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Managing for water-use efficient wood production in *Eucalyptus globulus* plantations

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ABSTRACT

This paper tests the hypothesis that thinning and nitrogen fertiliser can increase the mass of wood produced per volume of water used (evapotranspiration) by plantations of *Eucalyptus globulus*. We have called this plantation water productivity (PWP_{WOOD}) and argue that, for a given genotype, this term integrates the effects of management, site and climate on both production and evapotranspiration. This is done using annual estimates of wood production and evapotranspiration from age three years to harvest age (~age 10 years) in three *E. globulus* stocking density by nitrogen experiments. The ratio of annual rainfall to potential evaporation at these three sites varied from 0.85 to 0.45.

Plantation water productivity (PWP_{WOOD}) was calculated as the ratio of annual growth to annual evapotranspiration. In this study, the PWP_{WOOD} of *E. globulus* varied from 0.2 to 3.1 g kg^{-1} and was significantly increased by the application of nitrogen at two sites where growth was nitrogen limited. In fertilised stands, soil stored water was depleted early in the summer while in contrast, unfertilised stands used the water more slowly, thereby extending the growth season to late summer when average daily evaporation was much higher. Increased PWP_{WOOD} in response to nitrogen was associated with an increase in water stress that could be mitigated by reducing stocking density without affecting either production or PWP_{WOOD}.

Plantations are managed at the compartment scale while water resources are monitored and managed at the catchment scale or larger. At the compartment scale, growth and PWP_{WOOD} are correlated with evapotranspiration; managing plantations to maximise water use can also minimise the impact of wood production on water resources.

1. Introduction

Eucalyptus plantations are now established on more than 20 M hectares globally (Carle et al., 2002; FAO, 2013). These plantations provide wood, environmental services and a source of renewable energy (Bauhus et al., 2010). The area planted is increasing in drier areas, particularly in the developing world (Kröger, 2012). In many of the places where *Eucalyptus* plantations have been established, local communities and governments are, or have been, concerned about the effect of these plantations on water resources (Roberts and Rosier, 1993; Dye, 2013; Greenwood, 2013). These concerns may increase in the future in regions where climate change and population growth increases demand for water resources. Managing forest plantations to maximise the amount of wood produced from water used should minimise the effect of wood production on water resources. Plantation water productivity (PWP_{WOOD}) will be a key element of a social license for wood production in plantations.

During the last twenty-five years many researchers have quantified the effects of genotype, environment and management on

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the ratio of carbon assimilation to leaf conductance for forest plantations (e.g. Gross, 1989; Guehl et al., 1991; Aitken et al., 1995; Monclus et al., 2009) including eucalypts (Osorio et al., 1998; Li et al., 2000; Ngugi et al., 2003). Observations at this scale are highly variable and this large body of research has failed to provide a reliable basis for plantation management and land use planning to minimise hydrological impacts. Wood-production plantations are managed at the compartment, or larger, scales and over time frames that span decades. At such scales plantation water use (evapotranspiration) includes transpiration by crop trees, canopy interception, soil evaporation, and understory (weed) transpiration, and must consider the temporal heterogeneity in rainfall and runoff and the effect of management. Water-use efficiency is a term that has been used to describe many measures of water productivity from the leaf to the stand scale. In this paper we are interested in the productivity of commercial plantations. To avoid confusion with the many other quantities labeled water-use efficiency, we will use the term plantation water productivity (PWP_{WOOD}) rather than water-use efficiency.

Wood yield of a plantations (W, g) can be expressed as the product of transpiration (T, kg H_2O), the transpiration efficiency of dry matter accumulation (TE_{DM}, g DM kg^{-1} H_2O) and the partitioning of dry matter to harvestable stem wood (HI, g g^{-1}, Eq. (1) adapted from Passioura (1977) and Passioura and Angus (2010)).

$$W = T \times TE_{DM} \times HI \quad (1)$$

The volume (V, m^3) of wood produced is W divided by the specific gravity of wood (although the later is not truly independent of other terms in that water stress affects wood density, for the sake of this work it is assumed constant since changes in a species at a site are small in relation to other terms in the equation). Total plantation water use or evapotranspiration (E_t) is the sum of transpiration (T), evaporation from the soil (S) and canopy interception (I). The water productivity of a plantation is therefore given by Eq. (2), which may be transposed so that the numerical effects of TE, HI and the components of E_t are easier to visualise

$$PWP_{WOOD} = \frac{T \times TE_{DM} \times HI}{T + I + S} \quad (2)$$

$$PWP_{WOOD} = \frac{TE_{DM} HI}{1 + \left(\frac{S+I}{T}\right)} \quad (3)$$

In water-limited situations productivity should be positively correlated with PWP_{WOOD} and therefore with T, TE_{DM} and HI. However, these variables are not independent and increased TE_{DM} will often be associated with water limitation and a decrease in HI (Ryan et al., 2004; Hubbard et al., 2010). Furthermore, evapotranspiration is conservative over the longer term (Kelliher et al., 1995). The timing of water use relative to variation in air saturation deficit and the control of soil evaporation may, therefore, be more important determinants of PWP_{WOOD} than water use per se. In recent reviews for agricultural systems, Blum (2009) and Passioura and Angus (2010) argued that managing canopy development to increase the proportion of evapotranspiration that occurs as transpiration may be a more effective route to manipulating water productivity than via transpiration efficiency.

Varying stocking density either at planting or by thinning, applications of fertiliser, weed and pest control are the main options available for plantation managers to increase wood yield and carbon storage for a given plantation species. Pruning may increase the value of wood produced in a plantation, albeit reducing wood yield, and is a special case not considered here, though we note that the concept of value of production per unit resource input is fundamental to wise resource allocation in resource scarce situations. All the factors we mention, including pruning, have the potential to affect the key terms in Eq. (3), namely TE_{DM}, HI and $((S + I)/T)$.

In south-western Australia, thinning and application of nitrogen are key interventions for maximising productivity and mitigating the risk of drought mortality in plantations of both *Pinus pinaster* Ait. (Butcher, 1977) and *Eucalyptus globulus* Labill. (White et al., 2009). Application of nitrogen generally increases transpiration efficiency of trees with similar water status, via more efficient carboxylation and Rubisco regeneration (Warren et al., 2000) and through increased leaf area index which increases light capture (e.g. Smethurst et al., 2001). When drought is imposed, fertilised trees that have established a larger canopy may experience a more rapid onset of water stress that increases leaf-scale transpiration efficiency due primarily to stomatal closure (Graciano et al., 2005), but may in turn reduce partitioning to wood (Ryan et al., 2004). At the stand scale, research on the effect on TE_{WOOD} has yielded inconsistent results. At the stand scale the transpiration efficiency of wood production, TE_{WOOD}, was greater in mixtures of *E. globulus* and *Acacia mearnsii* De Wild (a nitrogen fixer) than in pure stands of either species due an increase in TE_{WOOD} of *E. globulus* in the mixture (Forrester et al., 2010). However, application of nitrogen fertiliser did not affect the TE_{WOOD} of *Eucalyptus nitens* Deane and Maiden (Maiden) in SE Australia (Forrester et al., 2012). Thinning increased TE_{WOOD} in *E. nitens*, possibly due to increased radiation-use efficiency in the more open stands (Forrester et al., 2012). This result is consistent with an increase in canopy growth efficiency (volume per LAI) observed after thinning of *E. globulus* (White et al., 2009). Very few studies have measured PWP_{WOOD} as defined in Eq. (3) and even fewer over a full rotation.

This paper presents observations, collected from age three years to harvest (at ~10 years of age), of the effects of nitrogen and thinning on PWP_{WOOD} in *E. globulus* plantations. These data are used to test the hypotheses that thinning and addition of nitrogen will increase the PWP_{WOOD} over the full rotation but that this will be associated with increased drought risk. Detailed seasonal patterns of evapotranspiration are described used to explore the mechanisms for observed changes in PWP_{WOOD} at a greater level of detail and over longer time span than the prior studies discussed above.

2. Materials and methods

2.1. Site descriptions

All measurements were made in experiments at Scott River (high rainfall and low evaporation), Wellstead (low rainfall and low evaporation) and Boyup Brook (low rainfall and high evaporation). These sites cover the climatic range of the *E. globulus* plantation estate in south-western Australia (Fig. 1), a region that has a Mediterranean climate with cool wet winters and hot dry summers. These experiments have been described previously (White et al., 2009, 2010).

Soil depth varied across the sites from 4.5 m to >10 m at Scott River and Boyup Brook and was uniformly >10 m at Wellstead. All sites had a sandy A-horizon, and showed evidence of laterite in the top 2 m with clay or clay-loam sub soils. Total N, organic carbon, electrical conductivity and pH are given by White et al. (2009). When the trees were approximately two-years old, nitrogen rate (0 and 250 kg ha^{-1} yr^{-1}) by stocking density (300 and 600 stems ha^{-1} and unthinned) treatments were established in a factorial design resulting in six plots in each of three replicate blocks. The average stocking density at the time of treatment was 934 stems ha^{-1} at Boyup Brook, 1145 stems ha^{-1} at Scott River and 1131 stems ha^{-1} at Wellstead. Within the experiments each plot was 40 m × 40 m or 10 rows × 20 trees with an internal measurement plot of 20 × 22 m.

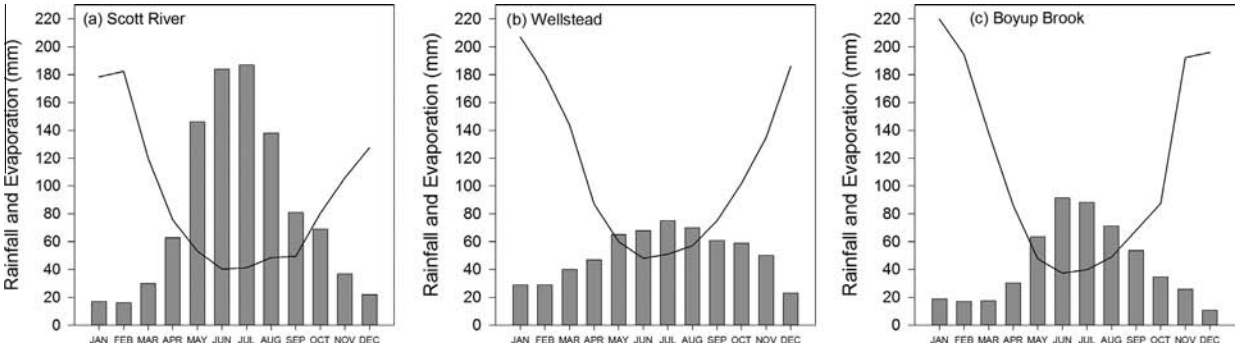

Fig. 1. Mean monthly rainfall (bars) and pan evaporation (line) from 1970 to 1996 at (a) Scott River, (b) Wellstead and (c) Boyup Brook.

2.2. Treatments and site management

Nitrogen was applied as urea in split applications; half of the designated annual rate was applied in early spring (September–October) and the other half in autumn (April–May); phosphorus, potassium, magnesium, manganese, zinc and copper were applied once to all plots (White et al., 2009).

Plots designated as low (300 stems ha^{-1}) and medium (600 stems ha^{-1}) density, were thinned in September (spring) 1998. Trees were removed to create a uniform spacing, regardless of their size or position in the canopy. All felled trees were removed from the trials. Each spring weeds were killed by a single application of glyphosate.

2.3. Stand growth

The height and diameter of all trees were measured annually in spring. Initially, height (h) was measured using a telescopic or sectioned height pole, then using a Digital Vertex III Hypsometer (Haglof, Sweden AB). Diameter at breast height (1.3 m above ground) over bark (d) was measured at a marked position on the tree. Annual measurements commenced in 1998 and ended in 2004. An additional measurement was made just prior to harvest in December 2005 at Scott River, February 2006 at Boyup Brook and June 2006 at Wellstead.

The conical volume over bark (v, m^3) of each tree was calculated using Eq. (4).

$$v = \left(\frac{\pi}{12}\right)\left(\frac{d}{100}\left(\frac{h}{h-1.3}\right)\right)^2 h \quad (4)$$

Stand volume (V, $m^3\ ha^{-1}$) was calculated using Eq. (5),

$$V = \frac{10,000}{A}\sum_{i=1}^{n} v_i \quad (5)$$

where v_i was the volume of the ith tree in each plot and A was the ground area (m^2) of the measurement plot.

2.4. Current annual volume increment (CAI_v)

The current annual volume increment (CAI_v, $m^3\ ha^{-1}\ y^{-1}$) was calculated for each full year between growth measurements as the difference between V measured at the beginning and end of that year.

2.5. Basic density and current annual increment in bone dry tonnes

Increment cores were collected at each site just prior to harvest, at about the same time as the last measure of h and d. Wood cores (12-mm diameter) were taken at breast height from five randomly selected trees in each plot. Measurements of h and d were obtained from each sampled tree. From each core, 2 mm-thick strips were used to measure the radial variation in air-dry density from pith-to-bark using SilviScan and a 0.25 mm sampling interval.

The air-dry wood density data was extracted from the relevant portion of each of the 4951 NIR spectra obtained from the 266 radial strips sampled. Cross-validation models were developed within the Bruker QUANT OPUS 5.5 software package (Bruker Optik, Ettingen Germany) using Partial Least Squares (PLS) regression (Martens and Naes, 1989). The software employs an optimisation procedure in which a range of spectral pre-processing methods and wave-number ranges are evaluated to determine the optimal calibration based on RMSECV and the number of latent variables (principal components) required. Outliers detected by the software's criteria were removed. Typically outliers arise from poor laboratory data, or from spectra that are not representative of the sample's chemistry.

We derived separate relationships for each plot at each site giving air-dry density at x% of the radius (ρ_x) as a linear function air-dry density at the pith (ρ_p) and x with a slope of b tonnes m^{-3}.

$$\rho_x = \rho_p + bx \quad (6)$$

At each measurement time mean diameter in each plot was expressed as a percentage of the final diameter. The basic density of wood for each measurement was calculated as the average of density estimated for the beginning and end of the period in question. Algorithms for estimating the density of whole trees or radial portions of trees from basic density at breast height are not well developed (Downes et al., 2010). Average basic density calculated in this way was applied to the current annual volume increment for that plot to give a current annual increment in bone-dry tonnes (CAI_{WOOD}). This may be an overestimate of wood production but the error will be small and comparisons amongst treatments are nonetheless valid.

2.6. Volumetric soil water fraction

Two 50-mm diameter holes were drilled to bedrock or 10 m in each plot at all sites. These holes were drilled in opposite corners of the internal measurement plots towards the end of the inter-row. Polyvinyl chloride (PVC) tubing with an internal diameter of 40 mm was placed in the holes and the gap (ca. 3 mm) backfilled with kaolin and cement slurry (Prebble et al., 1981) Soil water contents were measured using a neutron moisture meter (DIDCOT [Wallingford UK] and CPN [California Pacific Neutron, Pacheco, California] probes were used during this study). The interval between measurements varied from 1 to 6 months. Soil water content was measured at 0.3 m depth intervals to 1.5 m and then at 0.5 m intervals to bedrock or 8 m below ground. Measured neutron count ratios were converted to volumetric soil water fraction (θ) using

calibrations for sandy loam and clay horizons (as per Hingston et al. (1998)) and the values from individual tubes were averaged to give a plot value for θ. For each plot the total profile water content (M in mm) was calculated as

$$M = \sum_{i=1}^{n} \theta_i d_i \quad (7)$$

where d_i and θ_i respectively were the depth and volumetric soil water content of the ith soil depth interval.

2.7. Rainfall, temperature and potential evaporation

Long-term climate data were collated for each site (SILO, Jeffrey et al. (2001)) and included the measurement period from 1998 to 2006. Data included maximum and minimum temperature and daily rainfall and potential evaporation (FAO-56, Allen et al. (1998)). Rainfall (P) and potential evaporation (E_0) was calculated for the periods between soil water measurements.

2.8. Annual evapotranspiration (E_t)

Evapotranspiration (E_t) was calculated or the period between each soil water measurement for each treatment as the sum of annual rainfall P and change in total soil water content (ΔM, where a positive value represents a drying of the soil profile).

$$E_t = max(E_0, P + \Delta M) \quad (8)$$

This assumes that no drainage or surface run-off occurred provided $P + \Delta M$ was $<E_0$ (Honeysett et al., 1992, 1996). We believe this was a reasonable assumption, particularly at Scott River and Wellstead as these sites were both quite flat and the plantations were three-years old and well established when the study commenced. E_t is inclusive of interception, transpiration, soil evaporation and understory or weed transpiration. As noted earlier, weeds were controlled throughout the experiment so that weed transpiration was negligible. Only E_t calculated as a function of the change in soil water content is reported and not absolute water content. This allows for variation in the calibration (from Hingston et al., 1998) within and between sites due to physical (stoniness) and chemical (pH, ion concentrations) as these affect the intercept of the calibration (and hence absolute water content) and not the slope which determines change in soil water content between measurements and therefore E_t calculated using Eq. (8).

2.9. The water-productivity of wood production (PWP_{WOOD})

Plantation water productivity (PWP_{WOOD}), expressed in g wood kg^{-1} H_2O (PWP_{WOOD}) was calculated for each full year between growth measurements as the ratio of growth to E_t (note that 100 mm is equivalent to 1 ML ha^{-1}, and g kg^{-1} is equivalent to tonnes ML^{-1}). The soil was very deep at Wellstead and it was not possible to advance access tubes beyond 9 m. We may therefore have underestimated E_t and overestimated PWP_{WOOD} at this site, particularly later in the experiment when trees may have been drawing water from well below 9 m.

2.10. Mortality

White et al. (2009) reported mortality as high as 25% in one plot at Scott River and two plots at Boyup Brook. These mortality events were rare and associated with shallow soils. Here we have calculated the growth of the dead plot as the minimum growth of the other plots discounted by the mortality rate. This was only done for the three plots where mortality exceeded 10% in 2000–01.

2.11. Data analysis

Within sites we tested for the effects of non-commercial thinning, fertiliser application and stand age on response variables (growth, water use and water-use efficiency) using two-way analysis of variance with repeated measures. We also analysed each year separately to test the significance of site, thinning treatment and fertiliser treatment and their interactions. The treatment factors and their interactions were modelled as fixed effects, and individual plot identity as a random effect. Relationships between growth, water-use efficiency and explanatory variables such as soil water deficit were developed using linear regression.

3. Results

3.1. Wood density and wood volume

Site significantly affected wood density but neither stocking nor nitrogen affected wood density at any site. When wood production in tonnes (CAI_{WOOD}) was plotted as a function of CAI_V the intercept was not significantly different from zero and the slope was 0.49 tonnes m^{-3} for Wellstead and 0.53 tonnes m^{-3} for both Scott River and Boyup Brook. The effects of nitrogen and thinning on wood production were therefore similar to those found for volume growth (White et al., 2009). CAI_{WOOD} was significantly increased by the addition of nitrogen at Scott River and Boyup Brook, an effect that persisted until the end of the first rotation. Reducing stocking density, from unthinned to 300 stems ha^{-1} at age 2 years, significantly reduced wood production at all sites. At the end of the rotation, stand volume was the same ($p > 0.05$) in unthinned stands and in stands thinned at age 2 years to 600 stems ha^{-1}.

3.2. Plantation water productivity over the full rotation (PWP_{WOOD})

For data pooled across the three sites, plantation water-productivity (PWP_{WOOD}) between age 3 years and harvest (about age 10 years) increased in response to annual applications of nitrogen fertiliser from 1.15 to 1.4 g wood kg^{-1} H_2O (Table 1). The effect of nitrogen on the PWP_{WOOD} was significant at Scott River and Boyup Brook (Table 2). Stocking did not significantly affect PWP_{WOOD} between age 3 and 10 years at any of the sites.

3.3. Evapotranspiration

Annual evapotranspiration increased in response to the application of nitrogen at Scott River but not at Wellstead or Boyup Brook (Table 2). At Wellstead, E_t decreased significantly when stands were reduced at age 2 years from unthinned to 300 stems ha^{-1}. The effect of nitrogen addition on E_t at Scott River and Boyup Brook persisted for only two years after the first application while at Wellstead reduction of stocking density from unthinned to 300 stems ha^{-1} resulted in an 18-month lag in the depletion of the soil water store compared to the other treatments. Only at Scott

Table 1
Effects of nitrogen and stocking density on mean water productivity, from age 3- to 10-years, of wood production (PWP_{WOOD}). Within sites treatments with different superscripts are significantly different ($p < 0.05$). Units are g wood kg^{-1}.

	Scott River	Wellstead	Boyup Brook
Unfertilised	1.05[a]	1.48[a]	1.04[a]
Fertilised	1.42[b]	1.48[a]	1.28[b]
300 stems ha^{-1}	1.12[a]	1.55[a]	1.10[a]
600 stems ha^{-1}	1.31[a]	1.31[a]	1.16[a]
Unthinned	1.26[a]	1.60[a]	1.22[a]
Site	1.18	1.50	1.16

Table 2
Significance levels of the effects of N addition (N), stocking density (S) and stand age on PWP_{WOOD} and evapotranspiration (E_t).

	Scott River		Wellstead		Boyup Brook	
	PWP_{WOOD}	E_t	PWP_{WOOD}	E_t	PWP_{WOOD}	E_t
Nitrogen (N)	0.003	0.001	NS	NS	0.037	NS
Stocking (S)	NS	NS	NS	NS	NS	0.049
N × S	NS	NS	NS	NS	NS	NS
Age	0.001	0.001	0.001	0.001	NS	0.027
Age × N	0.028	0.004	NS	NS	NS	NS
Age × S	NS	NS	NS	0.001	NS	NS

River did either nitrogen or stocking affect water balance over the full rotation. The fertilised plots used approximately 200 mm more water than unfertilised plots, and at the end of the rotation the unfertilised plots had not fully exploited the soil water store.

3.4. Annual plantation water productivity (PWP_{WOOD})

A simple linear relationship between wood production (CAI_{WOOD}) and evapotranspiration was significant in all years for Scott River, Wellstead and Boyup Brook. The slope of this relationship, the average plantation water productivity (PWP_{WOOD}), was 2.4 g wood kg^{-1} H_2O in the fifth year of growth (Fig. 2) and decreased in each subsequent year.

3.5. Stand age and water deficit

A significant effect of age on PWP_{WOOD} was evident at Scott River and Wellstead (Table 2). In this case, age is confounded with soil water deficit. At all sites the maximum annual soil water deficit increased significantly as the stands aged (Mendham et al., 2011). At all sites PWP_{WOOD} was positively correlated with soil water deficit (a negative number) so that PWP_{WOOD} decreased as the soil water store was depleted. For example, at Scott River a linear relationship with minimum soil water explained 80% of variation in PWP_{WOOD} of fully stocked, fertilised stands (600 stems ha^{-1} and unthinned) but no relationship was evident for unfertilised stands (Fig. 3).

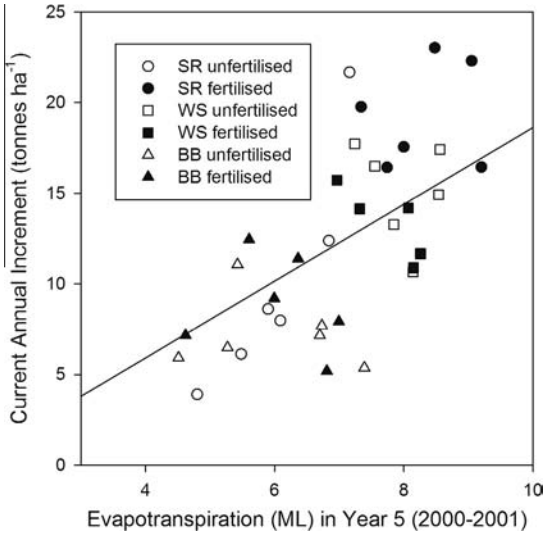

Fig. 2. Current annual increment plotted as a function of annual evapotranspiration for all plots at Scott River, Wellstead and Boyup Brook in the fifth year of growth. A single linear relationship with E_t explains 57% of the variation in CAI_{WOOD} and has a slope of 2.45 g wood kg^{-1} H_2O.

3.6. Nitrogen effects at Scott River and Boyup Brook

Nitrogen significantly increased PWP_{WOOD} at Scott River and Boyup Brook (Table 2) and this effect was significant in the fourth, fifth and sixth year of the rotation (Fig. 4). For all stocking densities the absolute and proportional difference in PWP_{WOOD} between fertilised and unfertilised stands was greatest in the second or third year after the first application of nitrogen.

3.6.1. Seasonal patterns of water use in fertilised and unfertilised stands; effects on annual plantation water productivity (PWP_{WOOD})

Cumulative evapotranspiration E_t, from April 1999 to September 2005, of the unthinned, fertilised and unfertilised plots at Scott River was 4769 and 4668 mm respectively (47.6 and 46.7 $MLha^{-1}$), a cumulative difference of <3% (Fig. 5). E_t of the fertilised plots was greater than in the unfertilised plots during spring and early summer or after a summer rainfall event such as in January 2002. Towards the end of summer and in early autumn in 2001, 2002, 2003 and 2004 the unfertilised plots used more water than the fertilised plots (Fig. 5). This occurred when predawn water potential was much lower, and by as much as 2 MPa, in the fertilised compared to the unfertilised plots (see Fig. 5 in White et al. (2009)). Unfertilised trees only ever used more water than fertilised trees late in the dry season when air saturation deficit was high and daily rates of average evaporation (Allen et al., 1998, FAO56) exceeded 4.5 mm (Fig. 6).

4. Discussion

In these experiments in south-western Australia, the water-productivity of wood production (PWP_{WOOD}) increased in response to the application of nitrogen but was not affected by thinning. Although there was a significant linear relationship between annual wood yield and water use, values of PWP_{WOOD} varied from

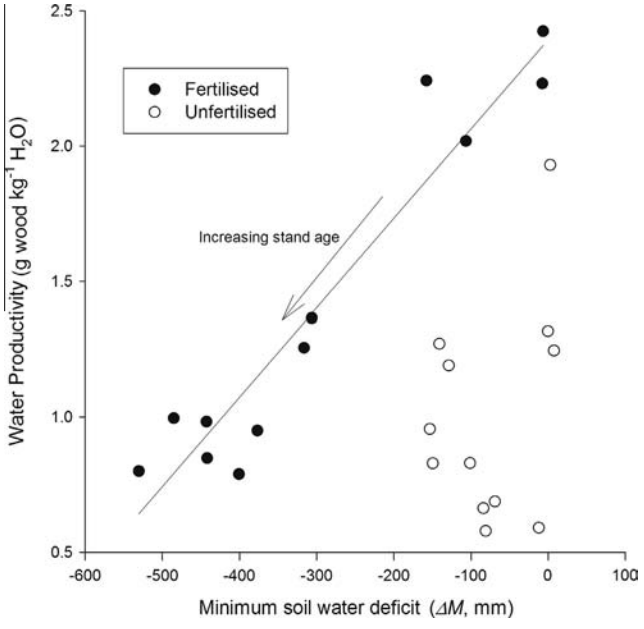

Fig. 3. Water productivity as a function of minimum annual soil water deficit for fertilised and unfertilised stands at Scott River (only 600 stem ha^{-1} and unthinned plots included). For the fertilised stands age tends to increase in the direction of the arrow (this trend is not absolute but the correlation between stand age and soil water deficit is strong). There is no relationship for the unfertilised stands that did not exhaust the stored soil water during the first rotation.

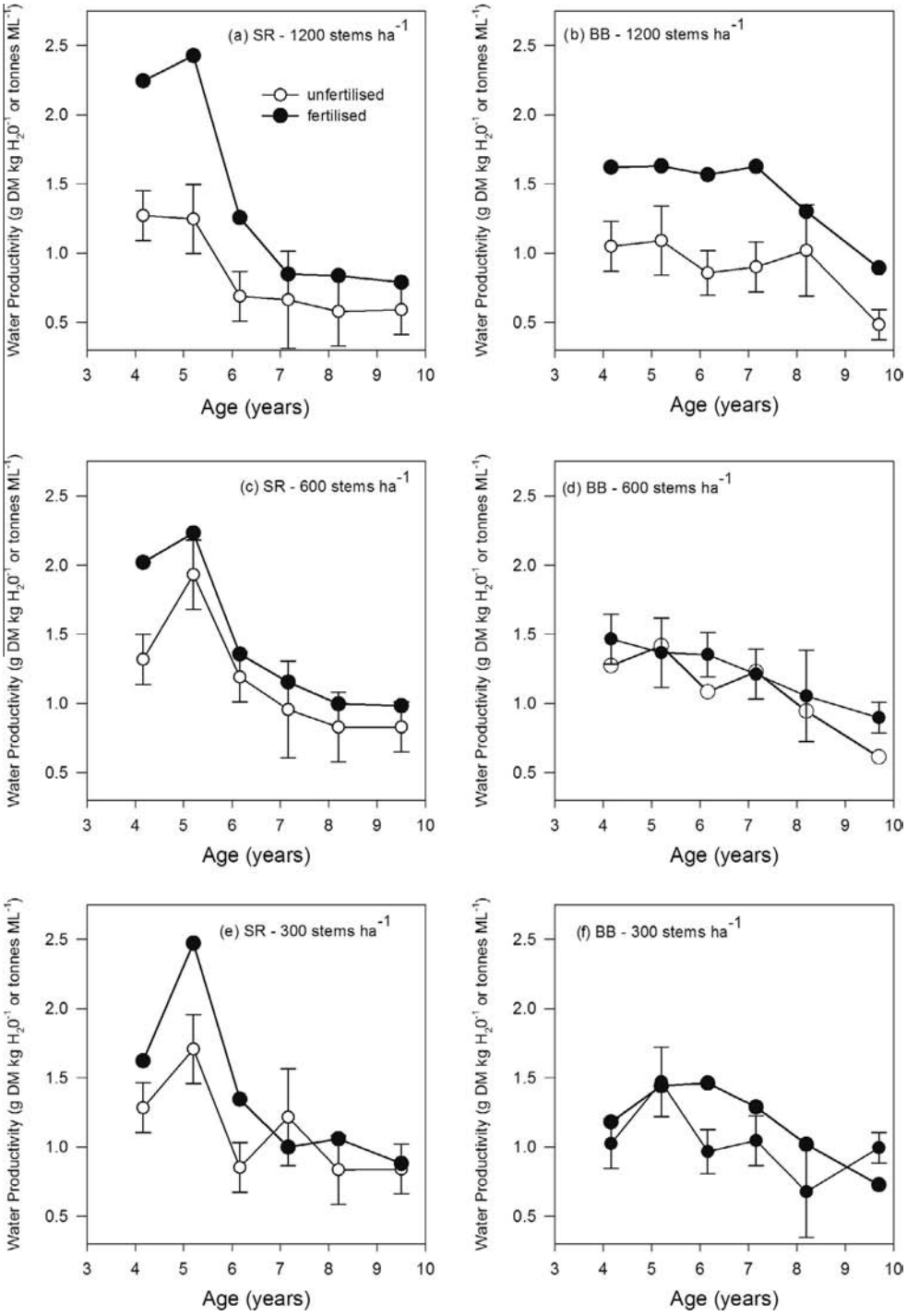

Fig. 4. Water productivity during the first rotation for fertilised and unfertilised stands at Scott River (SR) and Boyup Brook (BB) and by stocking density. The application of nitrogen significantly increased water use efficiency at all stocking densities at these sites.

0.3 to 3.1 g wood kg H_2O^{-1}. Some of this variation was due to progressive soil drying with stand age and some due to the effects of nitrogen. These results follow earlier papers that showed that the application of nitrogen significantly increased leaf area index (White et al., 2010) and volume growth (White et al., 2009), decreased predawn leaf water potential (White et al., 2009) and increased the soil water deficit (Mendham et al., 2011). Together with these early results, the data presented here, provide important insights into the effects of management on canopy development, water use, water productivity and drought risk.

PWP_{WOOD} varied from 0.3 to 3.1 g wood kg^{-1} H_2O at Scott River, 0.2 to 2.7 g wood kg^{-1} H_20 at Wellstead and 0.3 to 2.2 g wood kg^{-1} H_2O at Boyup Brook. There are few published values with which to benchmark these observations. Forrester et al. (2010), measured transpiration and evapotranspiration of *E. globulus* in pure stands and in mixtures with *A. mearnsii*. In pure stands, *E. globulus* produced approximately 0.6 g wood kg^{-1} of E_t (assuming the same average basic density as Scott River) but this increased by 50% to 0.9 g wood kg^{-1} in the mixture. Early in the second rotation at Scott River, Drake et al. (2012) found that unmanaged coppice

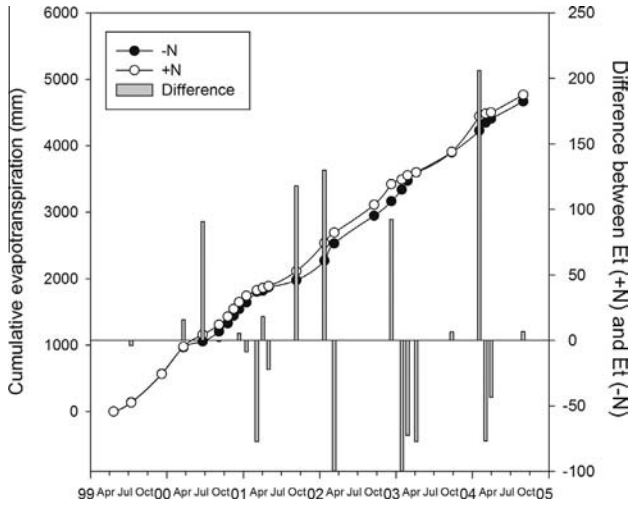

Fig. 5. Cumulative evapotranspiration from April 1999 to October 2004 for fertilised and unfertilised, unthinned stands at Scott River. The bars represent the difference between E_t of fertilised and unfertilised plots for each measurement interval. Bars above the line correspond to periods when fertilised trees used more water than unfertilised plots. The converse is true for bars below the line.

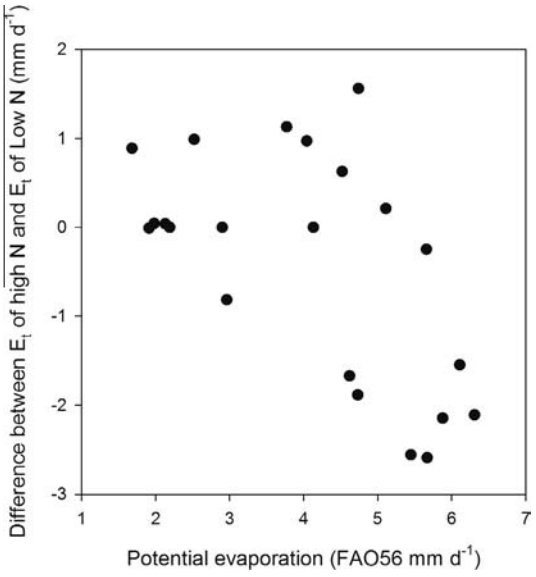

Fig. 6. The difference between E_t of fertilised and unfertilised plots as a function of average daily potential evaporation (FAO-56) at Scott River. The fertilised plots used more water than the unfertilised plots during spring and early summer when evaporation rates were moderate and occasionally after summer rainfall events. The unfertilised plots only used more water than the fertilised plots late in summer when potential evaporation was higher.

was more productive (PWP_{WOOD} 0.8–1.6 g kg^{-1}) than replanted seedlings (PWP_{WOOD} 0.6–0.9 g kg^{-1}). This range for coppiced *E. globulus* was very similar to that for irrigated *Eucalyptus grandis* × *urophylla* coppice (Hubbard et al., 2010). A number of researchers have quantified the transpiration efficiency of dry matter production (TE_{DM}) and wood production (TE_{WOOD}) and values for the former are generally higher for coppice than saplings (Lindroth and Cienciala, 1995; Wildy et al., 2004; Hubbard et al., 2010; Drake et al., 2012). The maximum values of PWP_{WOOD} reported here are higher and the minimum values of PWP_{WOOD} lower than previously published values for plantation systems.

In this study, when the site was fully occupied by well-stocked, fertilised stands, PWP_{WOOD} declined with stand age, and this was associated with an increase in soil water deficit. This trend was observed for all treatments at all sites. Many previous studies have observed an increase in the ratio of carbon assimilation to conductance (A/g; intrinsic water-use efficiency) in response to water stress and attribute this to stomatal closure (eg. Osorio and Pereira, 1993; Aitken et al., 1995; Osorio et al., 1998; Li, 1999; Warren et al., 2001; Searson et al., 2004; Akhter et al., 2005; Monclus et al., 2006, 2009; Gebrekirstos et al., 2010). At Scott River, Wellstead and Boyup Brook, water stress may have increased the instantaneous water-use efficiency of carbon assimilation (Drake et al., 2009, 2012) but this was associated with a decrease in PWP_{WOOD}. The decline in plant available soil water with stand age may have reduced the PWP_{WOOD} due to an effect of water stress on productivity, water use or partitioning. Ryan et al. (2004) observed that declines in resource availability, either nutrients or water, increased partitioning below ground in *Eucalyptus saligna* Smith. Stape et al. (2010) and Ryan et al. (2010) reported that allocation below ground increased in response to water stress in plantations of hybrid *E. grandis* x *urophylla*. Stand age and the associated decrease in plant available soil water (Mendham et al., 2011) may also have caused a decrease in xylem conductivity as was observed by (Fichot et al., 2009).

The application of nitrogen increased PWP_{wood} at both Scott River and Boyup Brook. This effect was most pronounced in between age 3 and 6 years and was significant in both the unthinned and 600 stem per hectare plots. Application of nitrogen increased the leaf area index by 50% at Boyup Brook and by more than 100% at Scott River (White et al., 2010). Foliar nitrogen concentration also increased on a mass basis and specific leaf area also increased after application of nitrogen at both sites (White et al., 2010). These changes in canopy characteristics were reflected in significantly higher wood production in the fertilised compared to the unfertilised plots (White et al., 2009). The increase in wood production was proportionally larger than the effect on evapotranspiration. There are at least three possible mechanisms for the observed increase in PWP_{WOOD} in response to application of nitrogen fertiliser. Nitrogen may have increased the partitioning of dry matter above ground and in particular to stem wood. This response has been observed in many tree species including *E. saligna* (Ryan et al., 2004) and *E. grandis* x *urophylla* hybrids (Ryan et al., 2010; Stape et al., 2010). In this study nitrogen increased the rate of evapotranspiration in winter and spring and it is also probable, though not measured, that the high leaf area index reduced soil evaporation in spring and decreased the ratio of evaporative losses to transpiration. The different seasonal patterns of evapotranspiration in fertilised and unfertilised plots at Scott River suggest another mechanism. The unfertilised plots had a lower leaf area and used less water than the fertilised plots in winter spring and early summer. This slower initial rate of water use depleted plant available soil water more slowly so that late in summer, when potential evaporation was greatest, the unfertilised plots sometimes used more water than the fertilised plots. Ultimately both treatments used similar total amounts of water but the higher leaf area index increased the proportion that occurred as transpiration in the fertilised plots and biased water use and growth to winter and early spring when evaporative demand was lower. Importantly these leaf- and stand-scale responses to the application of nitrogen significantly increased the water deficit and water stress experienced by the fertilised compared to unfertilised trees resulting in significant drought mortality in 2003 (White et al., 2009).

These comparative seasonal patterns of water use of fast-growing fertilised trees and slower growing unfertilised trees, highlight the limitations of water-use efficiency measured at the leaf scale for predicting PWP_{WOOD} at the stand scale. As one scales from seconds and leaves to years and stands, instantaneous leaf

level efficiency is one of a number of factors driving cumulative PWP_{WOOD}. The Mediterranean climate of south-western Australia is characterised by cool wet winters and hot dry summers. Rainfall is out of phase with evaporation resulting in large monthly water deficits during summer. Under these circumstances early season growth, driven by increased leaf area index and partitioning to stem wood, will deplete the soil water store and ultimately avoid inefficient water use later in the summer. Each of these strategies will move plantations towards their water limited production potential. Both of these mechanisms for increasing PWP_{WOOD} have the potential to increase water stress and the risk of drought mortality in dry summers.

One option for reducing this risk of drought mortality, that, at least at Scott River and Wellstead, did not reduce productivity is to reduce the stocking density. Over the full rotation, stands with 600 stems ha^{-1} produced as much wood as unthinned stands at these sites (White et al., 2009). In unthinned stands PWP_{WOOD} peaked a year earlier than in stands reduced to either 600 or 300 stems ha^{-1}. Forrester et al. (2012) found that thinning *E. nitens* plantations from 900 to 300 stems ha^{-1} increased the transpiration efficiency of above-ground biomass growth by 23%. This gain was attributed to the increased irradiance of the lower crown in the thinned stand. Other authors have shown that the instantaneous water-use efficiency of carbon assimilation can be reduced by the increased coupling of thinned canopies to prevailing conditions and by the increased irradiance of the lower crown (Breda et al., 1995; D'Alessandro et al., 2006). Again this highlights the importance of integrating responses to management at stand scale and over the full rotation. As we have shown, thinning can change the temporal pattern of water use but may not affect the full-rotation water use. Thinning is an effective way of managing risk without affecting water-use efficiency of commercial plantations of *E. globulus*. This mitigation of drought risk though timely thinning was also reported for *P. pinaster* (Butcher, 1977) and more recently in another commercially important plantation species, *Pinus radiata* D. Don. (Stone et al., 2011).

Recent synthesis publications from agriculture report a transition of thinking away from instantaneous transpiration efficiency towards a whole-of-system approach to maximising water-use efficiency and managing risk (Blum, 2009; Passioura and Angus, 2010). These reviews highlight the importance of estimating and managing water productivity, inclusive of all evaporative processes, rather than transpiration efficiency. They acknowledge the potential in agricultural systems for water productivity to be negatively correlated with transpiration efficiency. They talk of the potential for perverse outcomes from breeding systems that concentrate on instantaneous transpiration efficiency measured under controlled conditions. In common with Jones (1993) they refer to a confounding of drought responses with water-use efficiency. There is a real opportunity for us to learn from the experience of agriculture and to avoid the pitfalls of breeding and managing for outcomes at scales that are meaningless for plantation systems. In our water-limited plantation production systems we can improve the value of plantations by focusing on increasing the proportion of water use that is transpiration, increasing the proportion of dry matter that is allocated to wood and understanding the linkages between drought responses, value and drought risk.

Plantations are managed at the compartment scale while water resources are monitored and managed at the catchment scale or larger. At the compartment scale growth and PWP_{WOOD} will be correlated with water use. Managing plantations to maximise water use can also minimise the impact of growing a given volume of wood on water resources. This is because the same amount of wood can be grown on a smaller land base and with less water than if a more conservative approach is taken to management. This observation was also made by Stape et al. (2004) but is worth re-emphasizing as it is crucial for more effective management of plantations and water resources.

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