Water use by contour-planted belts of trees comprised of four *Eucalyptus* species

D.A. White[a,*], F.X. Dunin[b], N.C. Turner[b], B.H. Ward[c,1], J.H. Galbraith[a]

[a]*CSIRO Forestry and Forest Products, CSIRO Centre for Mediterranean Agricultural Research, Private Bag No. 5, Wembley, WA 6913, Australia*
[b]*CSIRO Plant Industry, CSIRO Centre for Mediterranean Agricultural Research, Private Bag No. 5, Wembley, WA 6913, Australia*
[c]*Agriculture Western Australia, P.O. Box 757, Katanning, WA 6317, Australia*

Abstract

Over a 12-month period, soil water content and water use were measured concurrently in a contour-planted belt of trees comprised of *Eucalyptus saligna* (Smith), *E. camaldulensis* (Dehnh), *E. leucoxylon* (F. Muell) and *E. platypus* (Hook). These data were used to calculate water uptake by the trees from current rainfall, and from sources other than current rainfall (U'), to describe the temporal pattern of switching between these water sources, and to calculate the number and spacing of tree-belts necessary to reduce groundwater recharge to 5 mm per year. The data were also used to quantify competition for water between trees and adjacent crops or pastures. The tree-belt used 595 mm on a projected crown area basis over a 12-month period. Of this, 440 mm was transpiration, 100 mm interception and 55 mm soil evaporation. Rainfall was 445 mm and was all captured by the upper 2 m of the soil profile. U' was 150 mm. Both soil water measurements and piezometric data from the same site indicated that most of U' was from groundwater flowing under the trees. This study confirms that where groundwater is accessible, contour-planted belts of trees are an effective means of reducing groundwater recharge with minimal tree-crop competition for water. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Groundwater; Salinity; Sapflow; Soil water; Transpiration; Water logging

* Corresponding author. Tel.: +61-8-9333-6693; fax: +61-8-9387-8991.
E-mail address: don.white@csiro.au (D.A. White).
[1] Present address: Water and Rivers Commission, P.O. Box 525, Albany, WA 6331, Australia.

Nomenclature

A_b	stem basal area (m^2)
A_c	projected crown area (m^2)
A_s	sapwood area (m^2)
$A_{s,i}$	sapwood area of the ith size class (m^2)
D	target recharge (mm)
D_a	recharge on land not occupied by trees (mm)
D_t	recharge under the trees (mm)
E	transpiration (mm)
E_{eq}	equilibrium evaporation (mm)
E_s	soil evaporation (mm)
E_t	evapotranspiration (mm)
E_0	potential evaporation (mm)
I	interception (mm)
$M, \Delta M$	soil water storage, change in soil water storage (mm)
$\Delta M_{z\,m}$	change in soil water content from 0 to z m (mm)
P	rainfall (mm)
R_s	net radiation estimated for below the canopy (W m^{-2})
S_d	daily sapflow (l per day)
$S'_d, S'_{d,i}$	daily sapflow per unit sapwood area, and for the ith size class (l m^{-2} per day)
S_h	hourly sapflow (l h^{-1})
U'	uptake by the trees from other than rainfall and water stored above z m (mm)
v, v'	heat pulse velocity and corrected heat pulse velocity (cm h^{-1})
V_h	volume fraction of water
V_w	volume fraction of wood
x	area that must be occupied by trees to reduce drainage to D mm (mm)
z	soil depth below which rain did not penetrate (m)

Greek letters

Δ	slope of the relation between saturated vapour pressure and temperature (kPa $°C^{-1}$)
γ	psychrometric constant (kPa $°C^{-1}$)
θ	volumetric soil water fraction

1. Introduction

Dryland salinity is the most pressing land management issue facing Australian agriculture. Over the last 150 years, land clearing and replacement of forest, woodland and heath with agriculture based on annual plants has resulted in increased drainage below plant root zones and recharge of groundwater systems (George et al., 1997). The rising water has brought salt into the root zones of crops and pastures. The potential for land clearing to increase dryland salinity has long been recognised (Despessis, 1902;

Wood, 1924; Williams, 1991; Sadler and Turner, 1994). Despite this, 1.8 Mha of land is now salt affected in Western Australia alone (McFarlane and Williamson, 2001).

At the paddock and catchment scale the spread of secondary salinity will only cease where recharge is less than discharge. This condition may be achieved either by decreasing recharge or by enhancing discharge through improved drainage. Considerable resources are being invested to develop agricultural systems that mimic the functional attributes of natural systems that confer sustainability (Dunin et al., 1999; Ewel, 1999; Hatton and Nulsen, 1999). In this context the most important attributes of native systems are their perennial nature, the deep rooting habit of the dominant plants and conservative water use during winter and early spring that allows for physiological activity during the dry season (Dunin et al., 1999). Trees will be a key element of sustainable agriculture. These may be planted for production of cineole, activated carbon, bio-energy, solid or reconstituted wood products, as carbon sinks or simply as one of many tools for managing groundwater recharge. Already there have been successful attempts to use trees (Farrington and Salama, 1996) and other woody perennials (Lefroy and Stirzaker, 1999) to control groundwater recharge.

Although substantial progress has been made, our ability to integrate trees into farming systems and predict their impact on recharge at the paddock scale is still limited. Stirzaker et al. (1999) modelled optimal tree densities and arrangements for control of rising water tables. Contour-planted belts of trees emerged as a design that achieved the hydrologic objective while minimising tree-crop competition. Contour-planted tree-belts can take advantage of lateral movement of groundwater over relatively short distances and therefore maximise the effective hydrologic area of trees (Stirzaker et al., 1999; Lefroy and Stirzaker, 1999). A key to determining the number and width of tree-belts necessary for managing groundwater recharge is an understanding of the capacity of trees to use deep soil water stores and groundwater. If trees can use water from sources additional to incident rainfall then the area over which groundwater recharge is controlled will exceed the ground area occupied. Knowledge of the sources of water used by trees will also enhance our capacity to quantify competition for water between trees and crops.

In sandy, transmissive soils, the capacity of *Eucalyptus* spp. and other woody perennials to use fresh and moderately saline groundwater at rates of up to 3 mm per day has been demonstrated in plantations (Cohen et al., 1997) and agroforestry systems (Cramer et al., 1999; George, 1991; Heuperman, 1999). In 1986, on a farm in southwestern Australia, 8 m wide contour-planted belts of trees were established as part of a whole farm approach to water management. These tree-belts were originally planted to prevent seasonal water logging, control wind erosion, to provide shelter for stock and as insurance against the future threat of salinity (Rundle and Rundle, 2002). The species originated from subtropical New South Wales (*Eucalyptus saligna* Smith), dry inland New South Wales (*Eucalyptus camaldulensis* Dehnh), central Victoria (*Eucalyptus leucoxylon* F. Muell) and coastal southwestern Australia (*Eucalyptus platypus* Hook). A previous study of their leaf water relations and stomatal behaviour showed that *E. saligna* and *E. camaldulensis* experienced little or no water stress at any time of year (White et al., 2000b). This paper assesses the contribution of these tree-belts to paddock scale water balance. Measurements of tree water use were coupled with soil water measurements below the trees to test the hypothesis that some of the species use groundwater and to quantify uptake from sources

other than current rainfall. Tree water use and relative dependence on rainfall, stored soil water and groundwater are presented for a 12-month period.

2. Materials and methods

2.1. Study site

All measurements were made at 'Ucarro' farm near Katanning in Western Australia (33°45′S, 117°27′E). Details of the study site and its management may be found in Hodgson et al. (2002). One of several strategies employed by the farmer to manage groundwater recharge was to plant belts of trees approximately 8 m wide, immediately down slope of 0.5 m deep interceptor drains installed at a 1:300 gradient along the contours (Rundle and Rundle, 2002). The tree-belts were established in 1986 and comprised four allopatric species: *E. camaldulensis*, *E. saligna*, *E. leucoxylon* and *E. platypus*. Within the belts trees were planted in three to four rows, also along the contour. *E. saligna* was always upslope of the other species and immediately downslope of the drain, *E. leucoxylon* and *E. camaldulensis* occupied the middle two rows and *E. platypus* was planted in the bottom row. The drains and tree-belts were established at approximately 200 m intervals and therefore occupied 4% of the total land area.

Eight measurement plots were established in a single tree-belt directly upslope of a major experiment comparing the water use patterns of lucerne (*Medicago sativa* L.) and subterranean clover (*Trifolium subterraneum* L.) (Hodgson et al., 2002; Ward et al., 2002). These plots were 8 m wide (the width of the belt) by 10 m long. Six of the plots were positioned to coincide with transects of neutron moisture meter access tubes (see below, also map included in Hodgson et al., 2002) and a further two were randomly located elsewhere in the tree-belt. All species were present in all eight plots.

2.2. Soil water content

At five positions within the strip of trees, neutron moisture meter access tubes were installed to a depth of 6 m. These corresponded to holes nm1, nm18, nm19, nm27 and nm44 on the site map in Hodgson et al. (2002). These were polyvinyl chloride tubes with an internal diameter of 40 mm installed in 50 mm holes and back filled with kaolin and cement slurry (Prebble et al., 1981). The volumetric soil water content (θ) was estimated from measurements made with a CPN neutron moisture meter (California Pacific Neutron, Pacheco, CA, -50 mCi Am-Be source). Measurements were made 0.15, 0.25, 0.35, 0.55, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00, 5.50 and 5.80 m below ground in each hole at approximately monthly intervals from August 1997 to July 1998. From July 1998 until July 1999 measurement was restricted to holes nm18 and nm27.

The volumetric soil water content (θ) was calculated using a calibration based on concurrent field measurements of θ and count ratio for a range of values of θ. Soil water storage (M, mm) was calculated for the entire profile and the following depth intervals: 0–0.45, 0.45–1.20, 1.20–2.00, 2.00–4.00 and 4.00–6.00 m. Change in soil water content (ΔM) was calculated between measurement times for the same depth intervals.

2.3. Stand structure

In September 1997, the diameter of each stem at a point 20 cm from the ground and the height and crown width along the north–south and east–west axes were measured for all trees within the eight plots. Crown area, projected vertically on the ground (A_c), was calculated for each tree and basal area was calculated for each stem (A_b). For each species individual stems were ranked from smallest to largest and cumulative basal area was calculated. Each species was then divided into three stem size classes so that each class included one third of the total basal area for each species. Stems from these three size classes are subsequently referred to as large, intermediate and small.

2.4. Measurement and calculation of stem water use

Measurement of sapflow commenced on 15 July 1998. One large stem from each species was measured throughout the experimental period. A further 16 stems were measured in groups consisting of five or six stems. The first group was measured for approximately 1 month, after which the sensors were moved to the second group. After a further month, the sensors were moved to the third group of trees before being returned to the first group after a total of 3 months. This cycle was repeated until measurements ceased on 5 July 1999. Stems were selected at random within size classes so that each size class of each species was represented at least once in each 3-month period (Table 1). Most combinations of size class and species were measured at least twice. The total sample size was 20 stems (Table 1).

Stem diameter was measured each time a sapflow sensor was installed or re-installed. Also at this time, 10 mm diameter cores were collected from each stem. The width of the sapwood band was determined by inspection as all four species had a pronounced colour change at the sapwood–heartwood boundary. Conducting sapwood area can exceed that indicated visually by a colour change (e.g. Hatton et al., 1995). If this was the case subsequent estimates of stem, tree and stand transpiration may slightly underestimate the actual value. The volume fraction of wood (V_w) and water (V_h) were determined from measurements of fresh, immersed and dry weight.

Sapflow was measured using either standard (SF100) or split probe (SF300) Greenspan Sapflow sensors (Greenspan Technology, Warwick, Qld., Australia). Two probe sets were installed in each stem. The probe sets were installed on opposite aspects (east and west if

Table 1
Number of trees included in each sample group, by species and size class

| | Permanent | Sample group 1 | | | Sample group 2 | | | Sample group 3 | | |
	Large	Large	Intermediate	Small	Large	Intermediate	Small	Large	Intermediate	Small
E. saligna	1	1			1					2
E. camaldulensis	1	1			1					1
E. leucoxylon	1	1	1		1	1		1		
E. platypus	1	1			1			1		1
Total	4	4	1		4	1		2		4

SF100 and all four cardinal directions for SF300 split probes) so that the thermistor pairs were 5, 10, 15 and 20 mm under the cambium. Where the sapwood band was not deep enough to accommodate this spacing an SF300 probe was used so that the thermistor pairs were evenly spaced across the sapwood band. The shallowest thermistor pair was always at least 5 mm under the cambium.

At 30 min intervals the line heater generated a 1.6 s heat pulse. Measured heat pulse velocity was corrected for errors due to wound width using the numerical solution of Swanson and Whitfield (1981) to give corrected heat pulse velocity. This was converted to sap flow velocity (v; Marshall, 1958) using an algorithm developed by Edwards and Warwick (1984). Wound width (mm) was estimated at the end of each measurement period by examining a cross-section of the wood surrounding the drill hole using a 100 X stereoscope and measuring the width of wood in which vessels were blocked by tyloses. Stem sapflow (S_h) was calculated by allocating an annulus of sapwood to each thermistor and calculating S_h as the sum of sapflow calculated for each annulus (Hatton et al., 1990). Daily sapflow (S_d) was calculated for each stem.

Relationships between S_d of reference and grouped trees were determined by linear regression. After the sensors were moved to the next group of trees these relationships were used to calculate S_d of the grouped trees until their next period of measurement (after Hatton and Vertessy, 1989; Vertessy et al., 1997). Relationships between reference and grouped trees were then redefined and applied until the next period of measurement.

2.5. Stand transpiration expressed per unit crown area

Basal (A_b) and sapwood areas (A_s) were calculated for measured stems when the sapflow sensors were first installed. Linear regression was used to develop a relationship to predict A_s from A_b. This relationship was applied to calculate sapwood area for each stem in the eight plots. Cumulative sapwood area was calculated for increasing stem size and a total sapwood area allocated to each size class of stems for each species. S_d of each tree was expressed per unit sapwood area (sapflux, S'_d, $1\,m^{-2}$ per day) and a mean value of sapflux (S'_d) was calculated for each size class of each species. Daily transpiration (E, mm) of each species was calculated as follows:

$$E = \frac{\sum_{i=1}^{3} S'_{d,i} A_{s,i}}{A_c} \tag{1}$$

where $S'_{d,i}$ was average daily sapflow ($1\,m^{-2}$) of sapwood area for the ith size class, $A_{s,i}$ the total sapwood area (m^2) of that class and A_c was the total crown area (m^2) of the species. E was calculated in the same way for the whole strip (i.e. total strip sap flow was projected on total strip crown area).

2.6. Weather data, potential evaporation, soil evaporation and interception

An automatic weather station was established 100 m down slope of the belt of trees containing the measurement plots. Total solar radiation, temperature, humidity, wind speed, barometric pressure and rainfall were sensed every 300 s and the average recorded hourly. Daily potential evaporation (E_0) was calculated after Priestley and Taylor (1972).

When daily P was <0.65 mm interception (I) was assumed equal to P. Otherwise I was calculated for each day as a linear function of rainfall (P) (Dunin et al., 1985)

$$I = 0.65 + 0.13P \tag{2}$$

In winter (June, July and August), soil evaporation (E_s) was assumed equivalent to equilibrium evaporation (E_{eq}; Denmead, 1984)

$$E_s = E_{eq} = \frac{\Delta}{\Delta + \gamma} R_s \tag{3}$$

where Δ is the slope of the relation between saturated vapour pressure and temperature and γ was the psychrometric constant. The average value of net radiation below the canopy (R_s) was assumed to be 20% of net radiation for the strip of trees, for which an average value of 250 W m^{-2} was used. This was based on the observation that at solar noon average interception of photosynthetically active radiation at eight randomly selected locations was 0.8 (White, unpublished data). Soil evaporation was assumed to proceed at 0.01 mm h^{-1} for 10 h a day on the remaining 275 days of the year. This was the lowest rate from a range of values for E_s from dry soil given by Leuning et al. (1994).

2.7. Annual and seasonal water balance of the strip of trees (1 July 1998–30 June 1999)

The E of the tree-belt was projected on the crown area because this was the ground area over which energy was absorbed by the trees. Observed changes in θ in winter of 1997 and 1998 were used to define the soil depth below which rainfall did not penetrate (z). The change in soil water storage between the soil surface and z m ($\Delta M_{z\,m}$) was calculated from neutron probe data.

Contour-planted tree-belts may use water from a number of sources other than rainfall and water stored directly underneath the trees between 0 and z m. These include rainfall and stored soil water in the area adjacent to the strip that is explored by tree roots, stored soil water held under the trees below z m, and perched and deep water tables. The total uptake from all of these sources was defined as U'.

Using this water balance, total tree-belt water use or evapotranspiration (E_t) may be calculated in two ways

$$E_t = I + E_s + E \tag{4}$$

or

$$E_t = P + \Delta M_{z\,m} + U' \tag{5}$$

Rearranging these equations gives

$$U' = I + E_s + E - P - \Delta M_{z\,m} \tag{6}$$

U' was calculated by substituting E estimated from sapflow measurements, $\Delta M_{z\,m}$ estimated from neutron probe data, P measured at the weather station and I and E_s calculated from Eqs. (2) and (3). Values of E, I, E_s, P, $\Delta M_{z\,m}$ and U' were estimated for the whole year and for each interval between soil water measurements. An alternative approach would be to measure the isotopic composition of transpired water and compare

this with putative sources of water. Unfortunately, the distribution of stable hydrogen isotopes in the soil was uniform so the sources of water could not be distinguished (Burgess et al., 2000).

3. Results

3.1. Changes in soil water content under the tree

Between 28 August 1997 and 21 January 1998, prior to the 12 months during which transpiration was measured, there was generally a net decrease in M of the 0–2, 2–4 and 4–6 m depth intervals (Fig. 1). Examining individual profiles for this period revealed that the amount of water used from 2 to 6 m was similar at three locations (e.g. Fig. 1a–c). At a fourth location (nm 44) there was no evidence of uptake from below 2 m. At this location, plot basal area was greater than for any of the other measurement plots; 27 m^2 ha^{-1} compared to an average of 20 m^2 ha^{-1} and a minimum of 11 m^2 ha^{-1}. The implications of the coincidence of maximum biomass with minimum apparent uptake are considered in the discussion. It is taken to indicate an input from a water source other than rainfall.

In order to determine the maximum depth of rainfall penetration, $\Delta M_{z\,m}$ was estimated for the 7 weeks between 29 April 1998 and 24 June 1998; 56 mm of rain was recorded during this period. Changes in soil water storage ($\Delta M_{z\,m}$) of the 0–2, 2–4 and 4–6 m depth range indicated that this rain did not penetrate beyond 2 m depth (Table 2). Some change was apparent in the 2–4 m layer but this was largely attributable to one location (nm 27) where some change was observed to be 3 m deep (Fig. 2). At nm1, this rainfall
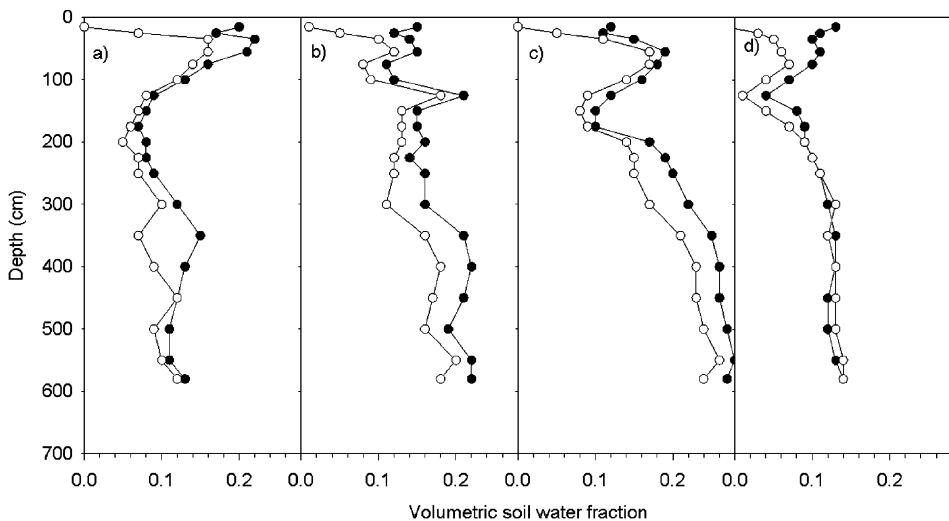

Fig. 1. Profile of volumetric soil water fraction (θ) on 28 August 1997 (●) and 21 January 1998 (○) for (a) nm1, (b) nm18, (c) nm19 and (d) nm44.

Table 2
Change in soil water content ($\Delta M \pm$ S.E. in mm, $n = 5$) of the 0–2, 2–4 and 4–6 m and the whole profile for three key periods and for the 12 months during which transpiration was measured (2 June 1998–3 June 1999)

Depth (m)	29 April 1998–24 June 1998, break of season	28 August 1998–21 January 1999, drying trend	24 June 1998–14 April 1999 drying trend ($n = 2$)	2 June 1998–3 June 1999 ($n = 2$)
0–6	66	−167	−184	−151
0–2	54 ± 6	−81 ± 4	−48	0
2–4	13 ± 6	−61 ± 16	−79	−44
4–6	−1 ± 3	−26 ± 15	−57	−107

was all absorbed by the upper 1 m of soil (Fig. 2a). All subsequent calculations are made assuming that all rainfall was absorbed by the upper 2 m of the soil profile.

Between 24 June 1998 and 14 April 1999, the average $\Delta M_{z\,m}$ under nm18 and nm27 was −184 mm. Nearly all of this change occurred below 2 m (Table 2, Fig. 3). For the 12 months during which sapflow was measured, mean $\Delta M_{z\,m}$ was 0 mm for the upper 2 m of the soil profile and −151 mm below 2 m (Table 2).

Between August 1997 and January 2000 there was a general trend of declining M for each of the 0–2, 2–4 and 4–6 m layers of the soil profile (Fig. 4). During this time M below 4 m occasionally increased against this long-term trend. These increases in M below 4 m were often greater than concurrent increases in M above 2 m and occasionally occurred in the absence of any changes in surface M (Fig. 4).
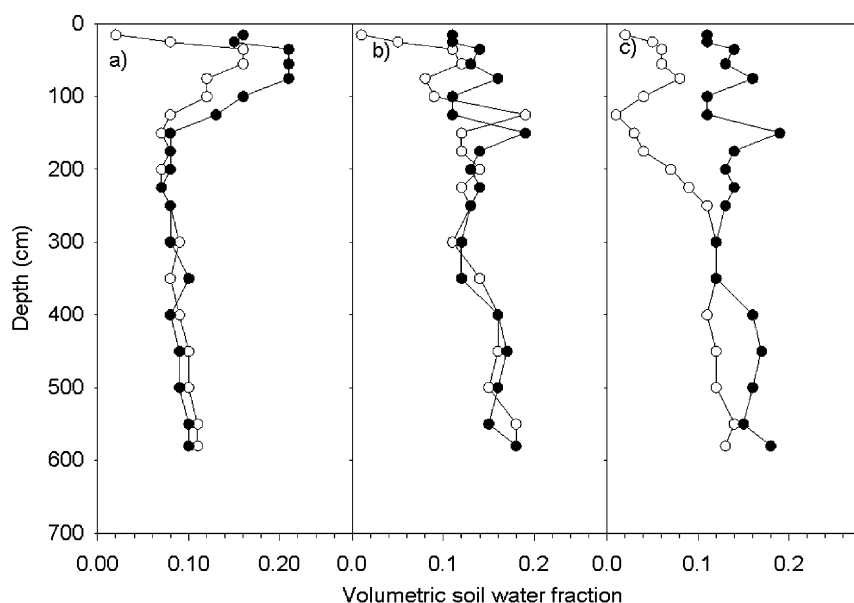

Fig. 2. Profile of volumetric soil water fraction (θ) on 29 April 1998 (○) and 24 June 1998 (●) for (a) nm1, (b) nm18 and (c) nm27.
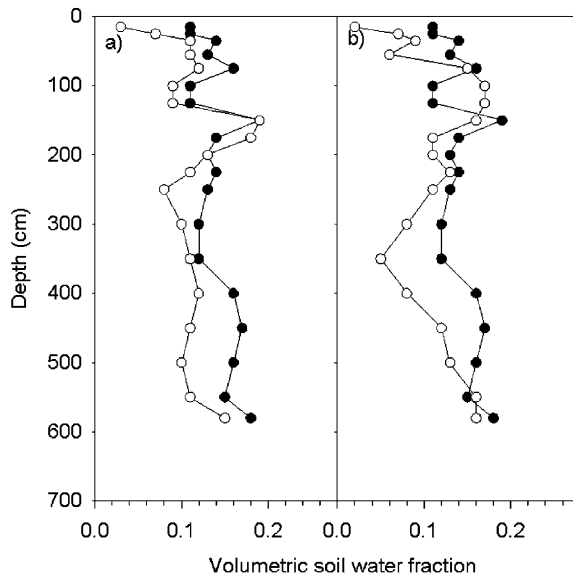
Fig. 3. Profile of volumetric soil water fraction (θ) on 24 June 1998 (●) and 14 April 1999 (○) for (a) nm18 and (b) nm27.

3.2. Stand structure

A linear relationship predicting stem sapwood area (A_s) from stem basal area (A_b) was highly significant ($P < 0.001$) for all species. No significant difference was found between species in either the slope or intercept of these relationships so the data was pooled. The pooled regression explained 94% of observed variation in A_s (Fig. 5) and was used to calculate A_s for every stem in the eight measurement plots. Where this regression predicted $A_s > A_b$ (i.e. for a very few small stems), the areas were assumed equivalent.

E. platypus contributed significantly less to strip basal area, crown area and sapwood area than any of *E. saligna*, *E. leucoxylon* or *E. camaldulensis* (Table 3). No significant differences were evident between the other species and their individual contributions to strip basal area, sapwood area and crown area were similar (Table 3). Individual trees comprised up to 38 stems. The average number of stems per tree was two for *E. camaldulensis*, four for *E. saligna*, five for *E. leucoxylon* and 12 for *E. platypus*. Total A_c of all trees in the eight measurement plots was 642 m^2.

3.3. Stand transpiration, soil evaporation and interception

Mean sap flux was always greater for large stems than either medium or small stems. This was true during wet and dry periods and applied to all species, although the difference was most pronounced for *E. saligna* (data not included).

Between 1 July 1998 and 30 June 1999, the rate of transpiration per unit crown area (E) remained fairly constant for *E. platypus* at about 0.8–1.2 mm per day (Fig. 6). The other
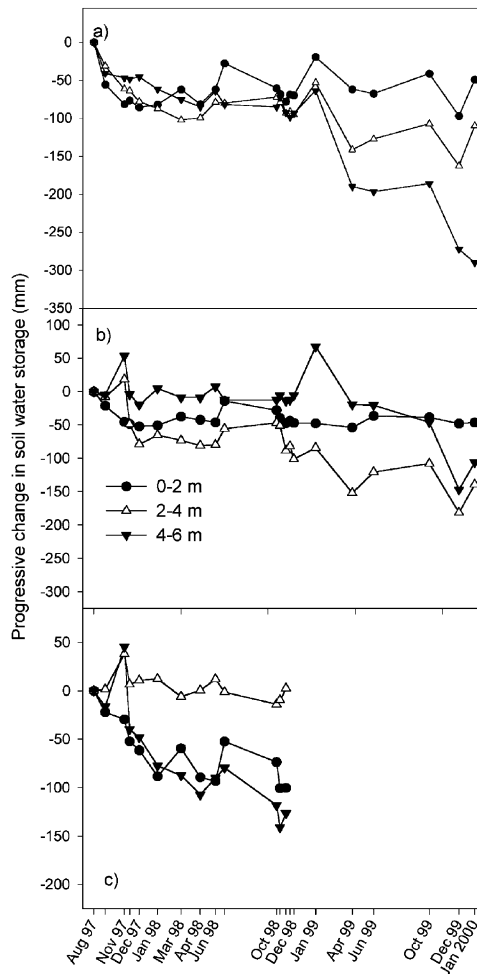
Fig. 4. Progressive change in soil water storage (ΔM) for 0–2, 2–4 and 4–6 m below ground in (a) nm18, (b) nm27 and (c) nm44.

species exhibited a marked increase in E during late spring and summer. This was most pronounced in *E. saligna*, which reached a peak of 2.9 mm per day in November 1998. *E. camaldulensis* and *E. leucoxylon* both peaked at 1.9 mm per day in November and February, respectively.

Annual E per unit A_c for *E. platypus*, *E. camaldulensis*, *E. leucoxylon* and *E. saligna* was 317, 369, 451 and 522 mm, combining to give a total E for the tree-belt of 439 mm (80 mm in winter, 115 mm in spring, 160 mm in summer and 84 mm in autumn, Fig. 6). Monthly evapotranspiration ($E_t = I + E_s + E$) was nearly equal to potential evaporation in July 1998, August 1998 and June 1999 and decreased to approximately 0.5 in the summer (Fig. 7).
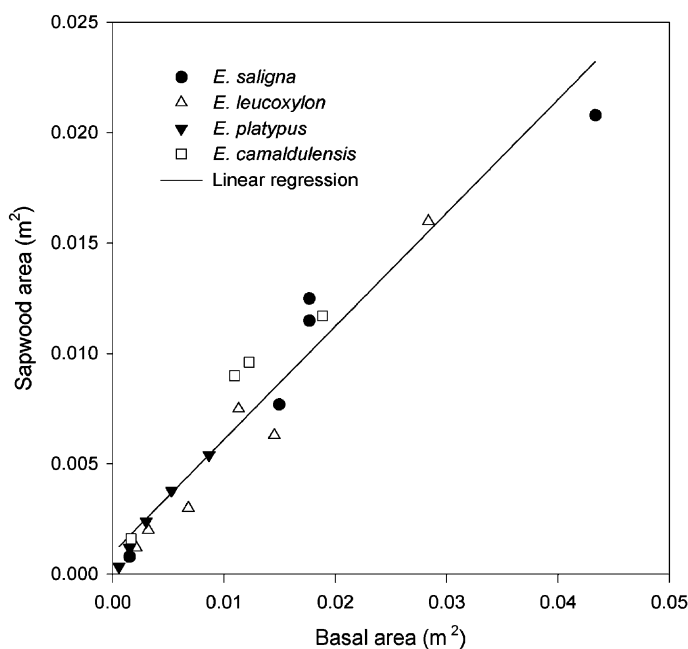
Fig. 5. Sapwood area (A_s, m^2) as a function of basal area (A_b, m^2) for *E. saligna*, *E. leucoxylon*, *E. platypus* and *E. camaldulensis*. Line is linear regression applied to all data, $A_s = 9.5 \times 10^{-4} + 0.51 A_b$, $r^2 = 0.94$.

3.4. Annual and seasonal water balance of the strip of trees (1 July 1998–30 June 1999)

Break of season changes in θ indicated that z, the depth below which rainfall did not penetrate, was 2 m. From 1 July 1998 to 30 July 1999, I was 101 mm, E was 439 mm and E_s was 54 mm. $\Delta M_{2\,m}$ was 0 mm from 3 June 1998 to 2 June 1999. Substituting these

Table 3
Number of stems, basal area (A_b), sapwood area (A_s) and projected crown area (A_c) by species and size class and for the whole strip[a]

|		*E. saligna*	*E. leucoxylon*	*E. platypus*	*E. camaldulensis*
Stem number	Small	35	56	60	13
	Intermediate	9	14	18	5
	Large	4	6	10	3
A_b (m^2 per 100 m of strip)	Small	0.17	0.18	0.04	0.14
	Intermediate	0.17	0.18	0.04	0.14
	Large	0.17	0.18	0.04	0.14
A_s (m^2 per 100 m of strip)	Small	0.11	0.13	0.04	0.08
	Intermediate	0.10	0.11	0.04	0.07
	Large	0.10	0.10	0.03	0.07
A_c (m^2 per 100 m of strip)	n/a	276	226	77	222

[a] All expressed per 100 m of strip.
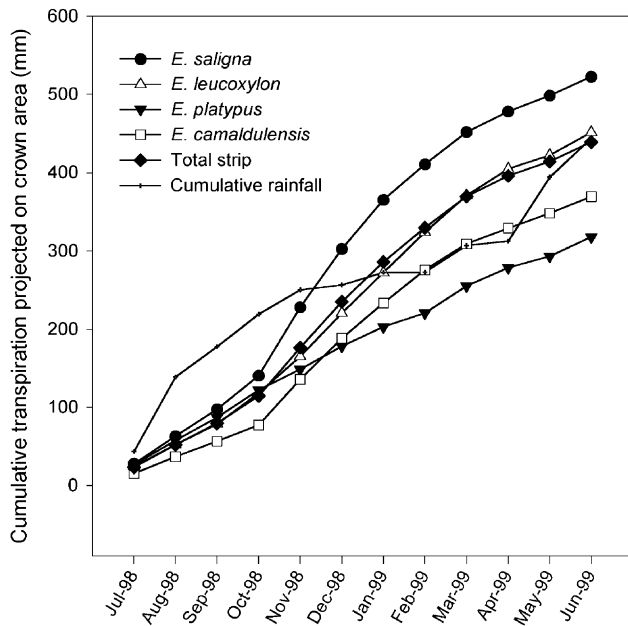
Fig. 6. Cumulative transpiration (E) per unit crown area and cumulative rainfall from 1 July 1998 to 30 June 1999. E is shown for the whole strip and individual species.
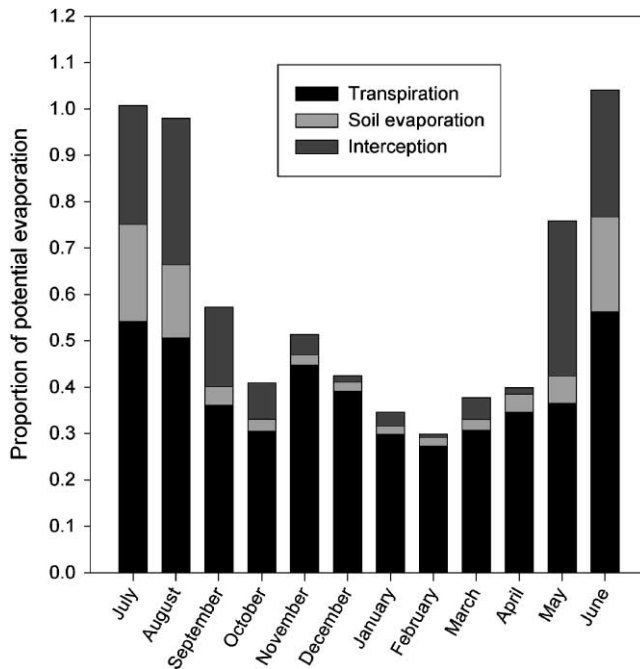

Fig. 7. Monthly mean soil evaporation (E_s), interception (I) and transpiration (E) by the tree-belt as a proportion of potential evaporation (E_0) from July 1998 to June 1999.
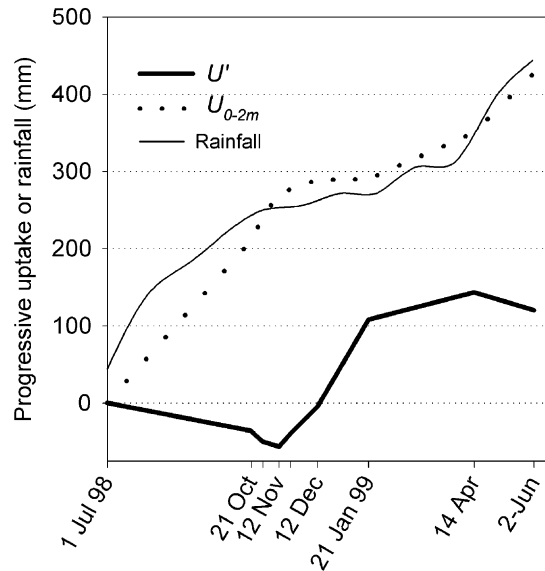
Fig. 8. Progressive uptake from 0 to 2 m below ground ($U_{0-2\,m}$) and from other sources (U') between 1 July 1998 and 3 June 1999.

values in Eq. (6) gives $U' = 150$ mm. Over the same period mean ΔM below 2 m was 151 mm (Table 2). Between 1 July 1998 and 12 November 1998 U' was -31 mm (Fig. 8). U' increased steeply between 12 November 1998 and 14 April 1999. All uptake that was not accounted for by rainfall or changes in the soil water content from 0 to 2 m occurred between mid spring and mid autumn (Fig. 8). In early winter 1999 U' was again negative.

4. Discussion

Uptake from sources other than rainfall (U') was estimated to be 150 mm between 1 July 1998 and 30 June 1999. The robustness of this estimate depends on the accuracy with which soil evaporation (E_s), interception (I), transpiration (E) and change in soil water content (ΔM) were estimated. The first section of this discussion considers the robustness of estimated E_s I, E and (ΔM) and discusses the estimated values in the context of previous studies. The second section discusses U' and the implications of the results for management of dryland salinity in southern Australia.

4.1. Evapotranspiration and its components

Estimation of the soil depth sufficient to capture all rainfall (z) was a key to estimating $\Delta M_{z\,m}$ and U'. Two metres of soil was sufficient to capture all rainfall for the duration of this study in all but one location; around nm27 ΔM in the 2–3 m soil layer was 31 mm between break of season and 24 June 1998. Substantial amounts of water were flowing

into this part of the strip along a dolerite dyke oriented at right angles to the tree-belt (Hodgson et al., 2002). This geology was not representative of a large proportion of the site so estimation of z was based on observations from the remaining holes. Measurements made using a SENTEK capacitance probe near nm27 confirmed that all rainfall was captured by the upper 2 m of soil in 1997 and 1998 (Burgess et al., 2001).

The dominant component of evapotranspiration was transpiration (E) by the trees (Fig. 7). E was estimated from measurements of heat pulse velocity made with thermistor pairs evenly spaced across the sapwood. Cyclical radial variation in sapflow has been observed in conifers (Dye et al., 1991) and ring porous hardwoods (Smith and Allen, 1996) and identified as a potential source of error in estimated tree water use. Notwithstanding these observations, the approach used in the current study has given good estimates of E for a range of diffuse porous hardwood species including *E. globulus* (White et al., 2000a) and *E. grandis* (Dye and Olbrich, 1993). Sapwood area was used to scale sap flow to give a stand estimate of strip E, thus avoiding any potential problems due to non-linearity in the relationship between leaf area and water use (Greenwood et al., 1992; Hatton and Wu, 1995; Wullschleger et al., 1998). For a comprehensive analysis of errors in estimating sapflow from point measurement of heat pulse velocity see Hatton et al. (1995).

The maximum rates of E by *E. platypus*, *E. camaldulensis*, *E. leucoxylon* and *E. saligna* were 1.2, 1.9, 1.9 and 2.9 mm per day. Over saline groundwater *E. camaldulensis* was previously observed to transpire at rates up to 3 mm per day in southern NSW (Benyon et al., 1999) and in a summer rainfall environment in Queensland (Cramer et al., 1999). In this study, at 'Ucarro', the coincidence of maximum net radiation with high vapour pressure deficits probably moderated stomatal conductance relative to these other studies. Stomatal conductance of *Eucalyptus* spp. can be sensitive to vapour pressure deficits (Dye and Olbrich, 1993; White et al., 1994, 1999). Observed rates of E at 'Ucarro' were also comparable to rates observed for windbreaks of *Acacia* spp. in the Sahel (Smith et al., 1998) and in an *E. camaldulensis* plantation in southwestern Australia (Salama et al., 1994). No other estimates of E have previously been reported for *E. saligna*, *E. leucoxylon* or *E. platypus*. The relative rates of these species in the current studies are generally consistent with observed seasonal variation in predawn water potential (Ψ_{pd}; White et al., 2000b); during spring and summer Ψ_{pd} was significantly lower for *E. platypus* than for any of the other species. The greater E by *E. saligna* relative to the other species may reflect an inherently greater maximum stomatal conductance or a weaker stomatal response to either vapour pressure deficit or soil water content. It is more likely, however, that it results from the fact that *E. saligna* was always planted upslope of the other species and immediately adjacent to a drain (Hodgson et al., 2002).

Based on Eq. (6), all of *E. saligna*, *E. leucoxylon* and *E. camaldulensis* used some water in excess of annual rainfall. The absence of any pure stands of each species and the non-random allocation of species within the strip makes it difficult to discern species effects on E from local site effects. However, the seasonal patterns of E are interesting. All four species and the strip as a whole transpired water at less than 1 mm per day for much of the winter and spring. In winter E combined with estimated E_s and I gave E_t approximately equal to E_0. In spring, when Ψ_{pd} was greater than -1 MPa for

E. camaldulensis and *E. saligna* (White et al., 2000b) rates of E_t for the strip, and by inference for these species, was much less than E_0. In the absence of any apparent water stress and during a period of moderate vapour pressure deficit these trees exhibited a conservative approach to water use. This is in contrast to *Pinus* spp. growing on the same property (Ward, personal communication, 1999). Given that narrow strips of trees and windbreaks are well coupled to the atmosphere (Smith et al., 1997a; Zhang et al., 1997; Smith and Jarvis, 1998), this conservative water use in spring is indicative of a relatively large canopy resistance. This is a key feature of Australian native vegetation in mid-to low-rainfall zones and helps ensure the sustainability of these perennial ecosystems (Dunin et al., 1999).

E_s was estimated as equilibrium evaporation during winter using a value for net radiation based on measurements of total solar radiation at the weather station and measured interception of PAR. For the remainder of the year it was estimated using the lowest value from a range of reported rates of vapour phase transport in dry soil. Thus, E_s was conservatively estimated. Interception was calculated using a relationship developed for dry sclerophyll *Eucalyptus* forest (Dunin and MacKay, 1982). Interception by strips and windbreaks may be enhanced by entrainment and advection compared to large forest blocks and plantations (Smith et al., 1997b). Thus, the estimated U' of 150 mm was also conservative.

4.2. Use of water from sources other than rainfall (U')

The results confirmed that *E. camaldulensis*, *E. leucoxylon* and *E. saligna* use water in excess of current rainfall and water stored in the upper 2 m of the soil profile. There was also compelling evidence that much of this water came from groundwater moving underneath the trees. All rainfall was accounted for in the upper 2 m of the soil profile (Burgess et al., 2000, Fig. 1). Despite this there were periodic increases in soil water content in the 2–4 and 4–6 m soil layers. Other authors have observed movement of water along preferential flow lines (Nulsen et al., 1986). If the increase at depth was due to preferential flow some of this water should have been observed at 2 m depth; it was not. Also, increases in soil water content at depth were only observed under the trees (Ward, personal communication, 1998) Piezometric measurements under the trees showed a general falling trend with periodic rises (Hatton et al., 2002). This is consistent with at least some of the water comprising U' being sourced from groundwater.

Another question of interest is how much of U' was drawn from the soil in direct competition with the crops and pastures adjacent to the trees? The change in soil water content from 2 to 6 m under the trees was almost exactly equivalent to U' (150 mm, Table 2). Seasonal changes in U' also showed that between 1 July and 12 November 1998, there was an increase of soil water storage (M) more than 2 m below the surface ($U' = -31$ mm, Fig. 8). After early April 1999 M increased again, this time by 19 mm. This increase in M below 2 m indicated that not all rainfall in this period was accounted for by E_t or an increase in water stored in the upper 2 m of the profile. If rainfall did not penetrate below 2 m, the water appearing at depth cannot come from either rainfall or from anywhere underneath the trees (Burgess et al., 2001). A possible explanation was provided by Burgess et al. (1998) who observed that, when the surface soil was wet after

recent rain, night-time sap flow could be detected towards the tree along lateral roots and downwards along tap roots. This observation was made in the same trees that were measured in the current study and was inferred elsewhere from analysis of stable isotopes in water (Schulze et al., 1998) and has been termed 'inverse hydraulic lift'. At 'Ucarro', Burgess et al. (2001) estimated that during winter at least 23 mm of water was redistributed by the tree vascular system from the surface to depth. The observation of declining U' during winter is consistent with trees redistributing water via their root systems. If this was the case then the approximately 31 mm of water was used by the trees compared favourably with the 23 mm estimated by Burgess et al. (2001) and was taken up by the tree root zone in the adjacent crops or pastures.

An annual amount of 31 mm may represent quite significant competition between trees and crops for water, particularly if the trees use this water in the critical period prior to anthesis in the crop. Notwithstanding this, the water use of the trees and adjacent plants was usually complementary in time and space. A key to minimising competition between trees and crops is to select trees that switch quickly between surface water and groundwater (Dawson and Pate, 1996; Stirzaker et al., 1999). Fig. 8 suggests that trees either use water from deep soil stores and groundwater (U') or from the surface ($U_{2\,m}$) and not from both simultaneously. Smith et al. (1998) also observed rapid switching between sources in windbreaks of *Acacia* spp. and *Azadirachta indica* A. Juss (neem) and found that where groundwater was within 6–8 m of the surface the trees only used surface water for a short period after rain (Smith et al., 1997b). Tree lucerne also switched quickly between water sources in an alley farming system (Lefroy and Stirzaker, 1999). Zohar (1985) found that *Eucalyptus* trees in a windbreak spread roots 20 m into adjacent cotton fields. However, this was an irrigated field so that there was always plentiful water at the surface.

The major conclusion that tree-belts are an effective means of controlling groundwater recharge must be qualified to account for variation in rainfall within and between seasons. Rainfall (P) was also an important determinant of U' (Eq. (6)) and was 444 mm for the study period. Variation in rainfall clearly has the potential to affect U'.

Assuming that increasing the number of strips results in an equiproportional increase in U' at the paddock scale, the proportion of land (x), that must be planted with trees to reduce paddock scale recharge to a desired value (D) is

$$x = \frac{D - D_a}{D_t - D_a} \tag{7}$$

where D_t is drainage under trees and D_a is drainage under the crop or pasture that occupies the rest of the landscape. Using a paddock scale water balance, Ward et al. (2002) estimated that over a 5-year period including 3 years under clover, one crop of wheat and one crop of canola, average annual drainage was 35 mm. For the same period, replacing clover with lucerne decreased average annual drainage to 18 mm. Substituting these values for D_a, Eq. (7) predicts that to reduce recharge to 5 mm per year at 'Ucarro', 16% of the farm must be occupied by 8 m wide tree-belts if the rest of the farm is under clover in rotation with crops. This value drops to 8% if lucerne is planted in rotation with the crops. These estimates are subject to the errors inherent in all the key variables, but do give cause for optimism that relatively narrow and quite widely spaced strips of trees may

be used with perennial pastures to effectively control recharge where groundwater is accessible by trees. Together with measurements of drainage under lucerne and clover and fluctuations in water tables (Hatton et al., 2002) the results of this study demonstrate the technical feasibility of controlling recharge using contour-planted tree-belts with perennial pastures in a phase farming system. This only applies where trees have access to fresh groundwater and confirms the prediction of Stirzaker et al. (1999) that under these circumstances trees can affect water tables over quite large distances. This is only the first step towards getting this system adopted by farmers. The challenge now is to demonstrate that this system is compatible with farmers' objectives and is economically feasible (Pannell, 1999).

Acknowledgements

References

Benyon, R.G., Marcar, N.E., Crawford, D.F., Nicholson, A.T., 1999. Growth and water use of *Eucalyptus camaldulensis* and *E. occidentalis* on a saline discharge site near Wellington, NSW, Australia. Agric. Water Manage. 39, 229–244.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Ong, C.K., 1998. The redistribution of soil water by tree root systems. Oecologia 115, 306–311.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Ward, B., 2000. Characterisation of hydrogen isotope profiles in an agroforestry system: implications for tracing water sources of trees. Agric. Water Manage. 45, 229–241.

Burgess, S.S.O., Adams, M.A., Turner, N.C., White, D.A., Ong, C.K., 2001. Tree roots: conduits for deep recharge of soil water. Oecologia 126, 158–165.

Cohen, Y., Edar, E., Dody, Y., Schiller, G., 1997. Underground water use by *Eucalyptus* trees in an arid climate. Trees 11, 356–362.

Cramer, V.A., Thorburn, P.J., Fraser, G.W., 1999. Transpiration and groundwater uptake from farm forest plots of *Casuarina glauca* and *Eucalyptus camaldulensis* in saline areas of southeast Queensland, Australia. Agric. Water Manage. 39, 187–204.

Dawson, T.E., Pate, J.S., 1996. Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology—a stable isotope investigation. Oecologia 107, 13–20.

Denmead, O.T., 1984. Plant physiological methods for studying evapotranspiration: problems of telling the forest from the trees. Agric. Water Manage. 8, 167–189.

Despessis, A., 1902. The Handbook of Viticulture and Horticulture of Western Australia. Western Australian Government Printer, Perth, WA, 620 pp.

Dunin, F.X., MacKay, S.M., 1982. Evaporation of eucalypt and coniferous forest communities. In: Proceedings of the First National Symposium on Forest Hydrology, Institute of Engineers. Australia, Barton, ACT. Publ 82/6, pp. 18–25.

Dunin, F.X., McIlroy, I.C., O'Loughlin, E.M., 1985. A lysimeter characterisation of evaporation by eucalypt forest and its representativeness for the local environment. In: Hutchinson, B.A., Hicks, B.B. (Eds.), The Forest–Atmosphere Interaction. Reidel, Dordrecht, pp. 271–291.

Dunin, F.X., Williams, J., Verburg, K., Keating, B.A., 1999. Can agricultural management emulate natural ecosystems in recharge control in south eastern Australia? Agrofor. Syst. 45, 343–364.

Dye, P.J., Olbrich, B.W., 1993. Estimating transpiration from 6-year-old *Eucalyptus grandis* trees: development of a canopy conductance model and comparison with independent sap flux measurements. Plant Cell Environ. 16, 45–53.

Dye, P.J., Olbrich, B.W., Poulter, A.G., 1991. The influence of growth rings in *Pinus patula* on heat pulse velocity and sap flow measurement. J. Exp. Bot. 42, 867–870.

Edwards, W.R.N., Warwick, N.W.M., 1984. Transpiration from a kiwifruit vine as estimated by the heat pulse technique and the Penman–Monteith equation. New Zealand J. Agric. Res. 27, 537–543.

Ewel, J.J., 1999. Natural systems as models for the design of suitable systems of land use. Agrofor. Syst. 45, 1–21.

Farrington, P., Salama, R.B., 1996. Controlling dryland salinity by planting trees in the best hydrogeological setting. Land Degrad. Develop. 7, 183–204.

George, R.J., 1991. Management of sandplain seeps in the wheatbelt of Western Australia. Agric. Water Manage. 19, 85–104.

George, R.J., McFarlane, D.J., Nulson, R.A., 1997. Salinity threatens the viability of ecosystems and agriculture in Western Australia. Hydrogeol. J. 5, 6–21.

Greenwood, E.A.N., Beresford, J.D., Bartle, J.R., Barron, R.J.W., 1992. Evaporation from vegetation in landscapes developing secondary salinity using the ventilated-chamber technique. II. Evaporation from a regenerating forest of *Eucalyptus wandoo* on land formerly cleared for agriculture. J. Hydrol. 58, 357–366.

Hatton, T.J., Nulsen, R., 1999. Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. Agrofor. Syst. 45, 203–214.

Hatton, T.J., Vertessy, R.A., 1989. Variability of sapflow in a *Pinus radiata* plantation and the robust estimation of transpiration. In: Proceedings of the Hydrology and Water Resources Symposium, Christchurch, November 1989, pp. 6–10.

Hatton, T.J., Wu, H.-I., 1995. Scaling theory to extrapolate individual tree water use to stand water use. Hydrol. Processes 9, 527–540.

Hatton, T.J., Catchpole, E.A., Vertessy, R.A., 1990. Integration of sap flow velocity to estimate plant water use. Tree Phys. 6, 201–209.

Hatton, T.J., Moore, S.J., Reece, P.H., 1995. Estimating stand transpiration in a *Eucalyptus populnea* woodland with the heat pulse method: measurement errors and sampling strategies. Tree Phys. 15, 219–227.

Hatton, T.J., Bartle, G.A., Salama, R.B., Silberstein, R.P., Hodgson, G.A., Ward, P.R., Lambert, P., Williamson, D.R., 2002. Predicting and controlling water logging and groundwater flow in sloping duplex soils in western Australia, Agric. Water Manage. 53, 57–81.

Heuperman, A., 1999. Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems. Agric. Water Manage. 39, 153–167.

Hodgson, G.A., Bartle, G.A., Silberstein, R.P., Hatton, T.J., Ward, B.H., 2002. Measuring and monitoring the effects of agroforestry and drainage in the 'Ucarro' sub-catchment. Agric. Water Manage. 53, 39–56.

Lefroy, E.C., Stirzaker, R.J., 1999. Agroforestry for water management in the cropping zone of southern Australia. Agrofor. Syst. 45, 277–302.

Leuning, R., Condon, A.G., Dunin, F.X., Zegelin, S., Denmead, O.T., 1994. Rainfall interception and evaporation from soil below a wheat canopy. Agric. For. Methods 67, 221–238.

Marshall, D.C., 1958. Measurement of sap flow in conifers by heat transport. Plant Phys. 33, 385–396.

Nulsen, R.A., Bligh, K.J., Baxter, I.N., Solin, E.J., Imrie, D.H., 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. Aust. J. Ecol. 11, 361–371.

Pannell, D.J., 1999. Social and economic challenges in the development of complex farming systems. Agrofor. Syst. 45, 393–409.

Prebble, R.E., Forrest, J.A., Honeysett, J.L., Hughes, M.W., McIntyre, D.S., Schrale, G., 1981. Field installation and maintenance. Soil Water Assessment by the Neutron method. CSIRO, Australia.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Rev. 100, 81–92.

Rundle, P.J., Rundle, B.F., 2002. A case study of farm-based solutions to water logging and secondary salinity in southwestern Australia. Agric. Water Manage. 53, 31–38.

Sadler, E.J., Turner, N.C., 1994. Water relationships in a sustainable agriculture system. In: Hatfield, J.L., Karlen, D.L. (Eds.), Sustainable Agriculture Systems. Lewis, Boca Raton, pp. 21–46.

Salama, R.B., Bartle, G.A., Farrington, P., 1994. Water use of plantation *Eucalyptus camaldulensis* estimated by groundwater hydrograph separation techniques and heat pulse method. J. Hydrol. 156, 163–180.

Schulze, E.D., Caldwell, M.M., Canadell, J., Mooney, H.A., Jackson, R.B., Parson, D., Scholed, R., Sala, O.E., Trimborn, P., 1998. Downward flux of water through roots (i.e. inverse hydraulic lift) in dry Kalahari sands. Oecologia 115, 460–462.

Smith, D.M., Allen, S.J., 1996. Measurement of sap flow in plant stems. J. Exp. Bot. 47, 1833–1844.

Smith, D.M., Jarvis, P.G., 1998. Physiological and environmental control of transpiration by trees in windbreaks. For. Ecol. Manage. 105, 159–173.

Smith, D.M., Jarvis, P.G., Odongo, J.C.W., 1997a. Energy budgets of windbreak canopies in the Sahel. Agric. For. Methods 86, 33–49.

Smith, D.M., Jarvis, P.G., Odongo, J.C.W., 1997b. Sources of water used by trees and millet in Sahelian windbreak systems. J. Hydrol. 198, 140–153.

Smith, D.M., Jarvis, P.G., Odongo, J.C.W., 1998. Management of windbreaks in the Sahel—the strategic implications of tree water use. Agrofor. Syst. 40, 83–96.

Stirzaker, R.J., Cook, F.J., Knight, J.H., 1999. Where to plant trees on cropping land for control of dryland salinity. Agric. Water Manage. 39, 115–133.

Swanson, R.H., Whitfield, D.W.A., 1981. A numerical analysis of heat pulse velocity theory and practice. J. Exp. Bot. 32, 221–239.

Vertessy, R.A., Hatton, T.J., Reece, P.H., O'Sullivan, S.K., Benyon, R.G., 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. Tree Phys. 17, 747–756.

Ward, P.R., Dunin, F.X., Micin, S.F., 2002. Water use and root growth by annual and perennial pastures and subsequent crops in a phase rotation. Agric. Water Manage. 53, 83–97.

White, D.A., Beadle, C.L., Honeysett, J.L., Worledge, D., 1994. The effect of drought stress on height, diameter and leaf area index of *Eucalyptus globulus* and *E. nitens*. In: Brown, A.G. (Ed.), ACIAR Proceedings of the Symposium on Australian Tree Species Research in China, Vol. 48. Canberra, pp. 71–76.

White, D.A., Beadle, C.L., Sands, P.J., Worledge, D., Honeysett, J.L., 1999. Quantifying the effect of cumulative water stress on stomatal conductance of *Eucalyptus globulus* and *E. nitens*: a phenomenological approach. Aust. J. Plant Phys. 26, 17–27.

White, D.A., Beadle, C.L., Worledge, D., 2000a. Control of transpiration in an irrigated *Eucalyptus globulus* Labill. plantation. Plant Cell Environ. 23, 123–134.

White, D.A., Turner, N.C., Galbraith, J.H., 2000b. Leaf water relations and stomatal behaviour of four allopatric *Eucalyptus* species planted in Mediterranean southwestern Australia. Tree Phys. 20, 1157–1165.

Williams, J., 1991. Search for sustainability: agriculture and its place in the natural ecosystem. Agric. Sci. 4, 32–39.

Wood, W.E., 1924. Increase in salt and streams following destruction of the native vegetation. J. Roy. Soc. Western Aust. 10, 35–47.

Wullschleger, S.D., Meinzer, F.C., Vertessy, R.A., 1998. A review of whole plant water use studies in trees. Tree Phys. 18, 499–512.

Zhang, H., Simmonds, L.P., Morison, J.I.L., Payne, D., 1997. Estimation of transpiration by single trees: comparison of sap flow measurement with a combination equation. Agric. For. Met. 87, 155–169.

Zohar, Y., 1985. Root distribution of a eucalypt shelterbelt. For. Ecol. Manage. 12, 305–307.