Forest Ecology and Management 259 (2010) 1754–1760

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Transpiration along an age series of *Eucalyptus globulus* plantations in southeastern Australia

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ARTICLE INFO

Article history:
Received 27 February 2009
Received in revised form 22 April 2009
Accepted 23 April 2009

Keywords:
Water use
Forest management
Heat pulse technique
Leaf area index
Water use efficiency
Sap flow

ABSTRACT

Many of the world's *Eucalyptus* plantations are grown on short rotations of 15 years or less, which often covers the most rapid phase of stand development and peaks in growth rates and leaf areas. Since transpiration is related to stand leaf area these short rotations that make use of rapid early growth rates, may also maximise plantation water use, which has implications for predicting their water requirements and impacts on catchment hydrology. This study examined the transpiration, leaf area and growth rates of *Eucalyptus globulus* Labill. plantations aged 2–8 years. Transpiration (E), estimated using the heat pulse technique, increased from 0.4 mm day^{-1} at age 2 years to a peak of about 1.6–1.9 mm day^{-1} in stands aged 5–7 years. This was associated with similar trends for stand leaf area index (LAI) and periodic annual increments of aboveground biomass, which both peaked at about age 4–6 years resulting in a linear relationship between E and LAI. While stand sapwood areas were continuing to increase at age 8 years, E was already declining due to reductions in sap velocity, from 13.5 cm h^{-1} at age 2 years to 6.3 cm h^{-1} at age 8 years and reduced sapwood area growth rates. Trees compensated for this reduction in sap velocity with declines in the leaf area (A_L) to sapwood area (A_S) relationship (A_L:A_S) with age. There was also a reduction in growth efficiency (aboveground biomass increment per LAI) with age. However, reductions in WUE were small after age 4 years, which explained the linear relationship between E and LAI. If E continues to decline successive short rotation lengths may not only make use of rapid early growth rates but could also increase plantation water use compared to longer rotations over the same period of time.

1. Introduction

The world's *Eucalyptus* plantation area has increased rapidly over the past two decades to about 19 million ha (Iglesias Trabado and Wilstermann, 2008). The driving forces for this expansion have been economic, social, favourable wood properties and growth rates, and environmental factors such as reducing pressure on native forests and carbon sequestration (Gerrand et al., 2002). Most of these plantations are grown on short rotations, of about 15 years or less, for pulp logs to produce paper products. The species planted are those that possess rapid early growth rates such that peaks in current annual growth increment and stand leaf area (and light interception) often occur within these short rotations (Beadle and Turnbull, 1992; West and Mattay, 1993; Florence, 1996). The timing and magnitude of these peaks depend on species, site and silviculture (Beadle and Turnbull, 1992; Florence, 1996; Ryan et al., 1997). Nevertheless the transpiration of fast growing stands is also likely to peak during this early phase of stand development and these dynamics need to be understood to best manage any impact on local and regional water supplies (Calder et al., 1997; Morris et al., 2004; Whitehead and Beadle, 2004).

Many studies have examined the water use and water use efficiency of *Eucalyptus* growing in different environments and under different silvicultural treatments (Whitehead and Beadle, 2004). However, few have examined how the water use of *Eucalyptus* plantations changes as stands develop, which is necessary to understand their role in local and global water and carbon cycling. This study sought to examine if plantation transpiration reaches a peak at an early age and then declines. This has implications for predicting water requirements and impacts of *Eucalyptus* plantations on catchment hydrology. For example, following fire or harvesting in native *Eucalyptus regnans* forests the catchment water yield is initially relatively high. As the forest begins to regenerate and leaf area increases, transpiration also increases reducing water yields to a minimum at around age 20–40 years. Catchment water yields then increase again until

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doi:10.1016/j.foreco.2009.04.023

Table 1
Site characteristics.

Site name	Treatment—age when transpiration was measured (years)	Latitude and longitude	Altitude (m, a.s.l.)	Soil description		Plant available water holding capacity to 4 m (mm)
				PPF[a]	ASC[b]	
Yendon	8.2	37°36′40″S, 144°1′50″E	528	Dy3.41	Bleached-mottled, natric, brown kurosol	526
Napoleons	7.2	37°40′50″S, 143°47′14″E	399	Db2.21	Mottled, magnesic, brown kurosol	607
	5.2	37°41′06″S, 143°47′20″E	394	Gn4.71	Acidic-mottled, magnesic, brown dermosol	468
	2.2	37°41′16″S, 143°47′16″E	411	Gn4.71	Acidic-sodic, magnesic, brown dermosol	623
Snake Valley	4.2	37°36′45″S, 143°38′24″E	415	Db2.41	Ferric-sodic, eutrophic, brown chromosol	416
	6.2	37°36′44″S, 143°38′34″E	411	Db2.41	Ferric-sodic, eutrophic, brown chromosol	416

[a] Principal profile form (Northcote, 1971).
[b] Australian soil classification (Isbell, 1998).

around 100–150 years. The water yield is well described by leaf area index (LAI) and annual growth rates in these stands, which all peak at a similar age (Ashton, 1976; Kuczera, 1987; Dunn and Connor, 1993; Haydon et al., 1996; Vertessy et al., 1996; Watson and Vertessy, 1996). Similar trends have been measured in *Eucalyptus saligna* and *Eucalyptus laevopinea* forests (Cornish and Vertessy, 2001) and studies in other genera have shown that stand transpiration peaks around the time of maximum growth rates and stand leaf area before declining with age (Köstner et al., 2002; Delzon and Loustau, 2005).

These same trends are likely to occur in *Eucalyptus* plantations, where peaks in current annual increments and LAI often occur before age 15 years and in some cases as early as age 2 or 3 years (Florence, 1996; Almeida et al., 2007; du Toit, 2008; Ryan et al., 2008). The objective of this study was to determine (i) if stand transpiration declined with age after reaching an early peak, (ii) if this decline is associated with a decline in leaf area index and current annual growth rates, and (iii) how water use efficiency (stand biomass or volume production per unit water transpired) changes with time? This study examined the transpiration of an age series of *E. globulus* Labill. plantations near Ballarat, Victoria, Australia. This consisted of plantations aged between 2 and 8 years within a locality of generally similar geology and climate. Stand transpiration was measured in Autumn and Spring (2004) to avoid the extremes in seasonal variation in vapour pressure deficit and potential evaporation.

2. Materials and methods

2.1. Study area and experimental design

The age series consisted of six age treatments that were spread across three sites within 20 km of Ballarat, Victoria, Australia. These sites included stands aged 2, 4, 5, 6, 7 and 8 years (Table 1). To avoid the influence of the variable inter-annual climate in this region, which could confound the age effects of stand development, an age series of plantations within a locality of similar climate and geology was used. The site index, defined as the mean dominant height of the largest 100 trees ha^{-1} at age 10 years, was 18.7 m (Veiga, 2008). This is equivalent to a mean annual volume increment at age 10 years of about 15 m^3 ha^{-1} year^{-1}. The climate is classed as temperate with mean maximum and minimum temperatures of 24.3 °C in January and 3.0 °C in July, respectively (Fig. 1). Annual precipitation is about 700 mm, with a winter maximum. The sites were managed as improved pasture prior to planting and there is negligible slope on any site (5% at maximum). A soil pit was dug at each site and the soils are described (Table 1). Seedlings of *E. globulus* (Jeeralang Provenance) were planted at a spacing of about 2.5 m × 4 m (1000 trees ha^{-1}). At least four plots (about 13 m × 20 m each) were established in each treatment to measure stand parameters. For each treatment stand parameters were measured approximately annually from about age 3 years, except in the age 2 years treatment for which stand parameters were only measured at age 2 years.

2.2. Meteorological data

Rainfall, air temperature, solar radiation, relative humidity and wind speed were recorded every 30 min for the duration of the study period using a Tain Micropower data logger (Tain Instruments, Box Hill, Australia), that was centrally located at the Napoleons site. These parameters were measured using a 0.1 mm dipping-bucket gauge, a PTAT (proportional to absolute temperature) temperature sensor, pyranometer, Vaisala humidity sensor and cup anemometer, respectively, mounted on a mast 7.5 m aboveground. Daily mean vapour pressure deficit (VPD; kPa) was calculated from half hourly humidity and temperature data as described in Morris et al. (2004).

2.3. Tree growth, sapwood area and leaf area

Aboveground biomass (including wood, bark, branches and leaves; B; kg) and volume underbark to a small-end diameter of 2 cm (V; m^3) was estimated from stem diameter, overbark at 1.3 m (D; cm) and total height (H_t; m) using allometric equations developed at these and other *E. globulus* plantations in south-eastern Australia (Wong et al., 1999; Veiga, 2008):

$$V = 2.8737 \times 10^{-5} D^2 H_t + 4.0837 \times 10^{-4} D \quad (\text{Adj. } R^2 = 0.997)$$

$$\ln(B) = 2.49 \ln(D) - 2.297 \quad (R^2 = 0.97)$$

Sapwood area (A_S; cm^2) was calculated from D, bark thickness and sapwood width measurements from increment cores taken from three or four points around the stem of 242 trees (including those selected for tree water use assessment) in 2004. The

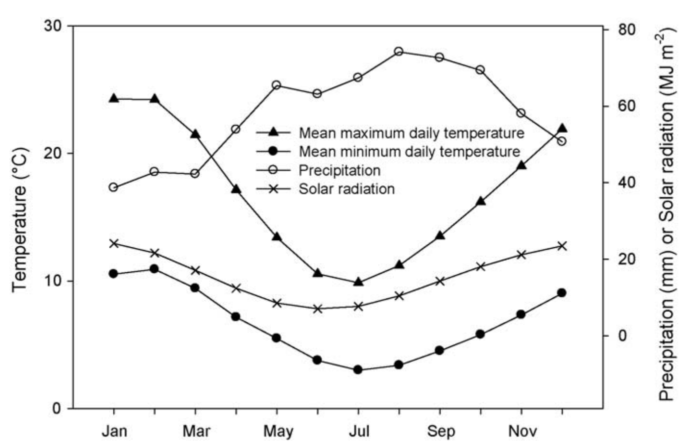

Fig. 1. Long-term (1900–2007) average temperatures, precipitation and solar radiation for the experimental sites.

sapwood–heartwood boundary was identified by a combination of colour differentiation, light transmission and the application of a 0.1% aqueous methyl orange stain. The relationship between D and A_S varied with age and a multiple linear regression was used to calculate A_S:

$$\ln(A_S) = -0.7266 + 2.2017\ln(D) - 0.3599\ln(\text{Age}) \quad (R^2 = 0.98).$$

The sapwood area was only estimated to age 8 years because no D to A_S data was available for older stands. Canopy leaf area (A_L; m^2) for each tree (and hence plot leaf area index; LAI) was estimated from D and age (years) using an equation developed at these sites and other *E. globulus* plantations in southeastern Australia (Veiga, 2008):

$$\ln(A_L) = -0.9 + 2.304\ln(D) - 1.004\ln(\text{Age}) \quad (R^2 = 0.806).$$

2.4. Sap flow measurements and stand transpiration

In each treatment transpiration (E) was monitored during three periods including Autumn/Winter (28 April to 14 June), early Spring (1 September to 6 October) and late Spring (7 October to 10 November) in 2004 using the heat pulse technique described by Edwards and Warwick (1984) and modified by Olbrich (1991). Twelve co-dominant trees were selected for sap flow measurements per treatment. In total 72 trees were sampled (3 trees observations were rejected due to heater and or logger failures) for periods of one to two weeks (4 trees per treatment during each measurement period).

A combination of two custom heat pulse velocity recorders from HortResearch (Palmerston North, New Zealand), two HeatPulser control instruments from Edwards Industries (Otaki, New Zealand) and CR10X data loggers from Campbell Scientific (Logan, USA) were used to record apparent heat pulse velocity at four points per tree (each at a different depth in the sapwood) at 30 min intervals using the method of Morris et al. (1998). For a given plot and measurement period each instrument gave similar results with no clear difference in the relationships between sap flux density (SFD; cm^3 cm^{-2} h^{-1}) or tree size.

SFD was calculated after correcting for the effects of wound diameter, probe separation and volume fractions of water and woody matrix in the sapwood as described by Khanzada et al. (1998). Whole tree SFD estimates were derived from each set of four point estimates (per tree) by calculating a second-degree polynomial regression against implantation depth below the cambium, then integrating this function around the stem. For some trees where probe failures reduced the number of point measurements, a weighted mean calculation was used (Hatton et al., 1990; Morris et al., 2004).

For a given age, SFD was not related to tree size ($P > 0.14$). Thus daily mean SFD values for individual trees were assumed to be unbiased estimates of the average plot SFD. Furthermore, differences in SFD between trees measured simultaneously or sequentially were usually small compared to daily variation within a tree. Daily plot transpiration (E; mm day^{-1}) was therefore estimated as the product of plot sapwood area and mean daily SFD.

Water use efficiency (WUE; kg of biomass or dm^3 wood per m^3 water transpired) was calculated using growth rates estimated from the derivative of linear (age 2 years treatment) or polynomial (all other treatments) regressions fitted to stand biomass or volume versus age data. A separate regression was fitted for each treatment. Linear regressions were used for the age 2 years treatment because the growth was assumed to have been linear up to that age.

2.5. Canopy conductance

Canopy conductance (g_c; m s^{-1}) was estimated from daily transpiration and vapour pressure deficit (Monteith and Unsworth, 1990) as

$$g_c = \frac{\gamma \lambda E}{\rho C_p \text{VPD}} \tag{1}$$

where E is mean rate (in kg m^{-2} s^{-1}) of daily plot transpiration, VPD (kPa) is mean daily vapour pressure deficit, γ is the psychrometric constant (66 Pa K^{-1}), λ is the latent heat of evaporation of water (2450 kJ kg^{-1}), ρ is the density of air (1.2 kg m^{-3}) and C_p is the specific heat of air at constant pressure (1010 J kg^{-1} K^{-1}). This equation may not be appropriate on days with high-energy environments, low wind speeds or large-leaved plants (Landsberg, 1986). Thus it was applied on days where the vapour deficit term of the Penman–Monteith equation (Landsberg and Gower, 1997) was at least five times larger than the radiation term (Morris et al., 2004), and aerodynamic conductance was large compared to canopy conductance (Landsberg, 1986).

2.6. Statistical analysis

Comparisons between treatment means were tested using Analysis of Variance (ANOVA) in Genstat^{TM} (VSN International Ltd., Hemel Hemestead, U.K.). Residual maximum likelihood analysis (REML) was used for individual tree comparisons to deal with the unbalanced design due to a logger failure. Regression analyses were also performed in Genstat^{TM}.

3. Results

Annual precipitation during 2004 was 708 mm, which is similar to the long-term average (1900–2007) of 699 mm, for which there is a Winter and Spring maximum. Annual pan evaporation during 2004 was 1094 mm, similar to the long-term average of 1069 mm. Solar radiation, temperature, vapour pressure deficit and pan evaporation were all higher in Spring than in Autumn or Winter (Fig. 2).

Aboveground biomass, volume, basal area, sapwood area and average tree D increased linearly with age ($R^2 > 0.84$) up to age 7.2 years (Table 2; Fig. 3). This trend suggests a mean annual volume increment at age 10 years of about 15 m^3 ha^{-1} year^{-1}. The slower stand growth for the 8.2-year-old treatment (Table 2) suggests that it is on a slightly lower quality site, most likely due to poorer nutrition, than the other treatments, however we do not have the data to test this hypothesis further. It is important to note that the variability in growth of different permanent sampling plots in Fig. 3 is the result of varying climates for each treatment at a given age as well as variation in soil characteristics. That is, each treatment was aged 4 years in a different year and hence experienced different growing conditions at that age relative to other treatments.

LAI increased with age from 1.0 at age 2.2 years to 3.7 at age 6.2 years (Table 2). This trend was clearly illustrated by the permanent sampling plots where peaks in LAI of about 3–4 occurred at around 4–6 years before gradually declining thereafter (Fig. 3). Similarly, periodic annual increments of aboveground biomass and volume (data not shown) peaked at around age 5 years. Periodic growth efficiency, defined as periodic aboveground biomass increment per unit LAI, also peaked at age 4–5 years at similar magnitudes as those found for *E. grandis* (du Toit, 2008).

Average daily transpiration (E) over the measurement period ranged from 0.4 to 1.89 mm day^{-1} in the 2.2- and 7.2-year-old stands, respectively (Table 2), and was linearly related to LAI

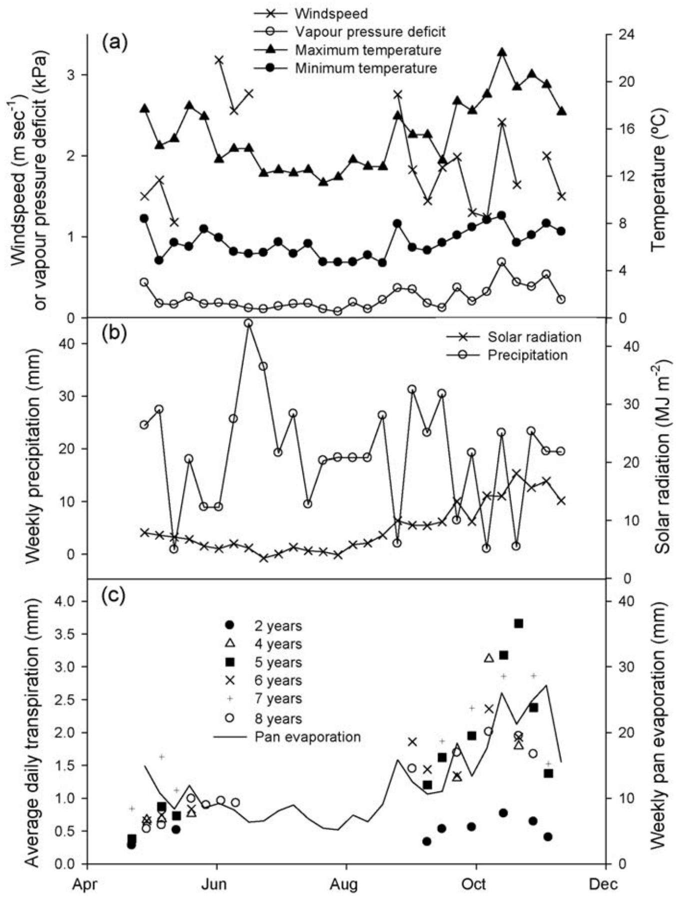

Fig. 2. Weather conditions and average daily transpiration measured during the experimental period. Data are (a) average daily wind speed, average daily vapour pressure deficit, maximum daily temperature, minimum daily temperature, (b) daily solar radiation (each data point averaged over a week), weekly precipitation, and (c) weekly pan evaporation and average daily transpiration (each data point averaged over a week).

(Fig. 4). For all treatments *E* was highest in spring (Fig. 2). *E* and sap velocity for all ages were related to maximum daily temperature, mean daily VPD, solar radiation and pan evaporation (Fig. 2). The proportion of precipitation that was transpired was only 21% at age 2.2 years but at least 50% at all other ages and up to 122% at age 7.2 years. Sap velocity and A_L:A_S declined with age (Fig. 5; Table 2), and there was no relationship between sap velocity and *D* for a given age. There was considerable variation in sap velocity with depth into the sapwood, however, no clear trend was found and the variability between trees was greater than the variability between treatments (data not shown) showing the importance of measuring sap velocity at different depths (Zang et al., 1996; Nadezhdina et al., 2002; Fiora and Cescatti, 2006).

Water use efficiency (WUE; kg of biomass or dm^3 wood per m^3 water transpired) peaked at around age 4–6 years (Fig. 5). The treatments with the highest *E* (treatments 5 and 7 years) did not have the highest WUE's.

Canopy conductance (g_c) declined with increasing vapour pressure deficit towards 0.1 or 0.3 cm s^{-1} for ages 2.2 and all older stands, respectively (Fig. 6). For all vapour pressure deficits g_c was higher in stands aged 4–8 years than in those aged 2.2 years, consistent with differences in transpiration. The g_c per unit LAI (g_{cLAI}) was slightly, but significantly, higher for the two treatments with higher *E* (ages 5 and 7 years) compared to those with lower *E* (ages 2, 4, 6 and 8 years), indicating that differences in g_c were not only due to differences in LAI.

4. Discussion

Transpiration increased from 0.4 mm day^{-1} in stands aged 2 years to a peak of 1.6–1.9 mm day^{-1} in stands aged 5 and 7 years before a decline to 1.1 mm day^{-1} at age 8 years. This was associated with similar trends for LAI, sapwood area, and periodic annual increments of aboveground biomass. The linear relationship between *E* and LAI (Fig. 4) was similar to that of other *E. globulus* stands in southern Australia (Benyon et al., 2006), and clearly illustrates the link between plantation water use and leaf area. Similarly, transpiration and/or LAI have declined with age after an early peak for other species (Roberts et al., 2001; Köstner et al., 2002; Delzon and Loustau, 2005; Almeida et al., 2007).

It is not unusual for growth increments and LAI of unthinned *Eucalyptus* plantations to peak early within a rotation and in some stands this can occur at age 2 or 3 years (Florence, 1996; Almeida et al., 2007; du Toit, 2008). Generally the higher the early growth rates the earlier the peak and the steeper the growth decline (Ryan et al., 1997). As a result of these stand dynamics and the linear relationship between *E* and LAI observed in this and other *E. globulus* plantations (Benyon et al., 2006), peaks in *E* are also likely during the short rotation lengths of these stands. If *E* continues to decline or stabilises significantly below this peak, as is often shown for LAI, successive short rotation lengths may not only make use of rapid early growth rates but could also increase plantation water use compared to longer rotations over the same period of time. Similar trends have been examined in native *Eucalyptus* forest. In these less intensively managed stands growth rates are slower and the peak LAI or current annual increments can occur later, such as

Table 2
Stand and tree parameters from ages 2.2 to 8.2 years. Means sharing the same letter are not significantly different ($P > 0.05$).

Parameter	Age treatment (years)					
	2.2	4.2	5.2	6.2	7.2	8.2
Aboveground biomass (Mg ha^{-1})	6.5a	42.1b	55.9c	91.5d	102.8e	89.8d
Sapwood area (m^2 ha^{-1})	1.1a	6.1b	7.3c	11.2d	10.6d	8.9e
Volume (m^3 ha^{-1})	5.6a	38b	54c	103d	110d	88e
Basal area (m^2 ha^{-1})	2.3a	9.7b	11.9c	18.0de	19.5e	17.7d
Mean *D* (cm)	4.8a	10.3b	12.2c	14.7d	14.5d	14.4d
Trees ha^{-1}	935a	1088b	968a	1006ab	1086b	1001a
LAI	1.0a	2.7b	2.8b	3.7c	3.5c	2.7b
Transpiration (*E*; mm day^{-1})	0.40a	1.34c	1.64d	1.36c	1.89e	1.12b
Percentage of precipitation transpired	21	114	109	74	122	56
Mean sap velocity (cm h^{-1})	13.5d	10.4c	9.2bc	5.3a	7.4ab	6.3a
Tree transpiration per LA (m^3 m^{-2} 10^4)	4.6a	6.2b	6.1b	4.1a	5.2ab	5ab
Stand transpiration per LAI (m^3 ha^{-1} day^{-1} water per LAI)	4.57c	4.98d	5.88e	3.72a	5.35f	4.25b
A_L:A_S (m^2 cm^{-2})	0.66e	0.42d	0.35c	0.3b	0.3b	0.28a
Volume fraction of water	0.588b	0.544a	0.541a	0.537a	0.523a	0.528a

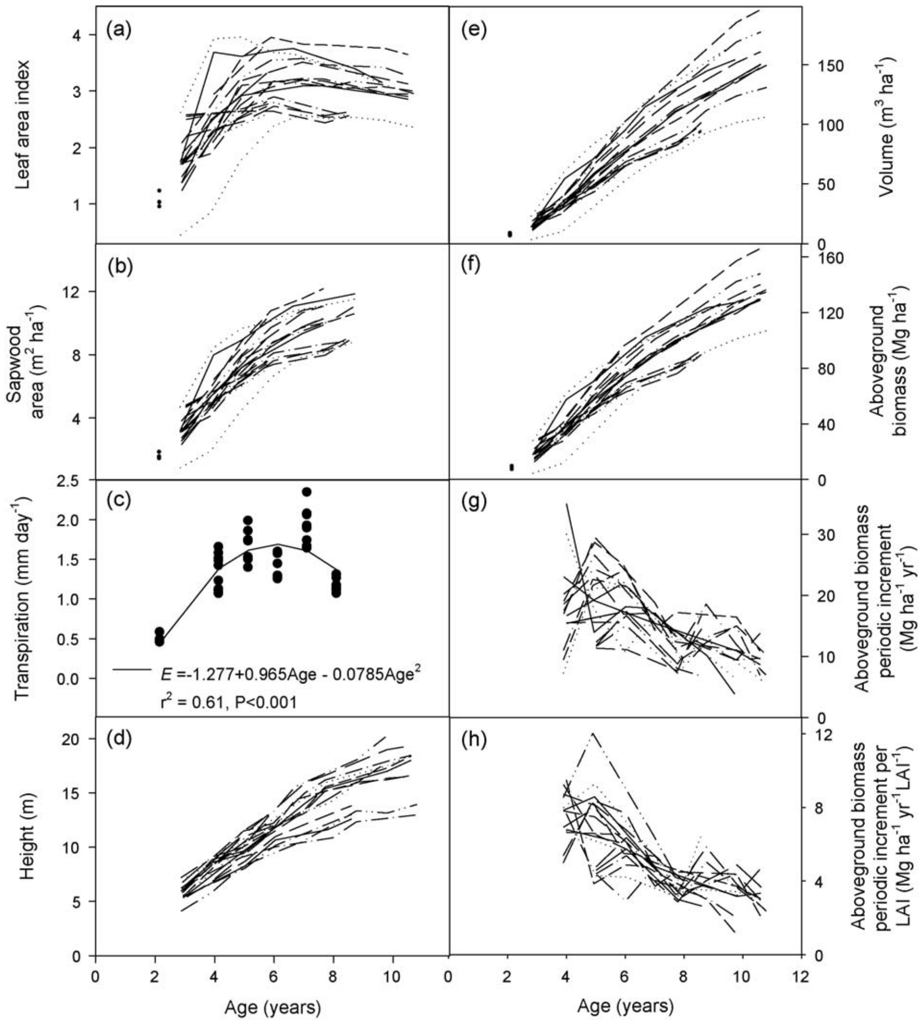

Fig. 3. Leaf area index (a), sapwood area (b), mean daily transpiration (c), height (d), volume (underbark; e), aboveground biomass (f), periodic biomass increment (g) and periodic biomass increment per LAI (h). Data points at age 2 years in (a), (b), (e) and (f) were the only points measured in that treatment; data was not collected until about age 3 years in all other treatments.

about age 20–40 years (Ashton, 1976; Beadle and Turnbull, 1992; Florence, 1996; Watson and Vertessy, 1996). Nevertheless, these peaks in E occur well within the rotation lengths (80–100 years) or the natural life span of these stands (300–400 years) and can raise concerns about water yield when forests are young.

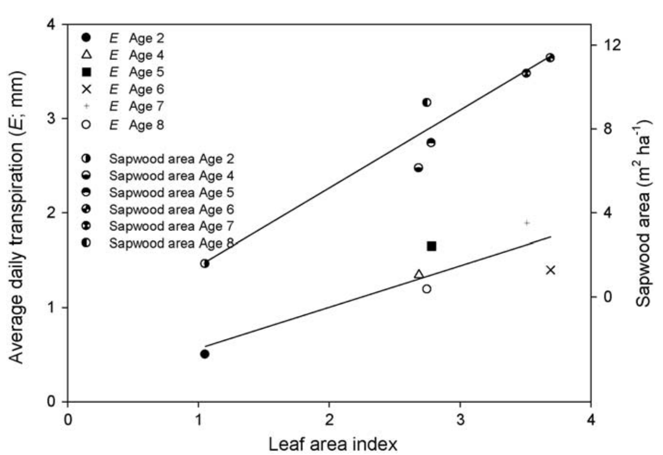

Fig. 4. Relationship between LAI and either average daily transpiration (E) during the measurement period or sapwood area. $E = 0.12 + 0.44 \times \text{LAI}$ ($R^2 = 0.68$; $P = 0.028$). Sapwood area = $-2.5 + 3.72 \times \text{LAI}$; $R^2 = 0.91$; $P = 0.002$).

The decline in stand transpiration after the peak at around age 5–7 years resulted from a decline in sapwood area growth rates and a decline in sap velocity. Sap velocity declined with age from the youngest stands aged 2 years (13.5 cm h^{-1}) to the oldest stands aged 8 years (6.3 cm h^{-1}). These sap velocities were similar to others recorded for *Eucalyptus* plantations (4.3–16.6 cm h^{-1}; Medhurst et al., 2002; Hubbard et al., 2004; Morris et al., 2004). In contrast, sap velocity is similar along much longer age series of native forests of *Eucalyptus sieberi* (Roberts et al., 2001) or *E. regnans* (Dunn and Connor, 1993). Thus declines in sap velocity with time in *Eucalyptus* appear to be greater during the early stages of development. The rate of decline in A_L:A_S was also lower in the older stands. The same trend has been found for many species as stands grow taller and age, and is considered a mechanism to help alleviate decreasing hydraulic conductance while maintaining g_c as stands develop (McDowell et al., 2002). The same mechanism appears to have taken place in the current study.

The WUE was used to show how much aboveground biomass was produced per unit of water transpired. High WUE would be favourable in regions where there are concerns about water availability. WUE may decline as the stands develop after canopy closure and the availability of, and competition for, resources changes. This would be consistent with observations that WUE increases with resource availability along gradients of water, nutrient and light availability (Stape et al., 2004). WUE and growth

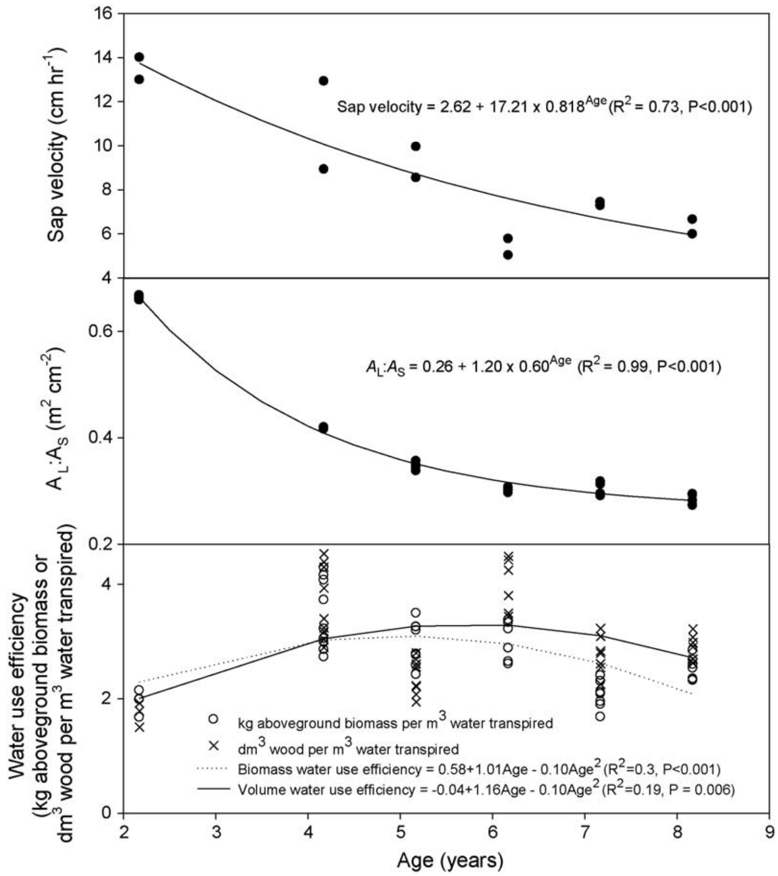

Fig. 5. Relationships between sap velocity, A_L:A_S, water use efficiency (WUE) and age.

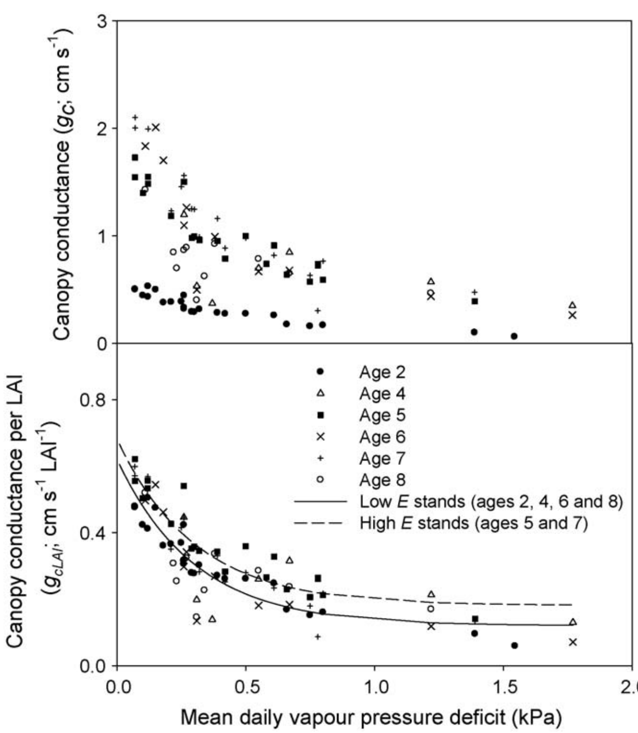

Fig. 6. Mean daily canopy conductance (g_c) or g_c per unit LAI (g_{cLAI}) against mean daily vapour pressure deficit (VPD) in *E. globulus* plantations aged between 2 and 8 years. Lines are g_{cLAI} as a function of VPD for stands with the highest rates of transpiration (E) and those with the lowest E.

efficiency peaked at around age 5 years and then declined with age (Table 2; Figs. 3 and 5). The decline in WUE was relatively small compared to the reduction in growth efficiency over the same period. This was explained, at least in part, by a slightly higher g_{cLAI} in stands with higher g_c or E (Fig. 6), which would act to reduce WUE relative to the growth efficiency. Declining WUE and transpiration per unit leaf area was also observed as stands aged and E, g_c and LAI declined in *Pinus pinaster* (Delzon and Loustau, 2005) and *Picea abies* (Köstner et al., 2002). WUE was also found to decline after an early peak in *E. grandis* plantations in Brazil (Almeida et al., 2007). The small (but significant) decline in WUE from age 4 to 8 years in the current study indicates that after the canopy has closed and the peak LAI has been reached, WUE may not change rapidly as stands age. It also helps to explain why the relationship between E and LAI is linear despite these differences in growth efficiency and WUE.

This study examined an age series of plantations, rather than a single stand through time, to avoid the variability in inter-annual climatic conditions. While care was taken to minimise the inter-site variability there were still differences that may have influenced the results. For example the plant available water holding capacity was lower at the treatments aged 4 and 6 years, although the latter still had relatively high growth and transpiration rates and it is assumed that the differences in plant available water holding capacity are more likely to influence the results in a drier year than that in the year studied. The inter-annual climatic variability is also likely to influence the transpiration and growth as well as the other relationships that were examined in this study. Thus replication between years as well as sites would provide valuable information about the consistency of the trends observed in the current study (Almeida et al., 2007) and requires further investigation.

This study shows that stand transpiration does decline after a peak at age 5–7 years in the *E. globulus* plantations examined. This was related to declines in LAI and current annual growth rates. Growth efficiency and WUE also declined in the older stands. While this study demonstrated a relationship between *E* and LAI, it was not possible to determine what caused the overall decline in LAI and productivity, and more detailed investigation will be required to answer this question.

Acknowledgments

Funding for this project came from the Victorian Department of Sustainability and Environment. The plantations were established and managed by Midway Plantations Pty Ltd. and site access and the provision of growth data from permanent sampling plots is gratefully acknowledged. The authors also wish to thank the landowner of the Napoleons site Mr Ian Lightfoot for his assistance. Thanks also to two anonymous reviewers who provided useful comments that improved the manuscript. This paper is dedicated to the memory of our colleague and friend Dr. Jim Morris who was the instigator and principal designer of this study.

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