Tree Physiology 16, 211–219

Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent

B. J. MYERS,[1] S. THEIVEYANATHAN,[1] N. D. O'BRIEN[1] and W. J. BOND[2]

[1] *CSIRO Division of Forestry, P.O. Box 4008, Canberra, ACT 2600, Australia*

[2] *CSIRO Division of Soils, GPO Box 639, Canberra, ACT 2601, Australia*

Received March 2, 1995

Summary We studied the growth and water balance of young plantations of *Pinus radiata* D. Don and *Eucalyptus grandis* W. Hill ex Maiden. irrigated with effluent for 3 years in a climate of high net evaporation. The plantations were irrigated weekly with secondary-treated municipal effluent at the estimated water-use rate, or at nominally twice or half this rate. Control plots were irrigated with bore water at their estimated water-use rate.

Both species grew rapidly when irrigated with either effluent or bore water. The eucalypts irrigated with effluent at the estimated water-use rate closed canopy in 24 months, and at 34 months, mean dominant height was 12.1 m, stand basal area was 12.2 $m^2 ha^{-1}$, volume was 51.2 $m^3 ha^{-1}$, LAI was 5.7, and foliage mass was 6.5 Mg ha^{-1}. The pines in the corresponding effluent treatment had not closed canopy by 34 months. At this time, mean height was 5.0 m, stand basal area was 9.6 $m^2 ha^{-1}$, volume was 29.7 m^3 ha^{-1}, LAI was 3.5, and foliage mass was 7.3 Mg ha^{-1}. Water use by eucalypts was consistently higher than by pines, commensurate with their more rapid early growth, but the difference was not in proportion to the difference in leaf area. In the third year (when the eucalypts had a closed canopy), the eucalypts used 22% more water than the pines, but the annual mean LAI of the eucalypts was three times greater than that of the pines. The results suggest that (1) plantation water use by the two species on the same site will be similar for the same stage of canopy development, (2) eucalypts are not inherently more profligate consumers of water than pines when soil water is not limiting, and (3) stomatal control limits growth and water use of *E. grandis* in arid environments.

Keywords: effluent irrigation, evapotranspiration, water balance.

Introduction

In recent years, eutrophication of river systems has caused frequent large blooms of toxic blue-green algae in many parts of Australia. One cause of this eutrophication is the discharge of nutrients into rivers, particularly phosphorus (P) and nitrogen (N), much of which comes from sewage effluent (GH&D 1991). Irrigation of tree plantations is becoming a popular alternative to river discharge for treating sewage effluent (Stewart and Boardman 1991). The preference for irrigating tree plantations over agricultural crops has been attributed to the high possible growth rates (Cromer et al. 1983, Stewart and Flinn 1984, Stewart et al. 1988) and the reported high rates of water use (Morris and Wehner 1987, Stewart 1988). There is also a common perception that eucalypts will use water at a higher rate than pines.

Environmental Protection Authority requirements on allowable loading rates for effluent irrigation stipulate that drainage must be minimized, except to maintain a salt balance in the root zone, to reduce the risk of contamination of groundwater with nitrates, salts or toxins (Thomas 1991, EPA NSW 1992). Compliance with these regulations requires a detailed understanding of the water balance of irrigated plantations. The few data that are available on water-use rates of irrigated plantations are contradictory. Morris and Wehner (1987) reported annual crop factors of 1.4 to 1.9 times pan evaporation and maximum daily water-use rates of 20 mm in summer (January) by 3-year-old eucalypt plantations irrigated with effluent in arid western Victoria. Dunin and Mackay (1982) reported a maximum daily water use of 7 mm in summer for a native eucalypt forest, with nonlimiting soil water availability, in coastal New South Wales. Myers and Talsma (1992) reported annual crop factors of up to 1.2 times pan evaporation and maximum daily water-use rates of 8 mm in summer (January) by 14-year-old irrigated *Pinus radiata* D. Don plantations in the Australian Capital Territory. Although these data appear to support the concept that eucalypts are more profligate consumers of water than pines, a valid comparison cannot be made because of the large differences in climates, soils, stage of stand development and experimental methodologies.

In 1991, CSIRO established the Wagga Wagga Effluent Plantation Project to measure and model the pathways through which effluent-irrigated eucalypt (*Eucalyptus grandis* W. Hill ex Maiden.) and pine (*P. radiata*) plantations use water and nutrients, with the aim of developing guidelines for the design and management of such enterprises (Myers et al. 1992, Polglase et al. 1994). This paper compares the growth and water use of these eucalypt and pine plantations during the first 3 years of effluent irrigation.

Methods

Site and stand description

The plantation was established in August–September 1991 adjacent to the Forest Hills sewage treatment works near Wagga Wagga, NSW. Both *P. radiata* and *E. grandis* were planted at 2×3 m spacing (1667 trees ha^{-1}). The pine plantation was established with cuttings from 12 genotypes (four clones from each of three families). The eucalypt plantation was established with seedlings of a single provenance from the subtropical north coastal area of NSW.

Mean annual rainfall at the site is 570 mm with a slightly winter-dominant distribution. Annual pan evaporation is 1860 mm, varying from a monthly low of 35 mm in June and July to a peak of 320 mm in January. Mean minimum and maximum temperatures are 3 and 31 °C, respectively. There is an average of 13 frosts per year. The suitability of the climate for land application of effluent is evident from the long-term average net evaporation for Wagga Wagga (pan evaporation minus rainfall) (Figure 1). Meteorological data (rainfall, air temperature, humidity, solar radiation, pan evaporation, wind speed, wind run and direction) are recorded at the site as hourly means or totals using an automatic weather station (Starlog, UNIDATA Australia, Perth, Western Australia).

The land was previously used for wheat cropping followed by about 10 years under pasture and sheep grazing during which phosphate fertilizers were applied on several occasions. The soils are a Red Chromosol and two Red Kandosols (Isbell 1993) (red podsolic and red earth, respectively, in the Great Soil Group Classification, Stace et al. 1968). They consist of a sandy loam or sandy clay-loam A horizon (20–45 cm deep) overlaying a sandy-clay to medium-clay B horizon. Before treatment, the soils had low salinity, were slightly acidic (pH 5.3 to 4.6) and well drained. Saturated hydraulic conductivity declined from 850 mm day^{-1} at 15 to 45 cm depth to 35 mm day^{-1} at 80 to 120 cm depth.

Experimental design and treatments

In both the *P. radiata* and *E. grandis* plantations, four irrigation treatments were applied to duplicate 0.2-ha plots. The rate of effluent irrigation was based on the water-use rates of the plantations and was varied seasonally in response to the climate and canopy development. Trees in the medium (M) treatment were irrigated with effluent at the estimated water-use rate of the plantation less rainfall. Trees in the high (H) treatment received 70–75% more effluent than trees in the M treatment, whereas trees in the low (L) treatment received nominally half as much effluent as trees in the M treatment. Trees in the fourth treatment were irrigated with bore water (W), also at the water-use rate of the plantation less rainfall.

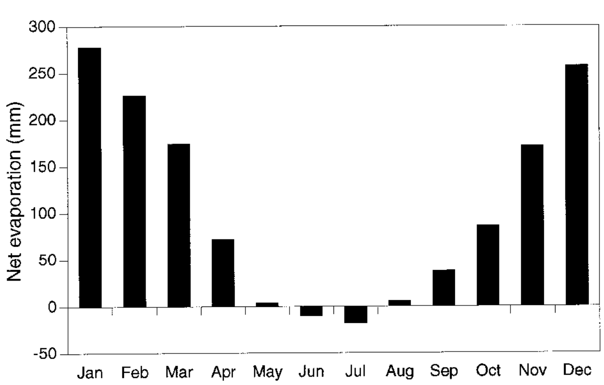

Figure 1. Twenty-five-year mean monthly net evaporation at Wagga Wagga, New South Wales.

For the purpose of irrigation scheduling, plantation water use was estimated by the water balance equation over 14-day intervals. Inputs were rainfall, canopy interception, irrigation volume and changes in soil water storage. Soil water content of all 16 treatment plots and the irrigated pasture was measured with a neutron probe every 2 weeks in three or six access tubes per plot at nine depths to 2 m.

Plots were irrigated weekly. The amount applied to the M and W plots during the first week after soil water measurement was the volume required to fill the top meter of soil to 90% of the drained upper limit (DUL) of soil water holding capacity. The DUL was taken as the wettest drained profile recorded, 2 days after substantial rain in spring (after Ritchie 1981). A refill level of 90% was used to reduce the risk of drainage occurring if rain fell shortly after irrigation. The amount of effluent applied during the second week equaled the estimated plantation water use for that week, calculated from:

$$\mathrm{WU} = \frac{\mathrm{W}_{t_2} - \mathrm{W}_{t_1} + \mathrm{IR_n} + P_\mathrm{n}}{t_2 - t_1}, \tag{1}$$

where WU is the average daily water used between times t_1 and t_2, W_{t_1} and W_{t_2} are soil water storage measured at times t_1 and t_2, respectively, and IR_n and P_n are the net irrigation applied and net precipitation received between t_1 and t_2, respectively (see below for method of estimating interception loss).

Secondary-treated municipal sewage effluent and bore water were distributed by means of an under-tree micro-sprinkler irrigation system at 4.6 mm h^{-1}. Irrigation scheduling was controlled and logged by a computer-based irrigation program (IRRICOM, Peter Cornish and Associates Pty. Ltd., Canberra, Australia).

The effluent was alkaline and contained moderately low concentrations of nutrients (average concentrations of 12 mg l^{-1} total N and 5 mg l^{-1} total P). The sewage was treated in a Pasveer channel to remove some of the C and N through alternating nitrification and denitrification cycles. The total elemental loading rates in the eucalypt and pine M treatments during the first 3 years were 241 and 198 kg N ha^{-1} and 121 and 100 kg P ha^{-1}, respectively. The added nutrients exceeded the accumulation capacity of the trees. Nitrogen and P were almost totally absent in the bore water.

Growth measurements

The height and diameter at breast height (DBH) of all trees were measured in both midsummer and midwinter. After the third growing season, only mean dominant height (largest 75 trees ha^{-1}) was measured in the eucalypts.

Each winter, 15–25 trees per species were harvested for biomass analysis. Each summer, five trees per species were harvested. Sample trees, selected across the range of treatments and tree size classes, were separated into foliage, branches, stem wood and bark to determine partitioning of aboveground biomass and nutrients. Allometric relationships between mass or nutrient content of a component and height or diameter of the sample trees were used to estimate the total biomass or nutrient content of that component for the plantation. Allometric relationships were not significantly different between irrigation treatments, so all trees contributed to a single equation for each component at each harvest. Leaf area index (LAI) was also estimated each summer and winter based on allometric relationships with height for the pines and DBH for the eucalypts. Leaf area of green foliage samples was measured with a leaf area meter (Delta T Image Analysis System, Delta T Devices Ltd., Cambridge, U.K.).

Water-use estimates

Seasonal water balance was calculated for nonirrigated and irrigated periods (Figure 2) that equate approximately to periods when rainfall exceeded evaporation and *vice versa*. Soil water storage to 2 m depth was calculated from soil water contents measured with a neutron probe (503 Hydroprobe, Campbell Pacific, Pachero, CA) every 2 weeks. Neutron calibration equations were obtained at the site for depths of 0.1, 0.2 and 0.3 m. Soil water measurements began progressively during the first irrigation season as access tubes were installed, and complete data were available only for the second half of the season. Because of the high conductivity of the soil, neither surface runoff nor subsurface lateral flow (as monitored by logging piezometers in the H treatments) have been recorded at this site, even during intense rainfall events. The main mechanism for water loss, therefore, other than evapotranspiration and interception, was drainage.

The water balance equation was solved for each 14-day cycle. Because irrigation was designed to leave a soil water deficit in the top meter of 25 mm or more, it was assumed that when there was less than 25 mm of rain in a 14-day cycle, drainage below 1 m (the arbitrarily defined depth of the root zone) would be zero. A crop factor was calculated for each of these dry 14-day cycles as the ratio between the calculated water use (Equation 1) and measured pan evaporation (E_p).

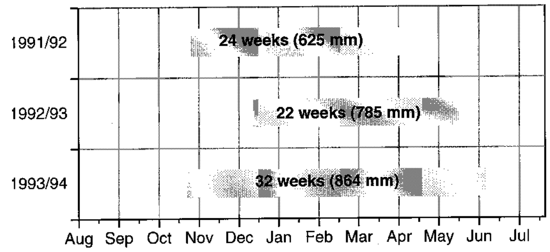

Figure 2. Length of irrigation season and the amount of effluent applied to the eucalypts in the M treatment during the first 3 years.

When more than 25 mm of rainfall occurred in a cycle, a crop factor for that wet cycle was calculated as the mean of the crop factors of the preceding and subsequent dry cycles. This was applied to the measured E_p to estimate the water use for the cycle. In this way, the water use of every 14-day cycle was either measured (dry cycles) or estimated (wet cycles) and accumulated to obtain monthly and seasonal water-use estimates. Only 31% of all cycles were wet, and these occurred predominantly in winter when up to 50% of cycles were wet. The proportion of wet cycles during the irrigation seasons was zero in the second year and 15% in the third year.

Water-use calculations were based on net irrigation and rainfall, i.e., total minus interception loss. Interception was measured during several rainfall and irrigation events in the M-treated pine and eucalypt plantations during the third season of irrigation using interception troughs and Time Domain Reflectometry (TDR). Scaled from these measurements, and those reported by Myers and Talsma (1992) for irrigated closed-canopy *P. radiata* stands, interception loss was calculated as a fixed rate per event within an irrigation season. The rate differed between rainfall and irrigation. The rates of interception loss per event are shown in Table 1.

The following assumptions were made to derive the interception rates for earlier years from those measured in the third season of irrigation: (1) rainfall interception increased approximately in proportion to tree canopy mass; (2) summer and winter interception varied approximately in proportion to E_p; (3) interception loss by pasture was estimated using the model developed for wheat by O'Leary et al. (1985) assuming an average LAI of 1.5; and (4) in 1991–92, interception by tree foliage plus pasture was the same as by pasture alone.

Table 1. Scale of interception loss (mm per event) used to calculate total interception losses. Values in bold were measured; other values were scaled from the measured values.

	1991–92	1992–93		1993–94	
	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated
Rainfall					
Eucalypt + pine	0.5	0.5	1.0	1.0	**2.0**
Pasture	0.5	0.25	0.5	0.25	0.5
Irrigation					
Eucalypt	0.5		2.0		**2.0**
Pine	0.5		2.0		**4.0**
Pasture	0.5		0.5		0.5

Drainage for each period was calculated as total irrigation plus rainfall received, less interception loss and water use. Cumulative drainage below 1 m during the first 2 years of the trial (June 1991 to June 1993) was also measured independently, using the chloride mass balance method between intensive soil samples (Bond et al. 1995). This cumulative measure was based on the difference between the total amount of chloride added in irrigation over 2 years, the change in chloride in the soil profile and chloride concentration of soil leachate measured monthly.

The total plantation water-use estimates include transpiration from trees and pasture and evaporation from soil. The water use attributable to transpiration by the tree component was calculated as follows. Before canopy closure, the proportions of the plantation area covered by trees and pasture were estimated from photographs taken from fixed positions at 6-month intervals. It was assumed that the pasture between the trees was transpiring at the same rate as was measured in the irrigated pasture plots. Transpiration from the trees was calculated as total plantation water use less pasture transpiration.

After canopy closure in the eucalypt plantation (third season of irrigation), total water use was reduced to two components only—evaporation from soil and transpiration from trees. Evaporation from soil was assumed to be proportional to the amount of net radiation (I) that penetrated to the soil surface, calculated as a function of LAI:

$$I = \exp(-k\mathrm{LAI}). \qquad (2)$$

A light extinction coefficient (k) of 0.5 was used (Jarvis and Leverenz 1983).

Results and discussion

Climate

Except for the 4 months after planting, the first 3 years of the project were considerably wetter and with less pan evaporation at the site than the long-term averages (Figure 3). Rainfall in the first 3 years totaled 610, 740 and 810 mm, respectively, compared to the long-term average of 570 mm. During the winter and spring of 1992, irrigation was not possible for the 8 months from May through December. The rainfall in 1992 (945 mm) was just 40 mm short of the wettest year on record. Pan evaporation in the 3 years was 1680, 1440 and 1480 mm, respectively, compared to the long-term average of 1860 mm. The effect of these weather patterns has been that the length of time during which effluent could be applied was shorter and the monthly loading rates were lower than those predicted by the WATLOAD hydraulic loading model for design of effluent-irrigated plantations (Myers 1992).

Stand growth

Both species grew rapidly when irrigated with either effluent or bore water, and there were significant differences between the species (Table 2, Figures 4 and 5). Eucalypts in the M treatment closed canopy in 24 months and continued a gradual increase in foliage mass to 6.5 Mg ha^{-1} at 34 months. This

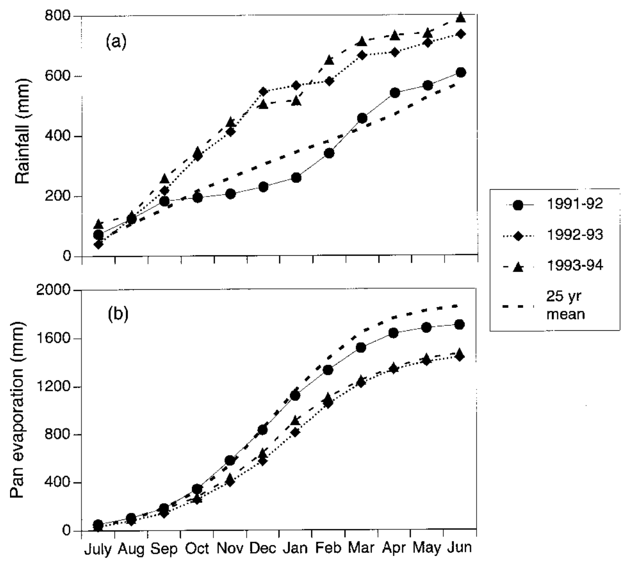

Figure 3. Cumulative monthly (a) rainfall and (b) pan evaporation from 1991 to 1994 and 25-year mean.

Table 2. Mean stand height (H), mean dominant height (MDH), mean diameter at breast height (DBH), stand basal area (BA), volume (V), leaf area index (LAI) and foliage mass (M_f) after three seasons of irrigation. Treatment regimes are defined in the text.

Treatment	H (m)	MDH (m)	DBH (cm)	BA (m^2 ha^{-1})	V (m^3 ha^{-1})	LAI	M_f (Mg ha^{-1})
Pine							
High	5.1	–	8.9	10.6	32.8	3.7	7.7
Medium	5.0	–	8.6	9.6	29.7	3.5	7.3
Low	4.8	–	8.0	8.4	25.6	3.3	6.9
Water	5.3	–	8.8	10.1	31.7	3.6	7.6
Eucalypt							
High	9.4	12.0	9.6	12.6	53.1	5.9	6.8
Medium	9.4	12.1	9.6	12.2	51.2	5.7	6.5
Low	8.7	11.0	8.5	9.9	39.7	4.2	4.8
Water	8.4	11.3	9.0	11.0	44.8	4.8	5.5

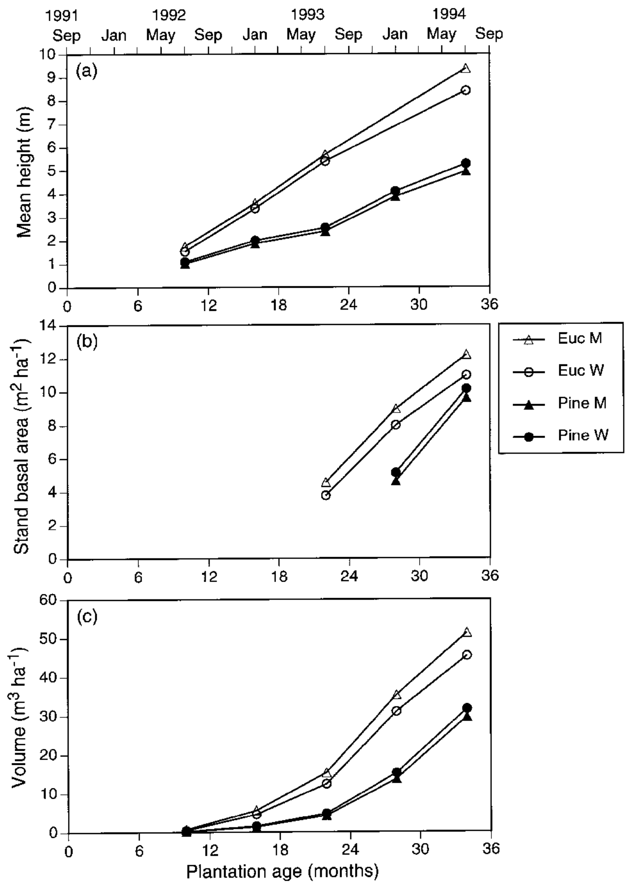

Figure 4. Cumulative growth in (a) mean height, (b) basal area and (c) volume of *E. grandis* and *P. radiata* stands irrigated with treated municipal effluent (M) or bore water (W) for 3 years.

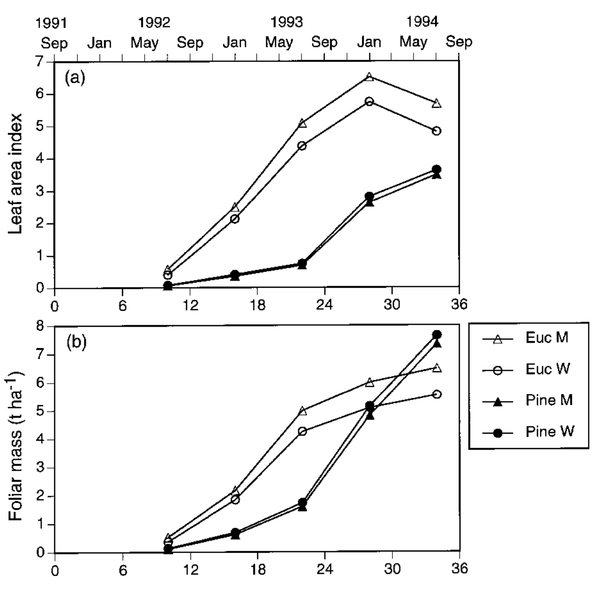

Figure 5. Foliage development in stands of *E. grandis* and *P. radiata* irrigated with treated municipal effluent (M) or bore water (W) for 3 years: (a) leaf area index and (b) foliage mass.

value is similar to the equilibrium value of 6.5 Mg ha^{-1} reported for a range of rain-fed *E. grandis* plantations in northern New South Wales (Bradstock 1981). The LAI peaked at 6.5 at 28 months and subsequently declined by 13 to 16% (Figure 5), reflecting limited defoliation by chrysomelid beetles. Mean annual volume increment (MAI) at 3 years was 17.1 m^3 ha^{-1} $year^{-1}$, and current annual increment (CAI) was 36.0 m^3 ha^{-1} $year^{-1}$. Total aboveground biomass at 3 years was 43.9 Mg ha^{-1}, which is considerably higher than that reported by Bradstock (1981) or Turner (1986) for rain-fed eucalypt stands.

Growth rates of *P. radiata* in all treatments were greater than those reported for fertile sites in New Zealand and Australia (Forrest and Ovington 1970, Madgwick et al. 1977). In contrast to the eucalypts, however, the pines in the M treatment had not yet closed canopy by 3 years and had achieved only about 50% of their projected maxima (Snowdon and Benson 1992). At this time, both the LAI and foliage mass were still increasing, and the foliage mass had exceeded that of the eucalypts. The MAI at 3 years was 9.9 m^3 ha^{-1} $year^{-1}$, and CAI was 25.4 m^3 ha^{-1} $year^{-1}$. Total aboveground biomass at 3 years was 23.6 Mg ha^{-1}.

The greater nutrient addition in the M treatment than in the W treatment (Polglase et al. 1994) resulted in faster development of leaf area, greater volume and biomass accumulation, and higher predawn leaf water potentials in the eucalypts. The same response was not found in the pines, because the mineralization rate of the native N at the site was in excess of that required by the pine trees during their slow early growth (Polglase et al. 1995).

Volume growth of the eucalypts and pines in treatment H was only 4 and 10% greater, respectively, than in treatment M, even though the trees cumulatively received 70 and 75% more effluent water and nutrients, respectively, over the 3 years. This demonstrates that growth in the M treatment was not limited by water or nutrient availability. Because of deliberate over-irrigation, much of the applied water, and hence nitrogen, leached past the root zone. In both species, growth was slower in the L treatment than in the W treatment, indicating that the site was limited more by water availability than by nutrients.

A threefold variation in growth rate (and by implication, water-use rate) has been reported for effluent-irrigated *E. grandis* in eastern Australia. Stem volume at age 3 years at Wagga Wagga was about half that of a fertilized plantation in the humid subtropics at Gympie, Queensland, with more than 1100 mm rainfall (Cromer et al. 1993), and it was nearly double that of effluent-irrigated stands at Robinvale in arid western Victoria (calculated from Stewart and Flinn 1984 and D. Flinn, personal communication). A correlation exists between stand volume at age 3 years and mean annual pan evaporation for six plantation sites in contrasting climates (Figure 6). These variations may be explained partly by a strong stomatal response to increasing vapor pressure deficit (VPD) in this subtropical species (Leuning 1990), and they bring into question the validity of predicting growth or water-use rates in arid climates based on results in more humid climates. We conclude that, insofar as water use can be inferred from growth, a simple crop factor relating plantation water use

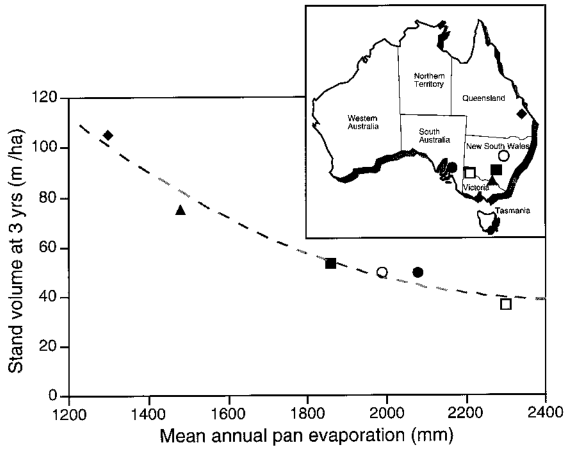

Figure 6. The relationship between measured or estimated stand volume at age 3 years and mean annual pan evaporation for five plantations of *E. grandis* in eastern Australia irrigated with effluent. (Gympie plantation was not irrigated with effluent but was fertilized and well watered for 3 years; R. Cromer, personal communication.) Symbols and sources: Wagga Wagga ■; Gympie ◆ (Cromer et al. 1993); Wodonga ▲ (Stewart et al. 1988 and T. Baker, personal communication); Dubbo ○ (calculated from Wilkinson 1993); Bolivar ● (D. Hanna, S. Shaw, R. Boardman and G. Schrale, unpublished report); Robinvale □ (calculated from Stewart and Flinn 1984 and D. Flinn, personal communication).

to pan evaporation cannot reliably be used over a wide range of climates to predict water use, because it does not account for the effect of VPD on stomatal response. Data do not exist to allow comparison of *P. radiata* growth rates under irrigation across a range of climates, but a result similar to that of *E. grandis* might be expected, because radiata pine also shows a strong stomatal response to VPD in irrigated stands (Heinrich and Sands 1990).

Water balance

The water balances for the plantations receiving the M and W treatments and for the pasture during the first 3 years are presented in Table 3. Estimates of water use before soil water measurements were made (shown in italics) are approximations based on relationships between measured irrigated and nonirrigated periods for pasture in the third year. The water balance approach of calculating water use during the 14-day wet cycles from the crop factors of adjacent 14-day dry cycles resulted in slight overestimates of plantation water use and crop factors. A comparison of the water balance estimate of drainage with the cumulative drainage measured over a 2-year interval from June 1991 to June 1993 by the chloride mass balance method (Bond 1995) showed that, for both species, the water balance approach overestimated the annual crop factor by 1 to 4%.

During the irrigated portion of the first year, the crop factor of the plantations was similar to the pasture crop factor of the following two irrigation seasons. As LAI and ground cover increased during the second and third seasons, the trees began to dominate plantation water use, and the crop factors increased relative to the pasture crop factor. The relationship between annual crop factor and annual mean LAI (Figure 7) suggests that, under irrigated conditions at Wagga Wagga, plantation water use by the two species will be similar at the same stage of canopy development. This is contrary to the common perception that eucalypts are inherently more profligate consumers of water than other species (Poore and Fries 1985).

The eucalypts had consistently higher water use than the pines, commensurate with their more rapid early canopy development, but the difference was not in proportion to the difference in leaf area. During the third season, the closed-canopy eucalypt plantation receiving the M treatment used only 22% more water than the corresponding pine plantation (crop factor of 0.93 versus 0.76), whereas the average LAI of the eucalypts was three times greater than that of the pines. A portion of the total water use by the pine plantation can be attributed to water uptake by the pasture before canopy closure. The proportion of total plantation water use attributable to the trees is shown in Table 4. After canopy closure in the eucalypts, when annual mean LAI was 6.1 and 5.3 in the M and W treatments, respectively, 5 to 7% of the water loss was by soil evaporation.

Eucalypts in both the M and W treatments had higher maximum daily water use than the corresponding pines (Table 5) and higher water-use rates throughout the irrigation season (Figure 8). Water-use rates were higher in eucalypts in the M treatment than in the W treatment. Figure 8 shows that the pattern of daily water use in the eucalypts in the M treatment was similar in the last 2 years of treatment, and that the difference between pines and eucalypts decreased in the third year as the difference in their leaf areas decreased.

The maximum monthly mean daily water use by closed-canopy effluent-irrigated eucalypts of 7.5 mm day^{-1} (Figure 8) was less than the 8.1 mm day^{-1} measured in irrigated and fertilized 14-year-old closed-canopy stands of *P. radiata* in the Australian Capital Territory (ACT) (Myers and Talsma 1992). Total annual water use was also less at Wagga Wagga (1403 mm compared to 1495 mm), even though pan evaporation for the period was 34% higher than at the ACT site. Leaf area of both stands was close to maximum. The lower water-use rates at Wagga Wagga are primarily a result of the strong stomatal response to increasing VPD shown in *E. grandis* (Leuning 1990) and in many other species (Stewart 1981). This response results in lower crop factors in more arid climates. The maximum annual crop factor for the closed-canopy irrigated pines in the cool temperate climate of the ACT site (pan evaporation of 1127 mm) was 1.19, whereas that for the closed-canopy M-treated eucalypts in the more arid climate at Wagga Wagga (pan evaporation of 1508 mm) was 0.93. This again demonstrates the fallacy of predicting water-use rates across vastly differing climates based on pan-evaporation crop factors. In this case, water use at Wagga Wagga would have been overestimated by 28%. However, a model such as the Penman-Monteith equation, which incorporates a function describing stomatal response to VPD (Monteith 1973), produced an accurate estimate of plantation water use at Wagga Wagga in various seasons (Figure 9).

Table 3. Seasonal plantation water balance (mm) of eucalypts, pines and pasture irrigated with effluent (Medium) and bore water (Water) for 3 years.

	1991–92			1992–93			1993–94		
	Nonirrigated	Irrigated	Total	Nonirrigated	Irrigated	Total	Nonirrigated	Irrigated	Total
Starting	1/9/91	7/11/91		24/4/92	24/12/92		28/5/93	4/11/93	
Finishing	6/11/91	23/4/92		23/12/92	27/5/93		3/11/93	16/6/94	
Number of weeks	9	24	33	35	22	57	24	32	56
Total precipitation	75	272	347	654	167	821	438	401	839
Pan evaporation	275	1235	1510	615	860	1475	336	1172	1508
Eucalypt (Medium)									
Total irrigation		625	625	0	785	785	0	864	864
Interception loss		16	16	30	60	90	33	126	159
Drainage		239	239	115	113	228	64	77	141
Water use	*209*	642	851	509	779	1288	341	1062	1403
Crop factor	*0.76*	0.52	0.56	0.83	0.91	0.87	1.01	0.91	0.93
Eucalypt (Water)									
Total irrigation		614	614	0	655	655	0	785	785
Interception loss		15	15	30	61	91	33	126	159
Drainage		229	229	164	91	255	102	90	192
Water use	*209*	642	851	460	670	1130	303	970	1273
Crop factor	*0.76*	0.52	0.56	0.75	0.78	0.77	0.90	0.83	0.84
Pine (Medium)									
Total irrigation		620	620	0	549	549	0	732	732
Interception loss		15	15	30	61	91	33	178	211
Drainage		235	235	167	95	262	176	37	213
Water use	*209*	642	851	457	560	1017	229	918	1147
Crop factor	*0.76*	0.52	0.56	0.74	0.65	0.69	0.68	0.78	0.76
Pine (Water)									
Total irrigation		588	588	0	493	493	0	695	695
Interception loss		15	15	30	63	93	33	184	217
Drainage		203	203	174	76	250	156	64	220
Water use	*209*	642	851	450	521	971	249	848	1097
Crop factor	*0.76*	0.52	0.56	0.73	0.61	0.66	0.74	0.72	0.73
Pasture (Medium)									
Total irrigation				*0*	328	328	0	535	535
Interception loss				*15*	19	34	8	30	38
Drainage				*208*	60	269	161	258	419
Water use				*431*	416	847	269	648	917
Crop factor				*0.70*	0.48	0.57	0.80	0.55	0.61

In summer 1993–94, peak rates of water use by the eucalypts were relatively high (7.6 to 7.9 mm day^{-1}) compared with other published rates summarized by Lima (1984). In Australia, plantation water use by small irrigated woodlots will be higher than by extensive plantations, whether irrigated or not, because advected energy will increase transpiration. The water-use rates in spring (November) of 4 to 6 mm day^{-1} (Figure 8) compare closely with rates of 4 to 5 mm day^{-1} measured in *P. radiata* in October by the heat pulse technique in a nearby area of New South Wales (Hatton and Vertessy 1990). The data do not support the high water-use rates of 20 mm day^{-1} and annual crop factors of 1.4 to 1.9 times pan evaporation reported for 3-year-old effluent-irrigated eucalypts by Morris and Wehner (1987).

Conclusions

The growth of both *E. grandis* and *P. radiata* under effluent irrigation for 3 years at Wagga Wagga was high. However, *E. grandis* was less productive at Wagga Wagga than in some other effluent-irrigated plantations growing in areas of lower evaporative demand, but it was more productive than plantations growing in areas of higher evaporative demand, suggesting that a strong stomatal response to VPD in this subtropical species limits its growth and water use in harsher climates even when soil water and nutrients are not limiting.

Eucalyptus grandis showed faster early growth than *P. radiata* and closed canopy in 2 years compared to an estimated 4 years for *P. radiata*. Commensurate with this more rapid early canopy development, plantation water use of the euca-

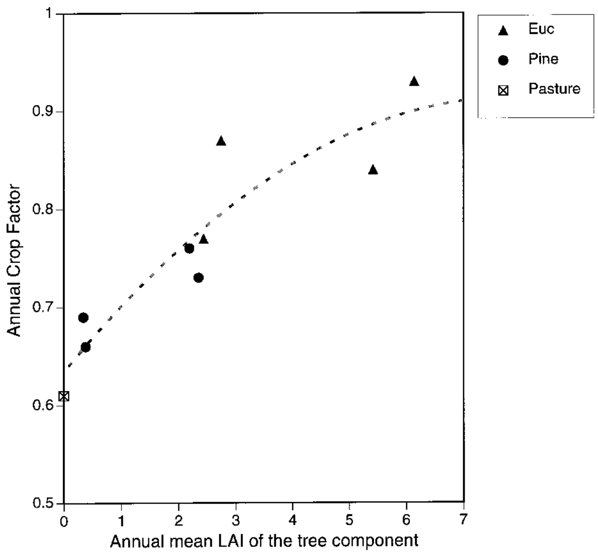

Figure 7. The relationship between annual crop factor and annual mean LAI of the tree component for eucalypts and pines during the second and third growing seasons.

Table 4. Tree water use as a proportion of total plantation water use (%): Medium = irrigated with effluent, Water = irrigated with bore water.

Season	Eucalypt (Medium)	Eucalypt (Water)	Pine (Medium)	Pine (Water)
1991–92	12	12	2	2
1992–93	72	68	25	21
1993–94	95	93	60	59

Table 5. Maximum daily plantation water use (mm day^{-1}, 14-day means) during the second and third irrigation seasons: Medium = irrigated with effluent, Water = irrigated with bore water.

Season	Eucalypt (Medium)	Eucalypt (Water)	Pine (Medium)	Pine (Water)	Pasture
1992–93	8.0	6.7	5.4	5.3	3.8
1993–94	7.9	7.6	6.4	6.4	4.9

lypts was greater than that of the pines. However, plantation water use before canopy closure was dominated by water use of the pasture so the difference in water use between the species was not in direct proportion to their leaf area. We conclude that plantation water use of the two species on the same site will be similar at the same stage of canopy development, and that eucalypts are not inherently more profligate consumers of water than pines when soil water is not limiting. We estimated that closed-canopy eucalypts have a maximum monthly mean daily water-use rate of less than 8 mm day^{-1} and an annual crop factor between 0.84 to 0.93 times pan evaporation.

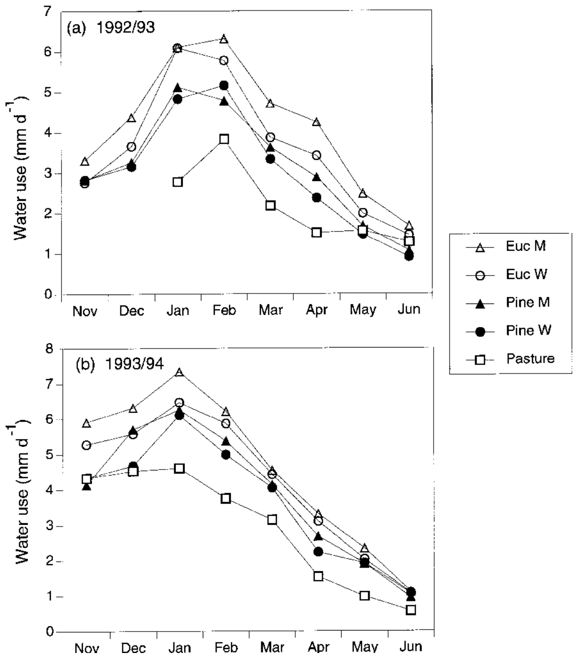

Figure 8. Seasonal patterns of daily plantation water use (monthly means) by stands of *E. grandis* and *P. radiata* and pasture irrigated with treated municipal effluent or bore water during the (a) 1992–93 and (b) 1993–94 seasons.

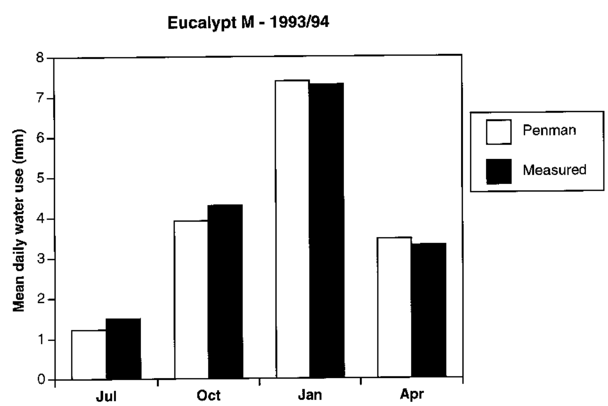

Figure 9. Mean daily water use of the eucalypts in the M treatment at different seasons during 1993–94 estimated from the water balance and compared with Penman-Monteith predictions.

Acknowledgments

The Wagga Wagga Effluent Plantation Project is financially supported by the Land and Water Resources R & D Corporation, Murray Darling Basin Commission, NSW Department of Land and Water Conservation (formerly NSW Public Works) and receives in kind support from Wagga Wagga City Council and Tahara Pastoral Pty. Ltd. We gratefully acknowledge the competent technical support of Mark Tunningley, Ian Craig, Leroy Stewart and Gordon McLachlan.

References

Bond, W.J., P.J. Polglase, C.J. Smith, R.A. Falkiner, B.J. Myers and S. Theiveyanathan. 1995. Effluent irrigation: implications for groundwater. *In* Murray Darling 1995—Groundwater and the Community, Wagga Wagga. Aust. Geol. Surv. Org., Record 1995/61, pp 40–44.

Bradstock, R. 1981. Biomass in an age series of *Eucalyptus grandis* plantations. Aust. For. Res. 11:111–127.

Cromer, R.N., D. Tompkins and N.J. Barr. 1983. Irrigation of *Pinus radiata* with waste water: tree growth in response to treatment. Aust. For. Res. 13:57–65.

Cromer, R.N., D.M. Cameron, S.J. Rance, P.A. Ryan and M. Brown. 1993. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. For. Ecol. Manage. 62:211–230.

Dunin, F.X. and S.M. Mackay. 1982. Evaporation of eucalypt and coniferous forest communities. *In* Proc. 1st Nat. Symp. on Forest Hydrology, Melbourne, pp 18–35.

EPA NSW. 1992. Guidelines for the utilisation of treated wastewater on land. Environment Protection Authority, NSW, 81 p.

Forrest, W.G. and J.D. Ovington. 1970. Organic matter changes in an age series of *Pinus radiata* plantations. J. Appl. Ecol. 7:177–186.

GH&D. 1991. Investigation of nutrient pollution in the Murray Darling River system. Report to Murray Darling Basin Commission by Gutteridge Haskins and Davey Pty. Ltd., 247 p.

Hatton, T.J. and R.A. Vertessy. 1990. Transpiration of plantation *Pinus radiata* estimated by the heat pulse method and the Bowen ratio. Hydrol. Processes 4:289–298.

Heinrich, P.A. and R. Sands. 1990. Water use by trees. *In* Proc. Woodlots Workshop. Ed. M. Dale. Mildura, pp 47–49.

Isbell, R.F. 1993. A classification system for Australian soils: 3rd approximation. CSIRO Division of Soils, Technical Report 2/1993, Canberra, 97 p.

Jarvis, P.G. and J.W. Leverenz. 1983. Productivity of temperate, deciduous and evergreen forests. *In* Encyclopedia of Plant Physiology, Vol. 12D. Physiological Plant Ecology IV. Ecosystem Processes: Mineral Cycling, Productivity and Man's Influence. Eds. O.L. Lange, P.S. Nobel, C.B. Osmond and H. Zeigler. Springer Verlag, Berlin, pp 233–280.

Leuning, R. 1990. Modelling stomatal behaviour and photosynthesis of *Eucalyptus grandis*. Aust. J. Plant Physiol. 17:159–175.

Lima, W.P. 1984. The hydrology of eucalypt forests in Australia. IPEF (Piracicaba) 28:11–32.

Madgwick, H.A.I., D.S. Jackson and P.J. Knight. 1977. Above-ground dry matter, energy, and nutrient content of trees in an age series of *Pinus radiata* plantations. N.Z. J. For. Sci. 7:445–468.

Monteith, J.L. 1973. Principles of environmental physics. Edward Arnold Publishers, London, 241 p.

Morris, J.D. and B.A. Wehner. 1987. Daily and annual water use by four eucalypt species irrigated with wastewater at Robinvale. Dept. of Conservation, Forests and Lands (Victoria), Research Rep. No. 329, 31 p.

Myers, B.J. 1992. Effluent loading rates for irrigated plantations—a water balance model. Aust. For. 55:39–47.

Myers, B.J. and T. Talsma. 1992. Site water balance and tree water status in irrigated and fertilised stands of *Pinus radiata*. For. Ecol. Manage. 52:17–42.

Myers, B.J., R.A. Falkiner and W.J.B. Crane. 1992. The Wagga effluent plantation project—a CSIRO study of sustainable water and nutrient management in effluent-irrigated plantations. *In* Proc. Effluent: Resource Opportunities–Recycled Water Seminar. Recycled Water Co-ordination Committee and AWWA, Wagga Wagga, NSW, Paper No. 7, 8 p.

O'Leary, G.J., D.J. Connor and D.H. White. 1985. A simulation model of the development, growth and yield of the wheat crop. Agric. Syst. 17:1–26.

Polglase, P.J., D. Tompkins, L.G. Stewart and R.A. Falkiner. 1995. *In situ* nitrogen mineralization and leaching in an effluent-irrigated pine plantation. J. Environ. Qual. In press.

Polglase, P.J., B.J. Myers, S. Theiveyanathan, R.A. Falkiner, C.J. Smith, N.D. O'Brien and W.J. Bond. 1994. Growth and water and nutrient balances in the Wagga effluent plantation project. *In* Proc. Expanding Reuse Horizons: Recycled Water Seminar. Recycled Water Co-ordination Committee and AWWA, Newcastle, NSW, pp 163–170.

Poore, M.E.D. and C. Fries. 1985. The ecological effects of *Eucalyptus*. FAO Forestry Paper 59, United Nations, Rome, 87 p.

Ritchie, J.T. 1981. Soil water availability. Plant Soil 58:327–338.

Snowdon, P. and M.L. Benson. 1992. Effects of combinations of irrigation and fertilisation on the growth and above-ground biomass production of *Pinus radiata*. For. Ecol. Manage. 52:87–116.

Stace, H.C.T., G.D. Hubble, R. Brewer, K.H. Northcote, J.R. Sleeman, M.J. Mulcahy and E.G. Hallsworth. 1968. A handbook of Australian soils. Rellim, Adelaide, 435 p.

Stewart, H.T.L. 1988. A review of irrigated forestry with Australian tree species. *In* Proc. Int. For. Conf. for the Aust. Bicentenary, Albury-Wodonga Development Corp., 18 p.

Stewart, H.T.L. and R. Boardman. 1991. The potential for irrigated plantation development in Australia. *In* Report of the National Plantations Advisory Committee, Appendix B. Dept. Primary Industries and Energy, Canberra, pp 95–142.

Stewart, H.T.L. and D.W. Flinn. 1984. Establishment and early growth of trees irrigated with wastewater at four sites in Victoria, Australia. For. Ecol. Manage. 8:243–256.

Stewart, H.T.L., P. Hopmans, D.W. Flinn, T.J. Hillman and J. Collopy. 1988. Evaluation of irrigated tree crops for land disposal of municipal effluent at Wodonga. Albury-Wodonga Development Corp. Tech. Rep No. 7, 28 p.

Stewart, K.B. 1981. Evaporation from forests. XVII IURFO World Forestry Congress, Kyoto, Japan, pp 130–138.

Thomas, M. 1991. Guidelines for wastewater irrigation. Revised Edn. Victorian Environment Protection Authority, Publication No. 168, 104 p.

Turner, J. 1986. Organic matter accumulation in a series of *Eucalyptus grandis* plantations. For. Ecol. Manage. 17:231–242.

Wilkinson, C. 1993. Bunglegumbie road waste water recycling project: report of plantation assessment at age 2. Dubbo City Council, Australia, 51 p.