Impacts of tree plantations on groundwater in south-eastern Australia

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Abstract. In some regions dependent on groundwater, such as the lower south-east of South Australia in the Green Triangle, deep-rooted, woody vegetation might have undesirable hydrological impacts by competing for finite, good-quality groundwater resources. In other regions, such as the Riverina in south-central New South Wales, where rising watertables and associated salinisation is threatening the viability of agriculture, woody vegetation might have beneficial hydrological impacts. In response to a growing need to better understand the impacts of tree plantations on groundwater, annual evapotranspiration and transpiration were measured at 21 plantation sites in the Green Triangle and the Riverina. Sources of tree water uptake from rainfall and groundwater were determined by measurements of evapotranspiration and soil water over periods of 2–5 years. In the Green Triangle, under a combination of permeable soil over groundwater of low salinity (\(<2000 \text{ mg L}^{-1}\)) at 6-m depth or less, in a highly transmissive aquifer, annual evapotranspiration at eight research sites in \textit{Pinus radiata} D.Don and \textit{Eucalyptus globoila} Labill. plantations averaged 1090 mm year\(^{-1}\) (range 847–1343 mm year\(^{-1}\)), compared with mean annual precipitation of 630 mm year\(^{-1}\). These plantation sites used groundwater at a mean annual rate of 435 mm year\(^{-1}\) (range 108–670 mm year\(^{-1}\)). At eight other plantation sites that had greater depth to the watertable or a root-impeding layer, annual evapotranspiration was equal to, or slightly less than, annual rainfall (mean 623 mm year\(^{-1}\), range 540–795 mm year\(^{-1}\)). In the Riverina, where groundwater was always present within 3 m of the surface, \textit{Eucalyptus grandis} Hill ex Maiden trees at three sites with medium or heavy clay, alkaline, sodic, saline subsoils used little or no groundwater, whereas \textit{E. grandis} and \textit{Corymbia maculata} (Hook.) K.D.Hill and L.A.S.Johnson trees at a site with a neutral sandy soil and groundwater of low salinity used 380 and 730 mm year\(^{-1}\) of groundwater (respectively 41 and 53\% of total annual evapotranspiration). We conclude that commonly grown \textit{Eucalyptus} species and \textit{P. radiata} are able to use groundwater under a combination of light- or medium-textured soil and shallow depth to a low-salinity watertable.

Introduction

Australia is a dry continent with limited water resources. Sustainable management of these resources requires a sound understanding of the availability of both surface and groundwater and how this is influenced by climate, soil and vegetation cover. In contrast, in some parts of the country, an increase in the amount of water in the landscape because of irrigation and clearing of deep-rooted perennial vegetation has caused salinisation of soils, threatening the health of remnant natural vegetation and aquatic ecosystems and the viability of agriculture.

Hydrological studies from across the world demonstrate that woody vegetation, including tree plantations, commonly uses more water annually than grasses and non-irrigated agricultural crops (Hibbert 1967; Bosch and Hewlett 1982). It is generally accepted that forests evapotranspire more water than shallow-rooted vegetation because they have lower albedo, intercept more rainfall (particularly conifers), possess deeper root systems and have taller, rougher canopies (Holmes and Sinclair 1986; Zhang et al. 1999).

In Australia, the area under industrial-plantation forestry has increased by \approx 6000 \text{ km}^2 in the past decade. As a proportion of the total area of agricultural land, this is a small change, but in a few individual catchments, new plantation forestry represents a significant change in land use. This has stimulated interest and debate over the potential for both adverse and beneficial impacts on water resources. In areas threatened by salinity, there is strong interest in determining the effectiveness of strategically locating trees to de-water landscapes where saline watertables have been rising. These issues have been summarised in Nambiar and Brown (2001) and O’Loughlin and Nambiar (2001).

Trees can reduce stream-flow and groundwater recharge, relative to shallower-rooted grasses and agricultural crops, and in areas underlain by shallow watertables, the deeper root systems of trees than herbaceous vegetation.
might enable them to access groundwater (Knight 1999). Several studies have quantified groundwater use by woody perennials, including natural riparian vegetation in various environments (Thorburn and Walker 1994; O’Grady et al. 2002, 2006), natural Savanna (O’Grady et al. 1999; Kelly et al. 2002) and small woodlots established over shallow groundwater (Thorburn 1999; Cramer et al. 1999; Morris and Collopy 1999; Vertessy et al. 2000). In some cases, natural vegetation, including eucalypts, has been shown to be reliant almost solely on groundwater. For example, Thorburn et al. (1993) observed that among various sites on the flood plain of the Murray River in South Australia, groundwater contributed between 40 and 100% of tree water use. To our knowledge, however, quantification of groundwater uptake by large-scale tree plantations established in locations with shallow depth-to-groundwater has not previously been undertaken.

In the Green Triangle region of south-eastern South Australia and south-western Victoria and the Riverina in south-central New South Wales, tree plantations have been established over shallow water tables in recent years. In both regions, impacts of tree plantations on groundwater need to be understood and quantified to enable assessment of potential beneficial or adverse effects on groundwater supplies, remnant natural vegetation and groundwater-dependent ecosystems. In the western half of the Green Triangle, mainly in south-eastern South Australia, centred on Mount Gambier (37.8°S, 140.8°E), 95% of available groundwater resources occur in a transmissive, unconfined or semi-confined aquifer which is commonly <20 m below ground level and in some places a few metres from the surface. Generally, there is little surface-run off and few permanent natural surface streams and lakes. Most of the rainfall not returned to the atmosphere via evapotranspiration drains vertically until it enters the unconfined aquifer as recharge (Hopton et al. 2001; South East Catchment Water Management Board 2003). Pinus radiata D.Don has been grown for timber production in this region for more than a century and currently occupies ~1000 km². In addition, a new industry to supply eucalypt chips for export has been established since the late 1990s, based on Eucalyptus globulus Labill which now occupies ~350 km² in south-eastern South Australia. Plantation forestry provides the raw material for nearly 30% of regional economic activity and 25% of regional employment (Green Triangle Regional Plantation Committee 2001).

Prior to European settlement in the 19th century, the region had a mixture of forest, woodland and wetland vegetation. In the past 150 years, 93% of this has been cleared and replaced with pasture, agricultural crops and plantation forests. Early studies in south-eastern South Australia indicated lower groundwater recharge under P. radiata plantations than with grassland (Holmes and Colville 1970a, 1970b; Allison and Hughes 1972; Colville and Holmes 1972). These studies found that, once the canopy of a plantation has fully closed, there is little, if any, groundwater recharge under these plantations. However, none of these early studies indicates whether deep-rooted vegetation, such as trees, obtains water from groundwater (Benyon 2002). Sustainable management of the region’s water resources requires accurate assessment of water use by the main land uses, including plantation forestry.

The Riverina, centred around Deniliquen in south-central New South Wales (35°5’S, 145°0’E) is underlain by the Murray Basin, made up of various layers of sediment containing relatively thin aquifers (0.5–6 m thick) and groundwater of varying salinity from almost fresh (<1000 mg L⁻¹) to highly saline (>10 000 mg L⁻¹). Soils are generally loamy at the surface, underlain by subsoils of various textures from coarse sand to heavy clay many metres deep. Groundwater levels over the past few decades have risen owing to access from irrigation channels and flood-irrigated crops, which occupy much of the region. Rising saline watertables pose a threat to the viability of irrigated agriculture in some locations. Small farm-forestry plantations, mainly of Eucalyptus grandis Hill ex Maiden and Corymbia maculata (Hook.) K.D.Hill & L.A.S.Johnson, have been established over the past 10 years. The question here is whether these woodlots have potential to use groundwater in some locations and help arrest the rise in watertables (Polglase et al. 2002).

Although the land and water-resource management issues differ between the two regions, the fundamental research questions are the same, including the following:

1. (d) do tree plantations use all the rainfall (is there any groundwater recharge), and
2. (c) can the trees access shallow groundwater, is there net aquifier discharge through direct uptake by tree roots; if so, how much groundwater can tree plantations use and what site factors determine the amount of groundwater uptake?

Over the past 10 years in the Green Triangle and south-central New South Wales, water balance and tree water-use studies have been used to quantify plantation water use in research plots of P. radiata, E. globulus, E. grandis and C. maculata. These studies provide key information on plantation water use for these major plantation species and how water use varies with rainfall, potential evapotranspiration, depth-to-groundwater, soil conditions and easily measurable plantation characteristics such as stem growth rates and leaf area index. This paper uses the results from these studies to identify site factors influencing the impacts of plantations on groundwater in the Green Triangle and the Riverina and to assess whether plantation growth rates can be used as an indicator of evapotranspiration.
Materials and methods

Quantifying groundwater recharge and uptake

Various techniques have been used to quantify groundwater use by plants in previous studies. Some have used measurements of changes in depth-to-watertable in comparison with measured evapotranspiration rates to indicate groundwater uptake (Dugas et al. 1990; Farrington et al. 1990).

This technique does not work at locations where aquifer transmissivity is high relative to evapotranspiration rates. Aquifer transmissivity in south-eastern South Australia is high (F. Stadler, pers. comm.).

Others have used measurements of concentrations of stable isotopes of O and H of groundwater, soil water and plant water to identify sources of water used by plants (Thorburn et al. 1993). However, in south-eastern South Australia, the isotope concentrations in deep soil water and groundwater are not sufficiently different to permit the use of this technique (McEwen and Leaney 1996).

At locations where there is negligible surface water flow or subsurface lateral flow within the vadose zone, groundwater uptake can be estimated by comparing measured evapotranspiration with rainfall inputs and changes in root-zone soil water. A statistically significantly higher evapotranspiration rate than the sum of rainfall and any reduction in soil water over a period, allows quantification of groundwater uptake. We used this method, i.e. components of the water balance were measured in experimental plots ranging in size from 20 × 20 m to 30 × 30 m, at various sites in the Green Triangle and the Riverina. Sources and amounts of water used by the trees were estimated by comparing evapotranspiration with rainfall and changes in soil water. In the Riverina, the plantations were occasionally irrigated. Additional water supplied by irrigation was accounted for. For each site, tree water use and some or all of the other components of evapotranspiration were measured.

At all sites, measurements of water use began at or after canopy closure and continued for between 2 and 5 years. Sites described in Table 1 include E. globulus (labelled ‘EGl’), P. radiata (’PR’), E. grandis (’EGr’) and C. maculata (’CM’). Plantation ages at commencement of measurement ranged from 3 to 6 years in the eucalypts and from 4 to 27 years in P. radiata. All sites had little or no understorey.

Table 1. Characteristics of the research sites

Column 1 indicates the site number, as referred to in the text, and the species, as defined in the text. Column 2 indicates the plantation age, to the nearest year, at the commencement and conclusion of measurements. Column 3 indicates the median depth to the watertable over the study period and the watertable depth range (in parentheses). Sites highlighted in bold used some groundwater (see results) n.m. indicates not measured.

<table>
<thead>
<tr>
<th>Site species</th>
<th>Age range (years)</th>
<th>Median watertable depth (m)*</th>
<th>Slope position</th>
<th>Soil description</th>
<th>Stocking (trees ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Triangle sites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. EGl</td>
<td>4–6</td>
<td>1.7 (0.4–2.7)</td>
<td>Extensive flats</td>
<td>Sandy to 0.4 m, medium sandy clay to 2.5 m</td>
<td>1175</td>
</tr>
<tr>
<td>2. EGl</td>
<td>6–9</td>
<td>1.9 (0.6–3.2)</td>
<td>Extensive flats</td>
<td>Sandy to 0.9 m, sandy clay to 1.2 m, medium to heavy clay to 2.5 m, sandy clay to 4 m</td>
<td>700</td>
</tr>
<tr>
<td>3. EGl</td>
<td>6–9</td>
<td>1.9 (0.8–3.4)</td>
<td>Extensive flats</td>
<td>Sandy to 1.2 m, sandy light to medium clay to 4 m</td>
<td>1200</td>
</tr>
<tr>
<td>4. EGl</td>
<td>5–10</td>
<td>3.0 (2.7–3.3)</td>
<td>Lower slope hollow among dunes</td>
<td>Sand with calcified sand at 1 to 1.5 m, sand to 3 m</td>
<td>818</td>
</tr>
<tr>
<td>5. EGl</td>
<td>4–7</td>
<td>3.2 (2.4–3.9)</td>
<td>Lower slope hollow among dunes</td>
<td>Sand and loamy sand to 1.6 m, light to medium sandy clay to 4 m</td>
<td>1175</td>
</tr>
<tr>
<td>6. EGl</td>
<td>4–7</td>
<td>10.3 (9.8–11.0)</td>
<td>Top of dune</td>
<td>Sand to 2.5 m, sandy light clay to 3 m</td>
<td>1200</td>
</tr>
<tr>
<td>7. EGl</td>
<td>4–8</td>
<td>4.4 (3.7–4.7)</td>
<td>Lower mid-slope</td>
<td>Sand to 0.4 m, sandy clay to &gt;3 m</td>
<td>1125</td>
</tr>
<tr>
<td>8. EGl</td>
<td>4–6</td>
<td>15.9 (15.4–16.1)</td>
<td>Mid-slope</td>
<td>Sand to 1.2 m, sandy clay to &gt;3 m</td>
<td>1025</td>
</tr>
<tr>
<td>9. EGl</td>
<td>4–7</td>
<td>7.6 (7.5–8.3)</td>
<td>Mid-slope</td>
<td>Medium to heavy clay to &gt;5 m</td>
<td>925</td>
</tr>
<tr>
<td>10. PR</td>
<td>4–7</td>
<td>3.9 (3.5–4.4)</td>
<td>Lower slope</td>
<td>Sand 0.6 m, sandy clay to &gt;3 m</td>
<td>1275</td>
</tr>
<tr>
<td>11. PR</td>
<td>4–9</td>
<td>6.0 (5.4–6.4)</td>
<td>Lower slope</td>
<td>Sand to 1.5 m, sandy clay to &gt;3 m</td>
<td>1200</td>
</tr>
<tr>
<td>12. PR</td>
<td>27–31</td>
<td>4.4 (4.1–5.2)</td>
<td>Mid-slope</td>
<td>Sand to 1.2 m, cemented hardpan at 1.2 m</td>
<td>374</td>
</tr>
<tr>
<td>13. PR</td>
<td>14–18</td>
<td>8.9 (8.7–9.3)</td>
<td>Mid-slope</td>
<td>Sand to 0.6 m, light to medium sandy clay to &gt;5 m</td>
<td>912</td>
</tr>
<tr>
<td>14. PR</td>
<td>20–24</td>
<td>8.6 (8.5–8.9)</td>
<td>Mid-slope</td>
<td>Sand to 2 m, sandy clay to &gt;3 m</td>
<td>432</td>
</tr>
<tr>
<td>15. PR</td>
<td>25–29</td>
<td>23.0 (22.9–23.3)</td>
<td>Lower slope</td>
<td>Sand to 1.0 m, sandy clay to &gt;3 m</td>
<td>374</td>
</tr>
<tr>
<td>16. PR</td>
<td>21–25</td>
<td>n.m.</td>
<td>Mid-slope</td>
<td>Sand to 0.7 m, light clay to 1.5 m</td>
<td>353</td>
</tr>
<tr>
<td>Riverina sites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. EGr</td>
<td>3–5</td>
<td>2.8 (2.5–3.0)</td>
<td>Extensive flats</td>
<td>Loam to 0.5 m, heavy clay to &gt;3 m</td>
<td>~1333</td>
</tr>
<tr>
<td>18. EGr</td>
<td>3–5</td>
<td>2.9 (2.8–3.0)</td>
<td>Extensive flats</td>
<td>Heavy clay to &gt;3 m</td>
<td>~1333</td>
</tr>
<tr>
<td>19. EGr</td>
<td>3–5</td>
<td>2.9 (2.8–3.0)</td>
<td>Extensive flats</td>
<td>Loam to 0.5 m, medium clay to &gt;3 m</td>
<td>~1333</td>
</tr>
<tr>
<td>20. EGr</td>
<td>3–5</td>
<td>2.7 (2.5–2.8)</td>
<td>Extensive flats – prior stream</td>
<td>Light sand to &gt;3 m</td>
<td>~1333</td>
</tr>
<tr>
<td>21. CM</td>
<td>3–5</td>
<td>3.1 (2.8–3.5)</td>
<td>Extensive flats – prior stream</td>
<td>Light sand to &gt;3 m</td>
<td>~1333</td>
</tr>
</tbody>
</table>

*The variation in depth-to-groundwater at each site was largely seasonal. Over the periods of measurement there was little overall change.
Determination of net water balances
At each site, for each period of several weeks between soil water measurements, net water balance (deep drainage or water uptake from groundwater) was estimated to be

\[ Q_{nw} = P - (I + E + T) - (S_h - S_w) \]  

(1)

where \( Q_{nw} \) = net water balance; either drainage (a positive value) or water uptake (a negative value) below the maximum depth of soil water measurement; \( P \) = gross total precipitation for the period, measured in a rain gauge in the open nearby, plus net irrigation in the case of Rivera sites; \( I \) = rainfall interception losses, estimated from measurements of throughfall; \( E \) = evaporative losses from the soil surface measured with mini lysimeters; \( T \) = transpiration determined by direct measurement with sap flow sensors; \( S_h \) = the current volumetric water content of the root zone measured with a neutron moisture meter; \( S_w \) = the previous volumetric water content of the root zone.

The sum of \( I, E, \) and \( T \) makes up the total evapotranspiration. Thus, for a given period, the net water balance is equal to net water applied (i.e. rain plus irrigation) from which evapotranspiration and any change in soil water is subtracted. A positive net water balance can imply either deep drainage, net surface runoff or subsurface lateral flow out of the research plot, or a combination of these, whereas a negative net water balance can imply net lateral movement of water into the research plot, either from higher upslope as overland flow or subsurface lateral flow, or as lateral flow through a watertable.

Climate
In the Green Triangle, for each site, rainfall in a rain gauge in an open area (located within 2 km for all sites) was recorded every time the site was visited (nominally every 2–4 weeks). In the Riverina, meteorological data (rainfall, pan evaporation, wet- and dry-bulb temperature, solar radiation and wind speed and direction) were recorded hourly with an automatic weather station (Starlog, UNIMADA, Australia) at one site.

Soil water
Soil water was measured at the end of each measurement period to maximum depths of 3 m at most sites and 6 m at three others (Sites 6, 9 and 14) with a neutron probe. At all sites with <3 m depth-to-groundwater, this was to the watertable or to the capillary fringe above the watertable. Measurements were collected every 2–4 weeks in five randomly located access holes at each site at depths of 0.075, 0.15, 0.3 m and then every 0.3 m to the maximum depth of measurement. For each site, a calibration curve was derived by using soil samples collected during installation of the access tubes.

Interception
At 10 sites in the Green Triangle (Sites 1–3, 5–7, 9, 11, 13, 14 in Table 1) throughfall was measured by using eight randomly located collection troughs. These were 90-degree, V-shaped pieces of aluminium, each 1.20 m long by 0.14 m wide, draining into a collection drum. The volume of water collected in each drum was measured whenever soil water was measured. Stem flow was not measured, but estimated assuming 10% of rainfall for \( P. \) radiata (Langford and O'Shaughnessy 1977) and 2% of rainfall for eucalypts (Vertessy et al. 2000). Interception loss was calculated as rainfall minus throughfall (including the 10 or 2% allowance for stem flow). For the six other Green Triangle sites, interception was estimated on the basis of the mean percentage interception determined for that species.

For the Riverina sites, interception was estimated on the basis of seasonal percentages previously measured for \( E. \) grandis in that climate (Myers et al. 1996).
Soil evaporation

In the Green Triangle, soil evaporation was measured at Sites 1–3, 5–7, 9, 11, 13 and 14, with five to nine mini-lisymeters per site. Each lysimeter contained a soil column collected to a depth of 0.27 m deep. Net rainfall beside each lysimeter was measured with a standard rain gauge. Drainage through the lysimeter was collected and measured. Evaporation from the soil column for each measurement period was estimated on the basis of rainfall, drainage and the change in weight over the period. Measurements were collected each time soil water was measured. The lysimeter surface was kept free of litter fall.

Because the lysimeters excluded live roots, rates of soil water depletion might be lower than in the surrounding soil. This would, at times, result in the soil water content inside the lysimeters being higher than in the corresponding depth of soil outside the lysimeters, causing an over-estimation of soil evaporation. Examination of the rate of soil evaporation from the lysimeters, in relation to soil water content over 2–3 years of measurements, indicated that for water content lower than ~50% of the maximum water content, there was a linear relationship between the evaporation rate and soil water content. For water content greater than 50% of the maximum water content there was no significant correlation between the rate of evaporation and soil water content. In these conditions, soil evaporation proceeded at a rate determined by weather rather than soil water content. Thus, for periods when soil water measurements indicated that soil water content in the top 0.3 m of soil outside the lysimeters was greater than 50% of the maximum water content, observed soil evaporation was used in the water-balance equation, on the assumption that the rate of soil evaporation would be the same inside and outside the lysimeter because it was unconstrained by water availability. For periods when soil water content in the top 0.3 m of soil outside the lysimeters was lower than 50% of the maximum, soil evaporation for the period was estimated on the basis of the average soil water for the period and a linear regression derived from the lysimeter data, relating daily evaporation rate to soil water content in the top 0.3 m of soil. For the remaining six Green Triangle sites, soil evaporation was estimated on the basis of the average rates observed at the sites where it was measured.

In the Riverina, soil evaporation was similarly determined from the measurements collected from mini-lysimeters. Measurements of daily soil evaporation over drying cycles of several days, on several occasions, were used to determine relationships between surface soil water content and daily evaporation rate.

Transpiration

Transpiration at all sites was determined with sapflow sensors employing the heat-pulse technique (Models SF100 and SF300, Greenspan Technology, Warwick, Qld). Sap velocities were recorded every 30 min in six or eight sample trees per site and transpiration each day was estimated as the product of observed mean sap velocity and plot sap conducting-wood area.

To select the sample trees, the stem diameters of all trees in each plot were measured and stem basal area over bark calculated. Plot total sapwood area was also calculated and each plot was divided into two or three classes of tree size. Each class contained an equal total basal area. In each plot, either four trees (if only two size classes were used) or two trees (if three size classes were used) for sap-flow measurement were randomly selected from each tree size class.

Estimates of wound size around the holes drilled for installation of the sensors were based on previous measurements (3 mm for eucalypts and 2.4 mm for radiata pine). Wood and water volume fractions were determined on several occasions from 5-mm-diameter cores. Within plots, these did not change significantly with time. Heat-pulse velocities were converted to sap velocities after Swanson and Whittfield (1981) and Edwards and Warwick (1984). To account for radial variation, the sapwood area was divided into two (SF100 sensors) or four (SF300 sensors) concentric rings of equal area, and one sensor (SF300) or two sensors (SF100) located at a random depth and azimuth within each ring, after Benyon (1999). Zero flows were identified by the method described by Benyon (1999). Mean sap velocity for a tree was calculated as the average of the two or four sample points within the tree.

In eucalypts, sapwood thickness was determined every 3–4 months with the sap-flow sensors after Hatton et al. (1995) and Benyon (1999). Young P. radiata trees (<15 years old) contained little or no heartwood. In older P. radiata trees, sapwood thickness was determined by examining the colour change in three 12-mm-diameter wood cores per sample tree. Tree sapwood area at the sap-flow measurement height was determined on the basis of measured stem diameter, bark thickness and sapwood thickness. For trees in which sap velocity and sapwood thickness were not measured, sapwood area was estimated from a linear regression with tree basal area over bark. Plot sapwood area was calculated by summing the estimated sapwood areas of all trees in the plot. Daily transpiration was estimated as the product of the 24-h mean sap velocity (0600 to 0600 hours) of the sample trees and plot sapwood area.

Statistical analyses

Statistical confidence limits were estimated for annual interception, annual transpiration and annual soil evaporation for each site. For interception, confidence limits were based on the variation in mean throughfall between collection troughs. For soil evaporation, they were based on the variation in mean evaporation between lysimeters and for transpiration they were based on the variation in mean sap velocity between sample trees.

Evapotranspiration is the sum of three independently measured variables. Assuming sampling errors in the measurements of one variable were independent of the sampling errors in the measurements of the other variables, a combined 95% confidence interval for evapotranspiration was initially estimated as the sum of the 62% confidence intervals for the three variables, on the basis that there is only a 5% probability the true mean of all three variables would fall either above or below the 62% confidence intervals at the same time (i.e. $0.38 \times 0.38 \times 0.38 \approx 0.05$). However, because the confidence intervals for interception and evaporation were small, relative to those for transpiration, it was found that the 95% confidence interval for evapotranspiration estimated by this method was narrower than the 95% confidence interval for transpiration alone. Thus, we have assumed that the 95% confidence interval for evapotranspiration is equal to that for transpiration.

Leaf area index

In the Green Triangle, measurements of leaf area and sapwood area at breast height from individual P. radiata trees (Teskey and Sheriff 1996) and E. globulus trees (D. N. Fife, CSIRO, unpubl. data) were used to derive linear relationships between tree leaf area and tree sapwood area for these two species. These relationships were applied to subsequent estimates of tree sapwood area to estimate tree leaf area and site leaf area index (LAI) two to four times per year during the study periods.

Results

Annual evapotranspiration

Annual evapotranspiration varied widely among sites and, overall, was not well correlated with rainfall (Green Triangle sites) or with rainfall plus net irrigation (Riverina sites) (Fig. 1). In about half the sites (Sites 1–5, 7, 10, 11, 19–21 in Tables 1, 2, annual evapotranspiration significantly exceeded...
The range in annual evapotranspiration among sites (from 415 to 1343 mm year$^{-1}$) was substantially higher than the range in annual water applied (from 362 to 784 mm year$^{-1}$). For all but one of the sites, annual water applied was in the range 489–784 mm year$^{-1}$. Excluding the one $P$. radiata site with very low rainfall (Site 10), the range in evapotranspiration among sites (928 mm year$^{-1}$) was more than three times greater than the range in water applied (295 mm year$^{-1}$).

The one-to-one line (water used = water applied) is also shown on Fig. 1. For about half the sites (Sites 6, 8, 9, 12–18), the one-to-one line passed through or slightly above the 95% statistical confidence interval for annual water use. However, for the remaining sites, the one-to-one line was well below the 95% confidence intervals for mean annual evapotranspiration, indicating another source of water was available to the trees in addition to rainfall and net irrigation (Sites 1–5, 7, 10, 11, 19–21).

Sources of water used by the trees

Table 2 shows for each site, the mean annual water applied, best available estimate of the theoretical potential evapotranspiration, actual evapotranspiration and the net water balance, as determined from Eqn 1. For the Green Triangle sites, the use of either point or areal potential evapotranspiration, as defined by Wang et al. (2001), was

Table 2. Annual water balance for each site

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Rain (+ net irr) (mm year$^{-1}$)</th>
<th>Potential evapotranspiration (mm year$^{-1}$)</th>
<th>Observed evapotranspiration (mm year$^{-1}$)</th>
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Fig. 1. Relationship between annual evapotranspiration (water use) and rainfall ($P$. radiata and $E$. globulus) or rainfall + net irrigation ($E$. grandis and $C$. maculata). Error bars indicate the 95% statistical confidence limits for water use. The solid line shows the one-to-one relationship (water used = water applied).
Plants and groundwater

Figure 2. Relationship between depth-to-groundwater and net water balance for closed-canopy *Pinus radiata* and *Eucalyptus globulus* sites in the Green Triangle and *E. grandis* and *Corymbia maculata* sites in the Riverina. Error bars indicate the 95% statistical confidence limits.

Sites 10 and 11, *E. grandis* Sites 19 and 20 and *C. maculata* Site 21), accounting for between 13 and 72% of annual water use. These sites had sandy or light or medium clay soils (Table 1). Of three sites where the trees were not using groundwater despite shallow depth-to-groundwater, two (*E. grandis* Sites 17 and 18) had heavy, sodic, clay subsoils, whereas one (*P. radiata* Site 12) had a cemented hardpan layer at 1.2-m depth. The latter used significantly less water than received from rainfall, implying net groundwater recharge.

Mean transpiration at the sites where the trees used groundwater was 767 mm year$^{-1}$, compared with 358 mm year$^{-1}$ for the sites where no groundwater use was detected, a difference of 409 mm year$^{-1}$. Thus, the difference in mean annual water use between sites using and not using groundwater was due to a difference in transpiration.

Relationship between leaf area index and water use

One of the aims of the Green Triangle studies was to determine how accurately water use of existing plantations could be estimated on the basis of plantation inventory data or variables measurable by remote sensing, such as leaf area index (LAI). For the Green Triangle dataset, the relationship between annual transpiration and leaf area index (Fig. 3) appeared to differ between sites using and not using groundwater. The three sites with the lowest LAI (Sites 8, 9 and 12) did not use groundwater and had low water use, whereas the three sites with the highest LAI (Sites 4, 10 and 11) used groundwater and had high annual water-use rates. However, of sites with LAI between 3.2 and...
was 350 mm year
4.2, five accessed groundwater (Sites 1–3, 5, 7) whereas
between 3.2 and 4.2. Two lines of best fit are shown.

Relationship between annual transpiration and leaf area index (LAI) for the Green Triangle sites. Filled circles indicate sites that used some groundwater. The grey box indicates plots having mean LAI over 3.2 and 4.2. Two lines of best fit are shown.

4.2, five accessed groundwater (Sites 1–3, 5, 7) whereas four did not (Sites 6, 13–15). Mean annual transpiration was 350 mm year$^{-1}$ higher for the five sites which accessed groundwater. The relationship between transpiration and LAI was not influenced by species (data not shown).

Discussion

Groundwater recharge under plantations

All but 2 of the 21 sites in the Green Triangle and the Riverina, listed in Table 1, used all of the available rainfall during the periods of measurement. In both regions, mean annual rainfall is substantially lower than annual potential evapotranspiration (Table 2), indicating that these are water-limited environments. Thus, in all cases there is potential for tree plantations to use more water than available from rainfall. Once the canopy of a plantation has closed, deep-drainage and groundwater recharge is likely to occur if root-zone water-holding capacity is exceeded during periods when cumulative rainfall is greater than cumulative evapotranspiration. This is possible in the Green Triangle where, from May to August, mean total rainfall exceeds mean total potential evapotranspiration by ∼200 mm.

The method used to estimate net water balances in this study cannot determine whether the proportion of rainfall which is unaccounted for, went to groundwater recharge, surface runoff or net subsurface lateral flows. A statistically significant positive net water balance was observed at Sites 9 and 12. Site 12, in south-eastern South Australia, has a sandy surface soil and gently sloping topography, with a hardpan present at 1.2-m depth. Hydraulic conductivity of the surface soil, although not measured, was probably high, and therefore surface runoff from the site, which was in a mid-slope position, was unlikely. It is possible that excess rainfall drained vertically to the hardpan layer, where it may have moved laterally further down-slope, rather than recharging the groundwater. Site 9, in south-western Victoria, was almost flat, with a heavy clay soil. Periodic measurements of soil water down to 6-m depth indicated that several wetting fronts moved slowly through the soil down to >6 m between August and November during a wet winter, suggesting the likelihood of deep drainage reaching the watertable at 7.5-m depth.

No studies in south-eastern Australia have measured evapotranspiration in the period of the rotation between harvesting of one tree crop and establishment of the canopy of the next. In south-eastern South Australia, Mitchell and Correll (1987) observed that the soil water profile fully recharged in the 1-year fallow period between the first and second rotation $P.$ radiata plantation, indicating the possibility of some groundwater recharge during this period. More research is needed if recharge during this period of each rotation is to be quantified and the net water balance over a full rotation estimated accurately.

Groundwater uptake by plantations

Significant groundwater uptake occurred at 11 of the study sites, providing between 13 and 72% of annual transpiration. In both the Green Triangle and the Riverina, the highest rate of net groundwater uptake was ∼700 mm year$^{-1}$. This is the highest absolute annual rate of groundwater uptake by trees that we are aware of. Thorburn (1999) collated results from 20 diverse field experiments on trees, crops, shrubs and pasture, from which estimates of groundwater uptake had been derived. These ranged from 10 to 590 mm year$^{-1}$ at all sites, depth-to-watertable was < 5 m; however, groundwater was moderately saline (> 3000 mg L$^{-1}$). In several studies in northern Victoria and south-eastern Queensland, groundwater uptake of 100–279 mm year$^{-1}$ by $E.$ camaldulensis and $E.$ grandis woodlots was estimated (Cramer et al. 1999; Morris and Collopy 1999; Vertessy et al. 2000). These sites were on shallow, slightly or moderately saline groundwater, in soils of generally low permeability. Under such conditions, annual evapotranspiration rates were substantially lower than potential evapotranspiration, and groundwater uptake may have been restricted by low soil hydraulic conductivity, low leaf area index or salt accumulation in the root zone.

In the Green Triangle and the Riverina, whether the trees accessed groundwater was the most significant factor influencing water use, accounting for 67% of the total among-site variation in mean annual evapotranspiration. Accessibility of groundwater was largely a function of depth-to-the-watertable and soil type.

For the eight sites in the Green Triangle that used some groundwater, the among-site range in water use was almost 500 mm year$^{-1}$. For these eight sites, the site and stand variables we measured were only weakly correlated with
Plantations and groundwater 

annual water use and groundwater uptake. There was no significant correlation between annual water use and rainfall ($r^2 = 0.01$), median depth-to-the-watertable ($r^2 = 0.13$) or LAI ($r^2 = 0.14$). There was, however, a significant ($r^2 = 0.51$, $P < 0.05$) correlation between theoretical potential evapotranspiration (as defined by Wang et al. 2001) and actual evapotranspiration for these sites. This was largely related to whether we considered the site fitted the Wang et al. (2001) definition of ‘areal’ or ‘point’ for determining potential evapotranspiration. For two sites located in the middle of large plantations (Sites 2 and 5), areal potential evapotranspiration was within or slightly above the 95% confidence limits for observed annual evapotranspiration. The remaining six sites were located either in small plantations (<1 km²), Sites 1 and 4, or within 100 m of a plantation edge (Sites 3, 7, 10, 11). For these, the theoretical point potential evapotranspiration was within the 90% statistical confidence limits for observed annual evapotranspiration. The y-intercept term for a regression relating observed evapotranspiration to potential evapotranspiration was not significantly different from 0, and the slope coefficient was not statistically significantly different from 1. Within the group of six sites considered representative of point potential evapotranspiration, there was a significant difference in annual water use between the site with lowest water use (Site 1) and the site with the highest water use (Site 11), but there were no other statistically significant differences. Thus, for the eight Green Triangle sites at which the trees accessed groundwater, the among-site variation in annual water use was partly a function of potential evapotranspiration. It is also possible that aquifer transmissivity or soil hydraulic conductivity in the root zone restricted the rate of water movement to the tree root zone at some sites, but not others, or that the distribution of roots between capillary fringe and surface soil varied among sites.

In the Riverina, two sites (Sites 17 and 18) where there was no detectable groundwater uptake by *E. grandis*, despite groundwater present at 3-m depth, had heavy, sodic, alkaline, saline clay subsoils below ~0.5-m depth. Groundwater at these sites was also saline. At Site 19, where groundwater uptake was estimated to be small, the texture of the clay subsoil was lighter than at Sites 17 and 18. The remaining Riverina sites (Sites 20 and 21), where *E. grandis* and *C. maculata* both used significant quantities of groundwater, had sandy soil and low groundwater salinity. In the Riverina, soil type had the greatest influence on plantation water use and groundwater uptake. The effect of soil type, however, was confounded with the effect of groundwater salinity, as those sites with heavy clay subsoils also had saline groundwater. These effects could be separated if additional sites with clay soils and low-salinity groundwater, or sandy soils and saline groundwater, were studied.

We conclude that the four species can take up groundwater at sites with a combination of shallow depth-to-groundwater with high aquifer transmissivity, low groundwater salinity, light-textured soil with no root-impeding layers, and annual potential evapotranspiration substantially exceeding annual rainfall. When all these conditions are present, plantation annual water use approaches theoretical potential evapotranspiration at most sites, once the canopy has closed.

We have suggested that groundwater uptake in the Green Triangle is partly a function of depth-to-the watertable. For trees to use groundwater, their roots must have penetrated to the depth of the capillary fringe above the watertable. Tree roots soon after planting are very shallow (<0.3 m). Clearly, it must take time for the root system to develop as individual trees grow in size and for roots to extend deep enough to access groundwater. Roots might continue to penetrate to greater depths as the trees age. This raises the question of whether there is a maximum depth for significant groundwater uptake. The results from the Green Triangle suggest this depth is somewhere between 6 and 8 m. Whether this is an indication of species maximum rooting depth, or resistance to water movement through the soil-root-tree-atmosphere pathway is not known.

At some sites, trees which currently are not using groundwater might eventually do so. However, all sites where trees used groundwater were doing so when measurement began at 3–5 years of age. At five eucalypt sites in the Green Triangle (Sites 5, 8 and 9) and the Riverina (Sites 17 and 18) trees were not using groundwater when measurements began at 3 or 4 years of age and still were not doing so by 5–7 years of age. In *P. radiata* in the Green Triangle, trees at the two youngest sites of this species (Sites 10 and 11) were already using groundwater when measurements began at 4 years of age, one from a watertable at 6-m depth. The five *P. radiata* sites which used no significant groundwater (Sites 12–16) were considerably older (age range 14–32 years). Site 12, with a watertable at 4.5 m, but a root-impeding layer at 1.2-m depth, used no groundwater. These trees were 28–31 years old during the period of measurement. Presumably, their roots would have penetrated to the watertable by then if they were going to. The trees at Sites 13 and 14, with watertables at ~8.5-m depth, were not using groundwater by the time measurements ceased at Ages 18 and 24 years. Thus, there was no evidence that accessibility of groundwater increased with tree age after canopy closure. We are not aware of many studies reporting groundwater uptake from deeper than ~5 m. Most studies of planted trees determined groundwater uptake from watertables only a few metres below the ground surface (Cramer et al. 1999; Morris and Collopy 1999; Thorburn 1999; Vertessy et al. 2000). However, O’Grady et al. (2006) inferred groundwater uptake by some trees in remnant riparian communities from up to 10-m depth. Species rooting depth, depth-to-groundwater and the availability of other water sources are all likely to
be important in determining groundwater use by vegetation (O’Grady et al. 2006).

Species differences in water use and groundwater uptake

Although our study was not designed to provide valid statistical comparisons of water use between species, the results do provide some indication of whether evapotranspiration differed between species. At most sites, only a single species was present, but one plantation in the Riverina included plots of E. grandis and C. maculata.

In the Green Triangle, there was no obvious difference in mean annual transpiration or evapotranspiration between P. radiata and E. globulus. Both species used some groundwater at locations where the watertable was within 6 m of the ground surface and where there were no distinct root-impeding layers. Annual interception loss, as a percentage of rainfall, was higher in P. radiata; however, this was balanced by lower soil evaporation. In both species, the total of interception loss and soil evaporation averaged ∼46% of annual rainfall, with similar variation between P. radiata and E. globulus sites (Table 3).

Sites 20 and 21 in the Riverina provided some evidence of a species difference in water use. Here, Polglase et al. (2002) observed groundwater uptake of ∼350 mm year⁻¹ higher in C. maculata than in an adjacent stand of E. grandis. Although the two species were not grown together in a statistically valid experimental design, the similarity of soil types under the two sites lead Falkiner et al. (2006) to speculate the difference was related to species, not soil. A study of fine-root distributions under each species in this plantation revealed a higher root-length density in the capillary fringe above the watertable in C. maculata than in E. grandis (Falkiner et al. 2006). Differences between species in the depths from which soil water or groundwater is accessed have been reported in mixed stands of native riparian vegetation (O’Grady et al. 2006) and mixed-eucalypt tree belts (White et al. 2000), indicating it is not uncommon for different tree species growing under the same site conditions to have different patterns of water uptake, even within the one genus.

Implications for groundwater management

Less than 20 km² of eucalypt plantations, in woodlots generally <1 km², have been established in the Riverina, some in soil types where root growth to the watertable is restricted. In this region, increased groundwater recharge associated with irrigation has resulted in rising saline water tables, posing a significant risk to the sustainability of agriculture. Establishment of tree plantations in strategic locations might be one way to ameliorate this risk. Polglase et al. (2002) suggested that establishment of ∼100 km² of plantations on sandy soils over prior streams, where trees would be able to take up groundwater of low salinity, would be sufficient to balance the excess groundwater recharge from irrigation in the region. These farm-forestry plantations might also have other economic and environmental benefits, such as wood production, carbon sequestration and enhancement of biodiversity.

In the Green Triangle, plantations have been grown on a commercial scale for many decades and support an important wood-processing industry in the region. In south-eastern South Australia, groundwater management plans already account for the lower rates of groundwater recharge under plantations than for pastures. However, no account has been taken of the possibility of groundwater uptake by trees in locations with shallow depth-to-groundwater and light-textured soils. Since the late 1990s, ∼350 km² of E. globulus plantations have been established on ex-pasture in an area to the west and north-west of Penola where depth-to-groundwater is generally shallow. The potential for these plantations to influence groundwater levels is currently being examined. More information is also being collected on the dependence of wetlands in this area on groundwater. Groundwater management plans in some parts of the region will be revised in the next few years to

Table 3. Interception, soil evaporation and transpiration

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more accurately account for the effects of various land uses on groundwater resources. Ultimately, policies for natural-resource management need to include the broadest possible analysis of all the economic, social and environmental benefits of alternative land uses.

Acknowledgments
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Plantations and groundwater


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