance over which trees reduced drainage to zero to the distance over which they reduced crop yield to zero. It is concluded that segregated monocultures of trees and crops would be a more appropriate strategy than a closely integrated system such as alley cropping in this case.

Additional keywords: agroforestry, stable isotope natural abundance, time domain reflectometry.

Introduction

Alley cropping is a form of agroforestry in which crops are grown in the alleys between spaced rows of trees or shrubs. Spaced agroforestry systems such as alley cropping and parkland agroforestry have been advocated as a means of increasing water use in the agricultural landscape of southern Australia and therefore contributing to the management of dryland salinity (Lefroy *et al*. 1992; Lefroy and Scott 1994). Salinity currently affects 1.8 million ha of land in south-western Australia and this is projected to rise to 6 million ha by the middle of next century (George *et al*. 1997). Alley cropping has been adopted to a limited extent by landholders, commonly on the assumption that there will be indirect benefits from reduced wind erosion, increased water use, and improved crop and animal productivity through changed microclimate (Stirzaker and Lefroy 1997). However, there are few empirical studies in Australia that quantify these effects (Bird 1998; Nuberg *et al*. in press; Sudmeyer *et al*. in press). In particular, questions remain about the relative impact of spaced trees on crop yield and water balance at field and catchment scale.

Sanchez (1995) identifies the aim of agroforestry as using trees to capture resources unused by crops without compromising crop yield. For such perfect complementarity to exist where agroforestry is used for water management, deep-rooted summer-active trees would need to capture all the drainage below shallow-rooted winter-active annual crops without depressing yield. On the other hand, perfect competition would occur if trees capture water entirely at the expense of the crop and drainage remains unaffected. For agroforestry to be an effective and economically viable

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option for water management, it is necessary to know where a particular tree-crop combination falls between these two extremes.

In practical terms this means quantifying the following features of a tree-crop system:

(1) the size of the soil zones occupied by tree and crop roots,
(2) deep drainage occurring under the sole crop,
(3) water use of spaced trees, and
(4) yield of crops with and without tree belts.

From these, the proportion of the landscape under trees and the spacing required to meet a particular drainage reduction target can be determined.

To assess the potential of alley cropping for managing deep drainage, a field experiment was established to compare water use, growth, and nitrogen cycling in conventional cropping, perennial pasture, and the fodder tree tagasaste (*Chamaecytisus proliferus* Link.) at alley and plantation densities. The site was on a deep sand near Moora, 150 km north of Perth (lat. 30°45´, long. 116°40´), where Asseng *et al.* (1998) had estimated median deep drainage under conventional cropping to be 140 mm/year. Tree growth and water use at high and low density, the influence of trees on crop yield, and nitrogen inputs by tagasaste alley cropping and plantation systems are described elsewhere (respectively Lefroy and Stirzaker 1999; Unkovich *et al.* 2000; Lefroy *et al.* 2001). This paper concentrates on components of the water balance in the alley crop and conventional cropping treatments. The aims of the experiment were to determine (*i*) the amount of water that alley trees used, (*ii*) the proportion that came from soil and groundwater, and (*iii*) the impact that alley trees had on deep drainage.

Given the difficulty of accounting for the fate of rainfall in mixed plant communities, 4 different approaches were combined in this study in order to answer the above questions. Neutron moisture meters (NMM) provided replicated measurements of soil water status at regular intervals and a means of measuring the spatial distribution of water across the agroforestry treatments. Time domain reflectometry (TDR) was used for fine scale continuous measurement of the water status of the highly transmissive soil in the 2 extreme treatments, tree plantation and annual crop. Sapflow gauges were used to measure tree transpiration and assist in partitioning soil water loss between transpiration and drainage. Stable isotope analyses were used to partition tree water use between soil and groundwater sources.

Materials and methods

The 8-ha site contained 5 treatments, each replicated twice in plots 50 m by 160 m (see fig. 1 in Lefroy *et al.* 2001). The treatments were sole crop, perennial grass-based pasture (*Chloris gayana*), tagasaste at plantation density, and tagasaste in spaced rows with and without cropping (alley crop and alley fallow respectively). Only the alley crop, alley fallow, and sole crop treatments are discussed here. The alley design was single rows of trees 30 m apart orientated north–south with 0.7 m between trees within a row, giving 6 rows of trees per plot with a density of approximately 550 trees/ha. In the alley fallow treatment, a chemical fallow was maintained between tree rows to enable measurement of tree water uptake in the absence of surface soil disturbance and competition from crop.

At the commencement of the experiment in May 1996, the 4-year-old trees were mechanically pruned from 2 m to 0.6 m high. They remained uncut for the following 3 years to evaluate growth, water use, and root extension of the freely coppicing trees. Grain lupins (*Lupinus angustifolius* var. Gungurru) were sown in sole crop and alley crop plots on 20 June 1996 followed by oats (*Avena sativa* var. Toodyay) on 8 June 1997 and *L. angustifolius* var. Merrit on 6 May 1998. Phosphorous was added at 13 kg/ha each autumn to all plots.

The soil was a coarse, very infertile acid sand with pH ($CaCl_2$) 5.2 at the surface and 4.8 between 1 and 3 m. Water holding capacity was very low, with a drained upper limit of 0.10 and a lower limit of 0.03 m^3/m^3. A permanent fresh (<1 dS/m) perched watertable has developed over a clay layer approximately 10 m below the surface and risen progressively since the original *Banksia*-dominated woodland vegetation was cleared in 1964. Depth to the watertable was monitored monthly at 11 wells distributed across the 8-ha site. The soil characteristics and very low relief at this site mean that the water balance is essentially vertical, and for the purposes of this study it was assumed that there was no runoff and no lateral water movement above the saturated zone. However, the highly transmissive nature of the soil meant that rapid lateral ingress of groundwater from outside the plot area provided continuous replacement of water transpired by the trees at the site.

Weather data

Rainfall, air temperature, wind speed, solar radiation, and relative humidity were measured using an on-site automatic weather station (Campbell Weather Watch 2000) and these parameters used to calculate Penman-Montieth potential evapotranspiration (Campbell 1977; Monteith and Unsworth 1990), referred to hereafter as E_0.

Soil water content

Soil water content was measured with neutron probes at 20-cm intervals to a depth of 3.7 m from July 1996 to December 1998 at 2-week intervals in winter and monthly over summer. Six access tubes were located in each sole crop plot and 11 in each alley crop and alley fallow plot, the latter along transects at 0, 1, 2, 4, 8, and 15 m either side of tree rows, giving a total of 56 access tubes. Neutron probes were calibrated gravimetrically in the field with separate calibration equations for 0–20, 20–80, 80–140, and >140 cm depth intervals to convert neutron counts to volumetric water content. The r^2 values for these equations were 0.72, 0.96, 0.97, and 0.95, respectively.

An assembly of TDR probes was installed in one sole crop plot on 27 April 1997. A 4-m well was excavated and lined with a 1.5-m-diameter concrete pipe. Ports were cut through the concrete liner on the undisturbed side of the well to allow probes to be inserted at depths of 20, 75, 150, 230, 275, and 360 cm. Probes were inserted horizontally after excavating 60 cm of soil and pushing the 40-cm wave guides into the undisturbed sand. A probe with 40-cm wave guides was also installed obliquely over the depth 0–20 cm. Measurement at hourly intervals commenced on 17 September, during the latter half of the oat crop, and continued until 30 December 1998, after the end of the following lupin crop.

Tree transpiration

Transpiration was measured using sapflow sensors (Hatton *et al.* 1990) fitted to selected tagasaste stems and moved to a fresh set of stems on a 6-monthly rotation. Six stems of varying size from 3 trees were logged

between December 1996 and December 1998 using Greenspan SF300 sensors. An additional 24 stems were logged from March 1998 to December 1998 with sensors using the heat ratio method (Burgess *et al*. 1998). Flux per stem was scaled up to plot level transpiration using data from 4-monthly surveys of stem size distribution (10 trees per treatment) and measurements of conductive wood area taken by immersing freshly cut stems in a 0.05% solution of basic fushian and assessing movement of dye up the stem after a 2-h period of transpiration.

Relative dependence of trees on soil and groundwater

Differences in deuterium:hydrogen (D:H) natural abundance isotope signals between tagasaste xylem sap, groundwater, and the xylem sap of annual plants (as representative of soil water) were used in a mixing model to estimate the relative amounts of soil and groundwater used by the tagasaste. Deep mechanical excavations showed that some tagasaste roots reached the watertable, branching and terminating at the capillary fringe at 4–5 m. Xylem sap from the last 30 cm of these sinker roots was found to conform closely (± 1.5‰) in its D:H value to that of groundwater collected from wells within 20 m of the excavations.

Xylem sap was collected by mild vacuum extraction of segments of non-transpiring stems to obtain reference sources of xylem mobile water (Dawson and Pate 1996). Sap samples were collected monthly from 10 shoot segments in each of 2 replicated alley crop and alley fallow plots between June 1996 and April 1998. Groundwater samples were collected synchronously from the 11 wells at the site. Samples of stem-bleeding xylem sap of relatively shallow-rooted annual weed species were collected monthly during the winter growing season.

Two annual weed species, wild radish (*Rhaphanus raphanistrum*) and wild turnip (*Brassica tournefortii*), were found to exude large volumes (up to 10 mL/h.plant), which permitted samples to collect rapidly in narrow tubes attached to the stem, therefore minimising D:H changes due to evaporation in the tube. Excavation showed that the roots of the weed species extended to between 1.5 and 2 m within the first 2 months of growth, exploiting the same mid to upper soil zone in which most non-sinker roots of tagasaste were located. As the annual species did not establish until the first rains of autumn (April–May) and had senesced by late November, application of the mixing model was restricted to the 7–8 month wet season.

Water from groundwater and xylem sap was extracted by cryogenic vacuum distillation (Ehleringer and Osmond 1989) and D:H values estimated by converting the constituent hydrogen and deuterium to gaseous form and analysing for isotope abundance using a high precision mass spectrometer (VG Isogas SIRA 10), as described by Dawson (1993) and Dawson and Pate (1996).

Results

Conceptual model of tree–crop interactions

The conceptual approach used in quantifying the interactions between trees and crops is shown in Fig. 1. The soil profile is divided into zones (S1–7) on the basis of the presence of tree roots, crop roots, both, or neither. Complete quantification of all transfers occurring within and between these zones was not possible as there was insufficient instrumentation to measure drainage and crop evapo-transpiration across the tree–crop interface. Emphasis was placed instead on measuring tree water uptake from soil and groundwater in the alley crop treatment and drainage in the sole crop treatment, and from this inferring drainage across the alley crop treatment.

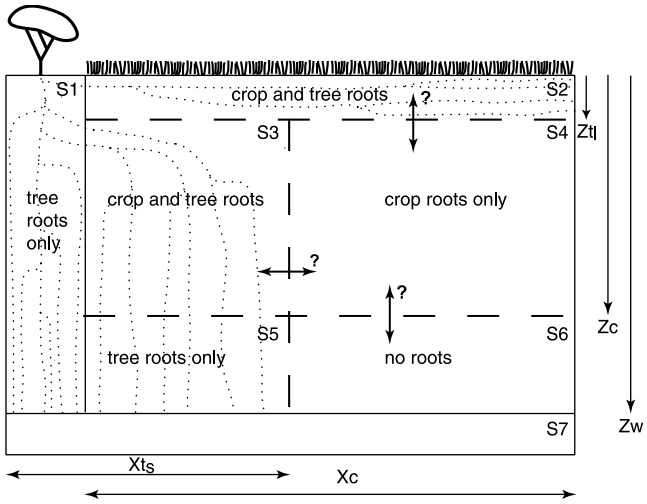

Fig. 1. Schematic representation of the interaction between trees and crops in an alley cropping system with the below-ground environment divided into zones (S1–7) occupied by tree roots, crop roots, both, or neither. Critical dimensions are depth of crop roots (Zc), depth to watertable (Zw), depth to which tree lateral roots extend (Zt_l), width of crop zone (Xc), and lateral extent of tree sinker roots (Xt_s). Lateral water movement above the saturated zone and runoff are assumed to be negligible. The saturated zone is S7.

Seasonal conditions and crop yields

Rainfall, grain yield in sole crop and alley crop, and the area occupied by tree canopies over the 3 years are shown in Table 1. Following cutting on 26 May 1996, the trees continued to grow over the following 2.5 years until canopy width reached 6 m by harvest in 1998, when tree canopies occupied 20% of the total land area in the alley treatments (tree rows 30 m apart). The long-term average rainfall recorded for Moora, 10 km SE of the site, is 462 mm (Bureau of Meteorology 1999).

Alley crop yields in Table 1 are calculated on a whole plot basis, including the area of land displaced by trees. When only the arable land in alley crop plots is considered, yield in alley crop was 29% higher than in sole crop in 1996, 4% higher in 1997, and 19% lower in 1998. The increase in the first year was observed in grain yield but not in above-ground biomass. Less flower and pod abortion was observed in alley crop than in sole crop plots in late spring of that year, possibly due to the shelter effect of the 2-m-high trees. No differences were detected in total biomass or grain yield of lupins grown in a replicated pot experiment using soil taken at 2, 4, 8, and 15 m from tree rows in alley crop plots and at random in sole crop plots, further suggesting that the yield differences observed in 1996 were due to above-ground rather than below-ground factors. In 1997, yield loss was due to displacement of arable land by the trees, not net competition, whereas in 1998, yield loss was due to both displacement and competition.

Table 1. Rainfall (mm), area under trees (%), and grain yield (t/ha) in sole crop and alley crop 1996–1998

Year	Crop	Rainfall	Area occupied by trees	Grain yield Sole crop	Grain yield Alley crop[A]	Influence of trees on yield (%)
1996	Lupins	445	8	0.52	0.64	+ 23*
1997	Oats	431	14	0.92	0.85	– 8
1998	Lupins	376	20	1.19	0.81	–32*

* Differences significant at $P = 0.05$. [A] Includes the area occupied by trees.

Rainfall distribution over the 3 seasons and the corresponding change in soil water content in sole crop plots are shown in Fig. 2 to give an indication of the situation that exists under conventional farming practice. In each season, a rise in the perched watertable occurred in the month after stored soil water store reached its maximum. The watertable fell 24 cm during the study period (May 1996 and December 1998) following 3 years of below average rainfall. This contrasts with the general long-term average rise of 20 cm/year reported by Speed *et al.* (1993) for this region. Given the highly transmissive nature of the aquifer and the large size of the topographic catchment, the response observed in the watertable would have been a whole-catchment phenomenon, with the trees in the 8-ha experimental plot having no discernible influence on the saturated zone.

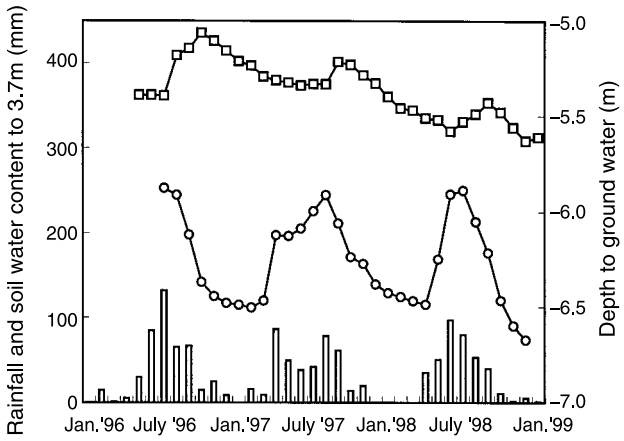

Fig. 2. Rainfall (bars), depth to groundwater (□), and monthly soil water content under sole crop treatment reflecting conventional practice in the region (○).

Total tree water use

Seasonal fluctuations in tree transpiration and E_0 are compared in Fig. 3. Transpiration in mm of water loss per month is expressed on the basis of the 20% of land occupied by trees in alley cropping at the end of the study (6-m-wide tree belts spaced 30 m apart), and on a whole-plot basis including the cropped area. Annual tree transpiration on a whole-plot basis was 170 mm in 1997 and 167 mm in 1998. When expressed in terms of the 20% occupied by tree canopies, transpiration loss was 0.54 of E_0 in 1997 and 0.57 in 1998.

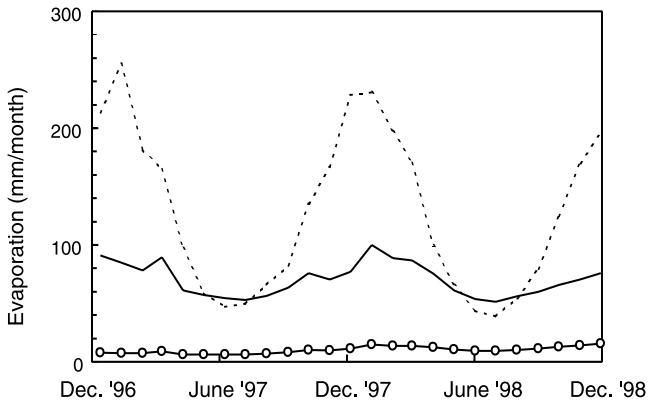

Fig. 3. Penman-Montieth potential evapotranspiration (E_0, ---) and tagasaste transpiration (T) over the 20% of land occupied by trees in alley cropping at maturity (—) and on a total plot area basis (○).

Tree water uptake from the unsaturated zone

Following cutting of the trees in May 1996, the soil profiles in all treatments had filled equally by late winter with integrated data from neutron probe readings across the plots showing that soil water content to 3.7 m reached maxima in late August. By harvest of the 1996 lupin crop, soil water content had been reduced to 36% of its winter maximum in alley crop, 44% in sole crop, and 54% in alley fallow. As shown in Fig. 4, these changes in soil water content were not distributed evenly across the alley plots but were confined to a narrow zone immediately below the tree rows. From these data it is possible to estimate the vertical and lateral extent of soil water extraction by tree roots.

Excavations in March and July 1997 indicated that a thin veneer of shallow lateral roots of tagasaste extended right across the 30-m-wide alleys within the top 60 cm of the soil (Lefroy *et al.* 2001). However, neutron probe data indicated that soil water extraction by trees below this depth extended only 2 m laterally at the time of crop harvest on 3 December 1996 (Fig. 4*a*,*k*), increasing to 4 m over the following summer (Fig. 4*b*,*l*). Little change occurred over the subsequent cropping season between April and December 1997. Then over the second summer, the lateral

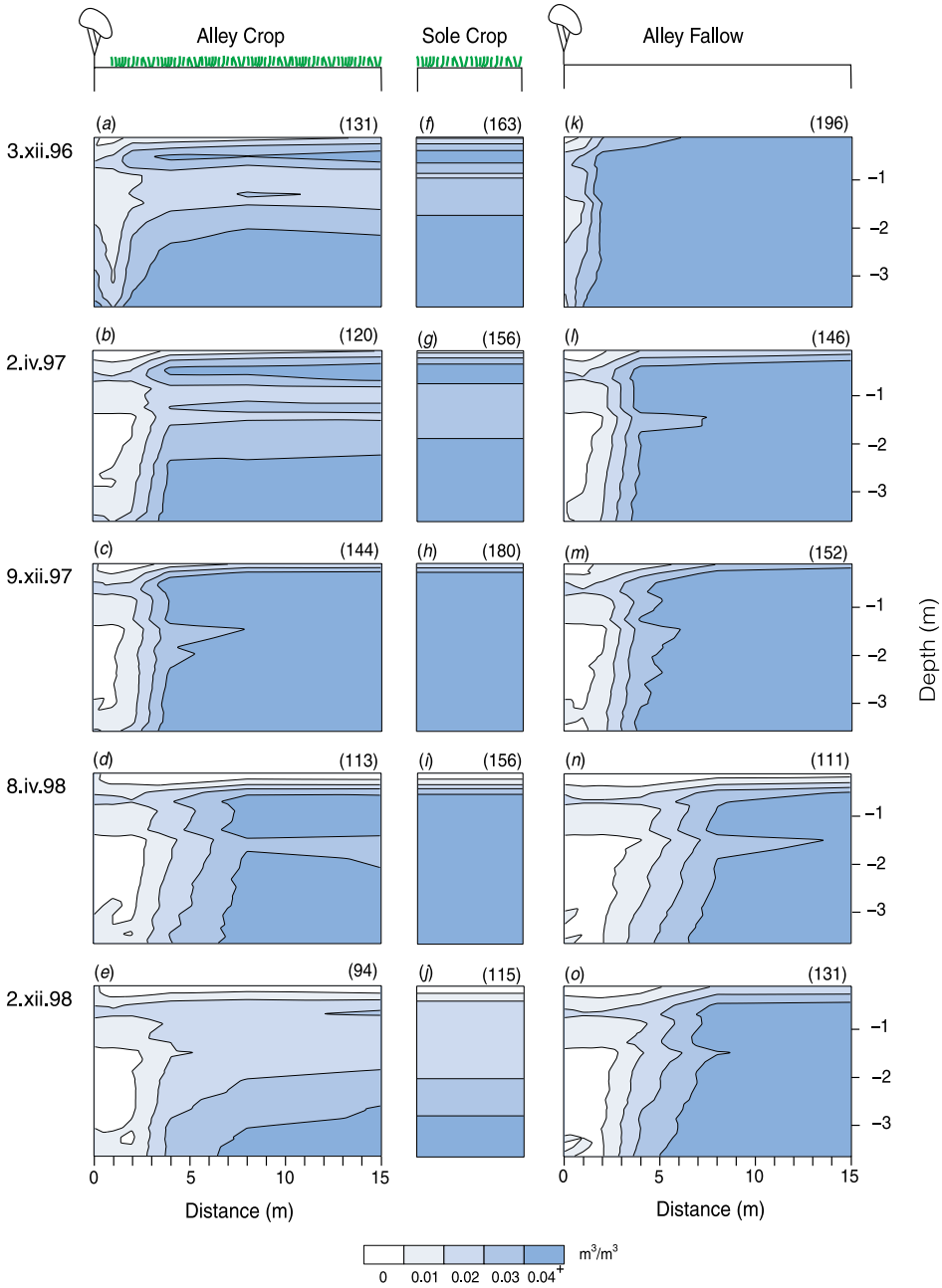

Fig. 4. Soil water content under alley crop (left), crop (centre), and alley fallow treatments (right) at harvest (December) and just prior to the break of season rains (April) from December 1996 to December 1998. Soil water content in alley crop and alley fallow are mean values (n = 4) of neutron probe measurements made at 19 depth intervals per hole (20-cm intervals from 10 to 370 cm) in 6 access tubes (0, 1, 2, 4, 8, and 15 m from the tree rows) plotted at a contour interval of 0.01 m^3/m^3. Soil water content in crop treatment is the mean of 12 access tubes. Numbers in parentheses are total soil water content (mm) integrated across each treatment.

domain of the tree root appeared to extend to a maximum of approximately 8 m (Fig. 4*d*,*n*). Comparing the distribution of soil water in alley crop (Fig. 4*a*–*e*) with alley fallow (Fig. 4*k*–*o*) shows that the lateral extent of water extraction by tree roots differed little between these two treatments, despite the absence of crop competition and physical damage to tree roots from cultivation in alley fallow. The extending lateral influence of the trees over the course of the study is also evident from data showing available soil water between 290 and 370 cm along a transect from the tree row to the centre of the alleys (Fig. 5). In 1996 and 1997, the change in soil water content below 290 cm would have been due solely

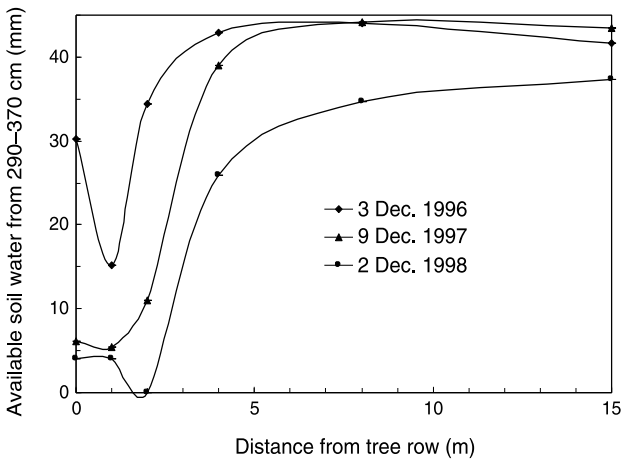

Fig. 5. Available soil water content below the crop root-zone in alley crop plots at Moora, WA, at crop harvest in 1996, 1997, and 1998 showing the lateral extension of tree roots.

to the trees, whereas in 1998, the deeper rooted lupin crop would have influenced the data of Fig. 5.

Partitioning tree water use between soil and groundwater sources

Two approaches were used to partition tree water uptake between soil and groundwater. Over summer, tree water uptake was estimated from neutron probe measurements of soil water depletion in alley crop plots over rainfree periods. In winter 1996 and 1997, differences in the D : H ratios of groundwater, tree xylem sap, and the xylem sap of annual herbaceous plants (as indicators of soil water D:H ratios) were used to calculate the proportion of tree transpiration derived from each source.

Soil water depletion in summer

The first step in using the water balance approach was to establish the boundaries of the soil zones shown in Fig. 1 to determine how much of the soil water depletion from each plot over rain-free periods could reasonably be attributed to tree uptake. The outer boundary of S3 and S5 (lateral extent of water extraction by trees) was taken to extend from 2 to 4 m over the first summer (Fig. 4*a*, *b*) and from 4 to 8 m over the second (Fig. 4*c*, *d*). The outer boundary of S1 was the distance from the centre of the tree row to the crop edge at harvest, 0.8 m over the first summer and 1.7 m over the second. The lower boundary of S2 was set at 60 cm, based on excavations in May and July 1997.

Water loss from each zone was calculated volumetrically from NMM data, summed, and then converted to mm on a whole plot basis. The theoretical upper limit of soil water uptake by trees would be the sum of soil water depletion from all soil zones containing tree roots (S1, S2, S3, and S5). However, water loss from S2 was very similar to loss from the top 60 cm in sole crop plots for all periods examined, indicating that this loss could equally be attributed to soil evaporation. The estimate of soil water extraction by trees was therefore taken to be the sum of S1, S3, and S5 plus that part of S2 within limit of the bulk of the trees roots (i.e. the outer boundary of S3 and S5). These values for tree water uptake and total tree transpiration measured by sapflow gauges are shown in Table 2 for the 13 rain-free summer periods over the course of the study.

Table 2. Soil water uptake by tagasaste trees in alley cropping derived from sapflow measurements of tree transpiration and neutron probe measurements of change in soil water content over rain-free periods in summer, expressed on a whole plot basis

Period Start	Period Finish	Days	Total tree water use (mm)	Soil water depletion[A] (mm)	Tree water uptake from soil (%)
22 Oct. 96	5 Nov. 96	14	6.7	3.3	48
3 Dec. 96	17 Dec. 96	14	8.4	1.3	15
17 Dec. 96	9 Jan. 97	23	14.1	1.9	13
9 Jan. 97	6 Feb. 97	28	14.9	1.4	10
5 Mar. 97	2 Apr. 97	28	15.6	1.1	7
16 Apr. 97	30 Apr. 97	14	5.7	4.2	74
15 Oct. 97	30 Oct. 7	15	7.5	2.7	36
30 Oct. 97	12 Nov. 97	13	6.1	1.9	31
25 Nov. 97	9 Dec. 97	14	6.8	1.1	16
9 Dec. 97	14 Jan. 98	36	20.1	4.0	20
14 Jan. 98	27 Jan. 98	13	8.6	1.0	12
11 Feb. 98	11 Mar. 98	28	17.5	2.2	13
11 Mar. 98	08 Apr. 98	28	15.8	2.1	13

[A] Sum of soil water depletion from soil zones S1, S3, and S5 plus that part of S2 within the outer boundary of S3 and S5 (see Figs 1 and 4).

Deuterium mixing model

The D:H ratios (δD of water ‰) for the various sources used in the mixing model are shown in Fig. 6*a*. This indicates clear discrimination between values for annual plant xylem sap (i.e. soil water) and groundwater. Dawson and Pate (1996) and Farrington *et al*. (1996) have shown that the degree of discrimination between soil and groundwater commonly seen in this environment is due to the fact that the major contributors to groundwater recharge are large rainfall events occurring in late winter (and therefore likely to move rapidly through the soil profile) that tend to have very negative δD values. The values for tagasaste were similar to those for annual plants at the beginning of the experiment, soon after the trees were cut, and became more negative over the course of the experiment.

The deuterium data for winter 1996 and 1997 were combined with the soil water extraction by trees estimated from water balance (Table 2) to derive a seasonal profile of relative dependence of alley crop trees on soil water from July 1996 to March 1998 (Fig. 6*b*). Good correlation between the 2 methods can be seen in April and October 1997, occasions when the presence of shallow rooted annual plants necessary for the deuterium method coincided with periods without rainfall.

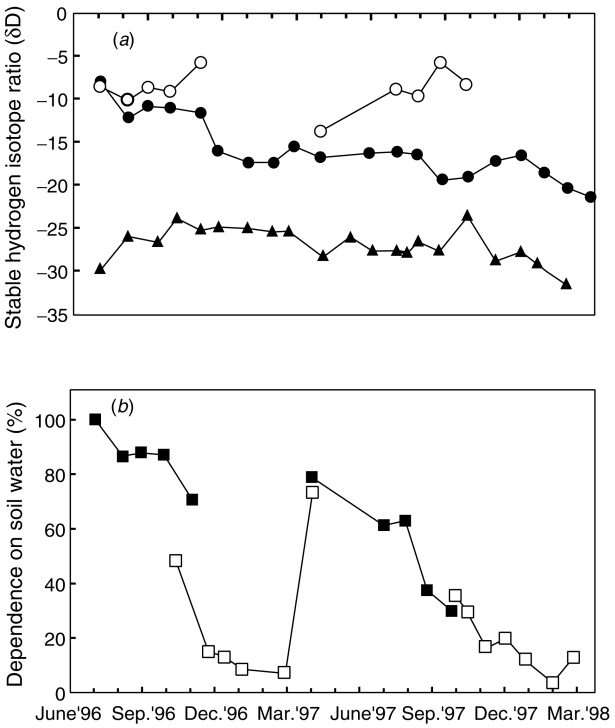

Fig. 6. (*a*) Stable isotope ratios (δD of water ‰) for tagasaste xylem sap (●), groundwater (▲), and annual plants as reference values for soil water (○). (*b*) Dependence of tagasaste trees on soil water from August 1996 to April 1998 using 2 methods: a mixing model based on deuterium:hydrogen ratios of xylem sap, groundwater, and annual plants (■), and water balance calculated for rain-free periods (□).

The combined data sets show declining dependence on soil water during the course of each winter, higher dependence on soil water in the first than second winter (86% and 54%, respectively), and rapid switching from soil to groundwater in late spring 1996 and back to soil water following an episodic rainfall event in April 1997. The actual amounts of water used by the trees from soil and groundwater sources during each crop growing season and between crops are shown in Table 3.

Rooting depths of the sole crop

Neutron probe data suggested that the maximum rooting depth of the 1996 lupin crop was 290 cm, whereas that of the 1997 oat crop was 170 cm and the 1998 lupin crop 350 cm. Hourly TDR measurements provided more detailed insight into the rooting dynamics of the latter 2 crops (Fig. 7). These data need to be interpreted with care because the change in water content with time is dependent on the rate that water arrives from the layer above, drains to the layer below, and is extracted by roots. Nevertheless, the data show that the rooting front of the oat crop definitely reached 150 cm, probably 230 cm, but not 360 cm.

The change in water content at 230 and 360 cm between September and November 1997 was very similar to that observed during a later fallow period in autumn 1999, which showed similar rates of loss at these water contents in the absence of a crop (data not shown). For the 1998 lupin crop, it appears that the loss of water at 150 cm between 18 June and 20 August was predominantly through drainage, but that the accelerated loss after 20 August (see arrow in Fig. 7) was a consequence of roots reaching this depth. A similar argument suggests that appreciable root extraction at 230 cm occurred around 15 September and, at 360 cm, commenced after 4 October, with drainage predominating prior to this.

The lupin crop clearly extracted more water from the 230 cm and 360 cm depths than the oat crop, dropping the water content to the lower limit for this soil. At the end of the season the lupin crop had extracted 66 mm more water than the oat crop from the 150–360 cm zone.

Estimated drainage from TDR

Drainage is very difficult to estimate from water content data, even with appropriate data on the relationship between hydraulic conductivity and water content, particularly in this transmissive soil where wetting fronts move quickly through the profile. For the purpose of this study, we used the hourly TDR data to provide an estimate of drainage in one location in sole crop from the end of the 1997 oat crop to the end of the 1998 lupin crop.

Between harvest of the oat crop and the opening rains of the 1998 season, the loss of water from the profile was 34 mm, almost all of which was assumed to be drainage from below 150 cm. However, as soil evaporation through

Table 3. Tree transpiration (T_{tree}, mm) derived from soil and groundwater (GW) on a seasonal basis from June 1996 to December 1998 based on Fig. 3 (transpiration) and Fig. 6*b* (dependence on groundwater) with estimated values for winter 1998 (in parentheses) based on the assumption that the same relationship between soil water dependence and rainfall distribution existed as observed in 1997

Season	Days	Rain (mm)	T_{tree} total	T_{tree} from soil	T_{tree} from GW	T_{tree} from GW (%)
Lupin crop 1 (20 June–3 December)	166	354	38	29	9	24
Summer fallow 1 (4 December–7 June)	185	183	93	20	73	79
Oat crop (8 June–9 December)	184	248	77	33	44	56
Summer fallow 2 (9 December–5 May)	146	38	84	9	75	89
Lupin crop 2 (6 May–2 December)	210	333	83	(36)	(47)	(57)

vapour transfer could have accounted for some of this, this estimate must be considered a maximum value. Opening season rains occurred on 16 April and the wetting front reached 20 cm. Following subsequent rains, the wetting front reached 75 cm on 21 May after total seasonal rainfall of 63 mm and 150 cm and 230 cm by 12 June after a total of 153 mm. The water content at 360 cm increased from 0.06 to 0.09 m^3/m^3 on 18 June and from 0.09 to 0.1 m^3/m^3 on 10 July. Thus we can assume that drainage continued at a low rate until 18 June, increased slightly until 10 July, and occurred rapidly after this date. The period of enhanced drainage beyond 360 cm continued until the time that the rooting front reached this depth, which was approximately 4 October. We can estimate the drainage between 10 July and 4 October by assuming that evapotranspiration would occur at close to E_0 at this time of the season (1–3 mm/day), since the leaf area was developing rapidly. The decrease in water store between these dates was 185 mm, rainfall was 121 mm, and E_0 was 175 mm, giving a drainage residual of 131 mm. However, this would have to be considered a minimum value as crop water use would not always reach potential rates. From 4 October until harvest on 2 December, during which time the profile was drier than at any time during the previous oat crop, we can assume that drainage was <0.1 mm/day, contributing a further 5 mm.

We are now in a position to estimate drainage past 360 cm from the end of the oat crop to the end of the following lupin crop by considering drainage as occurring in 4 distinct phases:

(1) over the summer–autumn period between harvest of the oat crop on 9 December and the opening season rains on 16 April, 34 mm was lost (0.27 mm/day), almost all of which was from below 150 cm;
(2) from opening rains on 16 April until the rapid drainage occurred after 10 July, we assume that drainage continued at a similar rate as above, giving a further 23 mm (85 days at 0.27 mm/day);
(3) for the period 10 July–4 October when the majority of the drainage occurred, 131 mm was lost assuming that crop water use was close to E_0;
(4) from 4 October until harvest on 2 December, when the profile was drier than at any other time, we assume a further 5 mm of drainage (<0.1 mm/day).

Cumulative drainage was therefore estimated to be the sum of the above, 193 mm.

Estimating drainage in alley crop

The components of the water balance for sole crop and alley crop for the period when drainage could be estimated from TDR (from harvest of the oat crop in December 1997 to harvest of the following lupin crop in December 1998) are shown in Table 4. For the sole crop, E_{crop} was estimated by difference from total rainfall, drainage, and the change in soil water storage over the period as measured by neutron probe:

$$E_{crop} = P - D - \Delta S$$

For alley crop, drainage was estimated by difference using the following equation:

$$D = P - E_{crop} - T_{soil} - T_{gw} - I - \Delta S$$

In the alley crop, E_{crop} was assumed to be 194 mm, the same as sole crop over the arable area (i.e. 80% of that in sole crop on the basis of arable area, given that no difference was detected in above-ground crop biomass at anthesis and harvest between sole crop and alley crop). Water use by the trees from the soil (T_{soil}) was 45 mm and water use by the trees from the groundwater (T_{gw}) was 122 mm (Table 3). Interception (I) was measured by TDR in the plantation treatment with a closed canopy to be 140 mm (Lefroy *et al.* 2001). In the alley crop treatment, interception was therefore assumed to be 20% of this (28 mm) on the basis of canopy cover. Table 4 shows the estimated drainage when groundwater uptake is excluded (to examine the case if

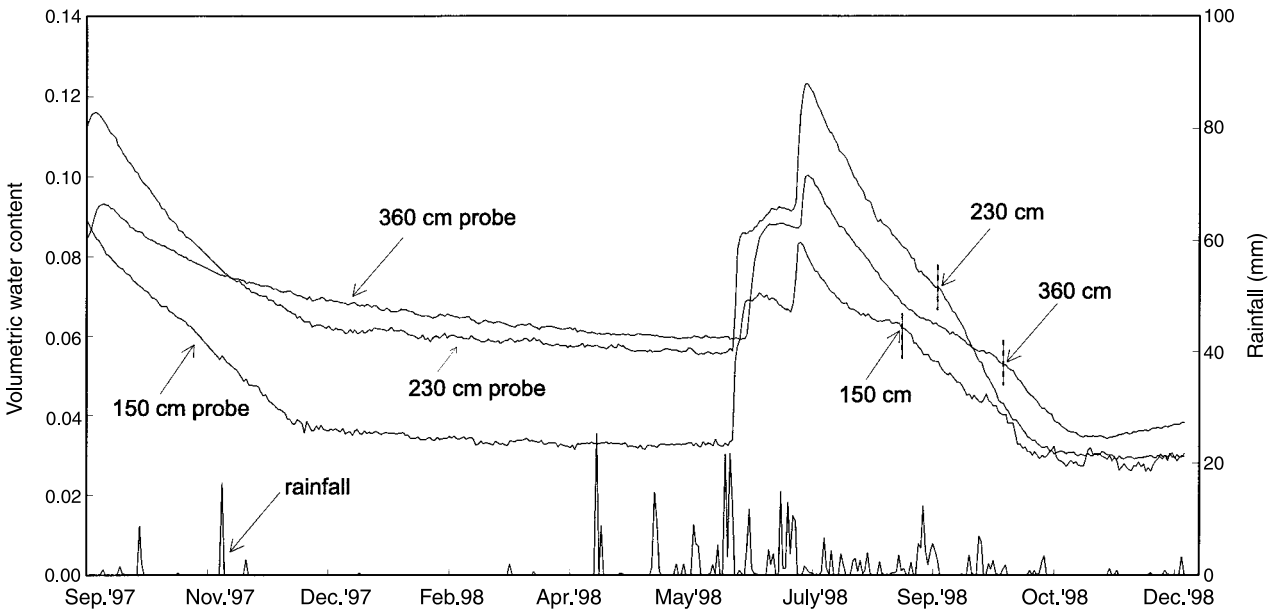

Fig. 7. Daily average TDR traces from probes located 150, 230, and 360 cm deep in the lupin crop from September 1997 to December 1998.

groundwater was too deep or salty to be used), and when the measured groundwater uptake is included.

The above estimates show that 6-m-wide belts of tagasaste spaced 30 m apart reduced seasonal drainage from 52% of rainfall under a sole crop to 42%. If we include the groundwater uptake by trees occurring predominantly in the summer months, drainage over the whole year is reduced to 9% of rainfall.

The general validity of these estimates can be examined by application of a second method. The very low soil water contents measured throughout the year out to 2 m either side of the tree rows suggested that drainage would have been minimal in this zone. We also know that the tagasaste had almost no influence on soil water content between 8 and 15 m from the tree rows (Fig. 4). Between 2 and 8 m from the tree row, both drainage and soil water uptake by trees occurred. We can therefore approximate drainage by assuming that it was zero over the first 2 m, the same as the sole crop between 8 and 15 m (193 mm/year), and half that in sole crop over the 2–8 m zone. This gives a seasonal drainage estimate of 129 mm and an annual drainage estimate of 7 mm, somewhat less than that calculated by the water balance method.

This study was undertaken to assess the effectiveness of adding spaced rows of trees to an annual cropping system to reduce the amount of deep drainage in a situation where trees had access to a permanent fresh watertable. In the final year of the study when the trees occupied 20% of the land area, estimated drainage was reduced from 193 mm/year to 32 mm/year. This occurred in a year when drainage was higher than the long-term value of 140 mm/year reported by modelling studies (Asseng *et al.* 1998).

The purpose of adding trees to cropping systems for salinity management is not to reduce drainage to zero in a single paddock, but to bring the average recharge from a catchment closer to the aquifer discharge capacity of that catchment. It is possible to compare the effectiveness of an integrated tree–crop system such as alley cropping with that of separate monocultures of crops and trees in reaching this target. Stirzaker *et al.* (in press) have quantified the complementarity that exists in a tree–crop system designed for water management by introducing the no-drainage-zone:no-yield-zone ratio. This ratio reflects the balance between the area of land protected by trees against drainage (Ellis *et al.* 1999) and the area of land over which trees influence crop yield (Lefroy and Scott 1994). Where this ratio is >1, there are advantages in mixing trees and crops; where it is <1, the dual objectives of drainage control and productivity would be best achieved through monocultures of trees and crops. For instance, in this case we know that drainage under the tagasaste plantation treatment was zero (Lefroy *et al.* 2001). Therefore, if we put 20% of the land under plantations, drainage would be reduced by 20% and yield by 20% (through displacement), giving a no-drainage zone:no-yield zone ratio of 1.

For the last year of the alley crop experiment, yield was reduced by 32%, giving a no-yield-zone over the half length between tree rows of 5 m (Fig. 8). This can be attributed to displacement of crops by trees (20%) and the net negative effects of tree–crop interactions (12%). If we ignore uptake of groundwater by trees, seasonal drainage reaching the watertable was reduced by 20% in the tree–crop mixture, giving a no-drainage-zone:no-yield-zone ratio of 0.6, indicating that there is a disadvantage in mixing tagasaste

Table 4. Components of the water balance for sole crop and alley crop from 9 December 1997 to 2 December 1998 (358 days)

E_{crop} is crop evapotranspiration, D is drainage, ΔS is the change in soil water content, T_{soil} is tree transpiration from the unsaturated zone, T_{gw} is the tree transpiration from groundwater, and I is rainfall interception by the tree canopy

Treatment	Rain	E_{crop}	ΔS	T_{soil}	T_{gw}	I	D	D/Rain
Sole crop	371	234	–65				193	0.52
Alley crop								
Excluding T_{gw}	371	194	–50	45	0	28	154	0.42
Including T_{gw}	371	194	–50	45	122	28	32	0.09

and crops compared with segregated monocultures of crops and trees. When we include groundwater uptake by trees, the ratio becomes 2.5 (an 83% decrease in annual net drainage giving a no-drainage-zone of 12.5 m and a 32% yield decrease as before). In the second instance, the tree–crop mixture has a proportionally greater effect on reducing drainage than on reducing yield, suggesting that alley cropping would be the best strategy.

However, when we move from paddock to catchment scale, the prognosis changes. In this particular case, the trees were located over a highly transmissive aquifer which potentially enables trees to reach groundwater draining below crops hundreds of metres away. As shallow fresh aquifers are a highly localised phenomenon, strategically sited plantations would be the most effective design. By reducing the length of the tree–crop interface, they would also reduce the degree of competition.

Alley cropping would be an appropriate strategy where there were less transmissive aquifers underlying a large proportion of a catchment. A more closely integrated tree–crop system would then be necessary to ensure that trees retained access to groundwater. Alley cropping would also be appropriate on highly transmissive sands if the root architecture of tagasaste trees were sufficiently plastic that in the absence of a fresh watertable, trees would exploit a wider zone of unsaturated soil than was evident in this study and maintain the rates of transpiration measured here. However, if evapotranspiration of spaced trees in the absence of a watertable was less than that measured in this experiment, the best strategy would be to strategically locate dense stands of trees over shallow fresh watertables. The limiting factor would then be the proportion of a catchment where trees had access to shallow, fresh watertables such that they could meet the recharge reduction target.

A surprising finding was that the lateral extension of tree roots in the alley fallow treatment was no greater than in alley crop. This was despite the absence of crop competition, the lack of disturbance of lateral roots through cultivation, and the fact that the soil profile 8 m from the tree rows was never less than half full. One possible explanation is that once the trees had commenced investing heavily in roots at the capillary fringe, they lacked the plasticity to increase capacity to scavenge laterally for water. Although the high quality of the groundwater in this study enabled us to measure rates of tree water use at the upper end of the range for this environment, it is atypical of southern Australia generally and limits our ability to extrapolate the data widely.

The average 16% reduction in crop yield in the alley treatment over 3 years compared with sole crop contrasts with the neutral to positive influence of windbreaks on crop yield reported in an international review by Kort (1988). Recent Australian studies have reported little if any benefit. to crop production from windbreaks (Carberry *et al*. in press; Sudmeyer *et al*. in press). Although any yield loss might be offset in economic terms by harvesting tagasaste biomass as a valuable source of autumn fodder, this would most likely reduce transpiration rates and consequently the area protected against deep drainage.

Drainage in sole crop in 1998 was particularly high due to rainfall distribution, with 47% occurring in June and July when evaporative demand was lowest. The drainage estimate of 52% of annual rainfall was higher than the long-term estimate of 30% for this region (Asseng *et al.*

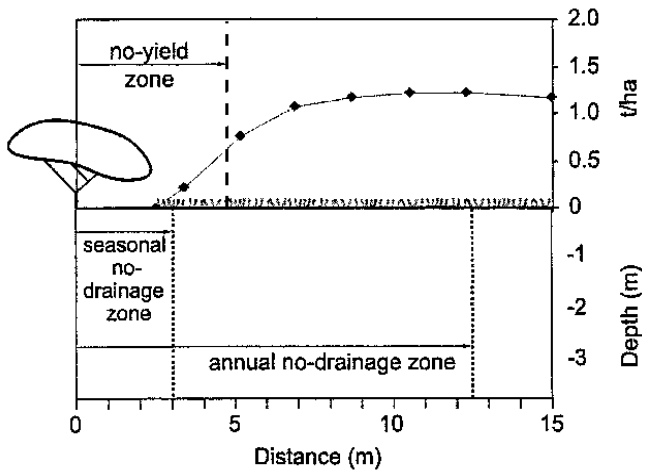

Fig. 8. The above and below ground influence of trees in a tagasaste alley cropping system in 1998, represented in binary form as the no-drainage and no-yield zones relative to sole crop. Where the ratio of the no-drainage and no-yield zones is >1, the trade-off between water management and crop yield will be more favourable in an integrated tree crop systems than in segregated systems (e.g. plantations). No-drainage zones based on data from Table 4 and yield data taken from Lefroy and Stirzaker (1999).

1998) and 38% for similar transmissive sands in the higher rainfall zone (Peck and Hurle 1973). By comparison, studies across a wider range of soil types in the cropping zone of southern Australia (250–500 mm/year) suggest deep drainage to be generally <20% of annual rainfall (Hatton and Nulsen 1999; Walker *et al*. 1999).

The trade-off between the environmental benefit of trees and grain yield seen in this study has parallels with alley cropping in other parts of the world. In the tropics, alley cropping has been promoted as a means of increasing soil fertility and controlling erosion (Kang *et al.* 1990). The trade off is between water and nutrients, with prunings from fast growing tree legumes being used as soil mulch with anticipated benefit to soil fertility and crop yields. Ong (1996), however, concluded in a review of alley cropping in Africa that the general experience was increased risk of crop failure due to competition for water, particularly in the lower rainfall subtropics (<1000 mm). Ong and Leakey (1999) suggest that alley cropping in the subtropics with fast growing trees is analogous to highly competitive, early stage succession in savannah ecosystems. The complementarity of resource use between trees and grasses, anticipated in much of the agroforestry literature and described in studies of subtropical savannahs, is likely to be a feature of later rather than earlier stages of succession. They conclude that where crop production is water-limited, the best strategy is to segregate trees from crops rather than integrate them, targeting landscape niches where unused resources accumulate. In other words, assume that competition dominates in young agroforestry systems and apply nitrogen fertiliser rather than tree mulch.

Research in southern Europe has also challenged the assumption that complementarity of resource use between trees and herbaceous plants will be the norm as a result of vertical stratification of their root systems. Adding high value spaced trees to fodder crops in southern France was seen as a means of making more efficient use of water and nutrients and diversifying farm income. Water balance studies, however, showed that the herbaceous components (*Onobrychis sativa* L. and *Festuca arundinacea*) had greater rooting depth than the tree (*Prunes avium* L.) and reduced water use and growth of trees compared with those in monoculture (Dupraz *et al*. 1995, 1998). In Australia the choice is stark and of a very different nature: increase leaf area in agricultural landscapes on a permanent basis and live with some degree of trade-off or accept increasing levels of salinity (Hatton and Nulsen 1999; Walker *et al*. 1999). That implies understanding, and where possible reducing, the yield penalties at the tree–crop interface. This study highlights the importance of knowing the extent to which tree root architecture varies within and between species. Further research identifying the water capture zone of trees with and without access to fresh watertables would contribute to the more effective use of agroforestry systems for water management.

Acknowledgments

This research was funded jointly by the Grains Research and Development Corporation and the Rural Industries Research and Development Corporation. The experimental site was established by Tim Wiley on land generously made available by Christine Brown. Conrad Allmark, David Arthur, Murray Unkovich, Steven Arthur, and Christine Davies assisted with data collection and analysis.

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Manuscript received 23 February 2000, accepted 3 July 2000