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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)).

$$W = T \times TE_{DM} \times HI \tag{1}$$

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

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

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

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.