

## *E. camaldulensis* Optimal Planting Density in Desert Western Australia in View of Its Photosynthetic Properties

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**Abstract:** The growth rate of *Eucalyptus camaldulensis* at an irrigated plantation in a semi-arid area was same as at a non-irrigated plantation near the seashore (450 mm<sup>-1</sup> precip.). The Leaf Area Index (LAI) and planting density at the former site (0.48, 207 trees ha<sup>-1</sup>) were less than at the latter site (0.98, 1667 trees ha<sup>-1</sup>). We surveyed the photosynthetic properties of *E. camaldulensis* at each site in the summer (dry) and winter (wet) seasons. The leaves were found to have a higher  $V_{cmax}$  than the leaves of other tree species, and  $V_{cmax}$  did not differ between the sites and seasons.  $J_{max}$  for *E. camaldulensis* was near the median for investigated tree species. The response of stomatal conductance to soil water potential did not differ between the sites. These findings suggest that *E. camaldulensis* is highly light-demanding, which means that self-shading of leaves greatly reduces photosynthetic efficiency in the shaded leaves. We conclude that the planting density under semi-arid conditions should be low, to keep the LAI from exceeding 1. The estimated maximum stem and branch biomass production is estimated to be about 3~5 Mg ha<sup>-1</sup>y<sup>-1</sup>.

**Key words:** *Eucalyptus camaldulensis*, Planting density, Photosynthesis, Photosynthetic efficiency, Semi-arid land

### 1. Introduction

In arid and semi-arid regions, drought conditions reduce plant growth. Toward afforesting such regions, we must develop silvicultural techniques that guide the afforestation process from the present arid vegetation (Kojima *et al.*, 2006), techniques that must be based on knowledge of the physiological processes that govern tree growth (Landsberg, 2003). *Eucalyptus camaldulensis* is the most widely distributed eucalypt in Australia. The species excels among eucalypts in salt and drought tolerance (Dale and Dieters, 2007). We have tried to afforest semi-arid land with *E. camaldulensis* for carbon sequestration at an irrigated experimental site (Site C) by water harvesting and hardpan blasting (Yamada *et al.*, 2003, 2004). It is known that *E. camaldulensis* has significantly higher growth rate at a blasted area than at a non-blasted area (Shiono *et al.*, 2007). The leaves of *E. camaldulensis* tend to have constant  $V_{cmax}$  values even at different area-based leaf nitrogen concentrations (Utsugi, 2006).

This paper compares the growth rate and photosynthetic capacity of *E. camaldulensis* at different planting densities under a given water condition. We discuss the optimal planting density in light of the photosynthetic properties of the leaves.

### 2. Materials and Methods

The study was conducted at two experimental silvicultural sites for *E. camaldulensis* in Western Australia. One is Sturt Meadows pastoral station (STM, 28°53' S, 121°45' E) near the town of Leonora. The mean annual precipitation is 200 mm y<sup>-1</sup>, most of which falls between April and August. We set up the experimental site (Site C) near STM (Utsugi, 2006). The other is the Calingiri experimental site (Site Calingiri; 31°12' S, 116°28' E) near town of Northam, 120 km from the west coast.

The water supply at Site C corresponds to precipitation of approximately 500 mm y<sup>-1</sup>. The precipitation at Site Calingiri is 450 mm y<sup>-1</sup>. The *E. camaldulensis* was planted at Site C and Site Calingiri in June 1999 and June 2001, respectively. The respective planting densities are 207 and 1667

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trees  $\text{ha}^{-1}$ . At both study sites, the total nitrogen content in the soil was 0.1% at 5 cm in depth and 0.05% at 25 cm in depth. The stem and branch biomass production was estimated using an allometric equation (Suganuma *et al.*, 2006). The Leaf Area Index (LAI) at Site C was calculated from leaf biomass divided by the mean of leaf mass per area (LMA) ( $307 \text{ g m}^{-2}$ , Utsugi *et al.*, 2006) sampled in September 2003. The LAI at Site Calingiri was measured using a canopy analyzer (LI-2000, Li-Cor Biosciences, Inc., Nebraska, USA) in July 2006.

All gas exchange measurements were made with a portable steady-state photosynthesis system (Li-6400, Li-Cor Biosciences, Inc.). The experiment was done in winter (June to September) and summer (November to March) at each experimental site. We selected 5 to 9 fully expanded leaves for measurement. We measured the leaf photosynthesis response to leaf intercellular  $\text{CO}_2$  concentration (A-Ci) between 06:00 and 10:00. Before measuring A-Ci, all leaves for measuring were shielded from direct sunlight to keep the leaf temperature from increasing. Leaves were acclimated in a chamber for at least 10 min at 20~25 degrees. The temperature in the chamber was set according to the air temperature. For the plotting of A-Ci curves, the light in the chamber was maintained at  $1500 \mu\text{mol m}^{-2} \text{ s}^{-1}$  of photosynthetic photon flux density. We measured the photosynthetic rate at the  $\text{CO}_2$  concentrations of 360, 200, 360, 500, 1500, 1200, 300, 200 and  $50 \mu\text{mol mol}^{-1}$  in the chamber. During the gas exchange measurement for the A-Ci curve, the leaf to air vapor pressure deficit (L-VPD) in the chamber was kept below 1.2 kPa and the leaf temperature was held between 20~25 degrees. Stomatal conductance during the measurement was found to exceed  $0.1 \text{ mmol m}^{-2} \text{ s}^{-1}$ . This procedure avoided the risk of stomatal patchiness. Maximal ribulose-1,5-bisphosphate carboxylase (rubisco) activity ( $V_{c_{\max}}$ ) and maximal electron transport mediated RuBP regeneration capacity ( $J_{\max}$ ) were calculated using a biochemical model (Farquhar *et al.*, 1982). These values were converted to 25-degree values ( $V_{c_{\max}25}$  and  $J_{\max}25$ ) using an equation of temperature dependence (Kosugi, 2003). Following the gas exchange measurements, mass-based nitrogen concentration ( $N_m$ , %) and area-based nitrogen content ( $N_a$ ,  $\text{N gm}^{-2}$ ) were measured for the sample leaves. The hourly changes in photosynthesis for one day and predawn leaf water potential were measured at each site and at a natural forest stand (Site LP) near Site C (Utsugi *et al.*, 2006). The response of stomatal conductance ( $G_s$ ) to net photosynthesis ( $A_n$ ), relative humidity at the leaf surface (RHs) and leaf surface  $\text{CO}_2$  concentration ( $C_s$ ) was calculated using the Ball-Berry empirical stomatal conductance model (Ball *et al.* 1987).

$$G_s = m \times A_n \times \text{RHs} / C_s + G_{s_{\min}} \quad (1)$$

Where  $G_{s_{\min}}$  and  $m$  are the intercept and slope obtained from least-squares regression. All statistical analyses were conducted using Statistica 5.0J, and means are reported  $\pm$  standard error.

### 3. Results and Discussion

For the fifth year after planting, the annual stem and branch growth rate ( $G_{\text{RSB}}$ ) was the same for Site C ( $4.5 \pm 0.32 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ) and Site Calingiri ( $4.2 \pm 0.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ). The LAI at Site C and Site Calingiri were  $0.47 \pm 0.02$  and  $0.93 \pm 0.04$  respectively (Fig. 1). Even if the planting density at Site C increased such that LAI rose to 1, the  $G_{\text{RSB}}$  could not be expected to increase remarkably.

The mass-based nitrogen concentration ( $N_m$ ) did not differ among the seasons nor among the study

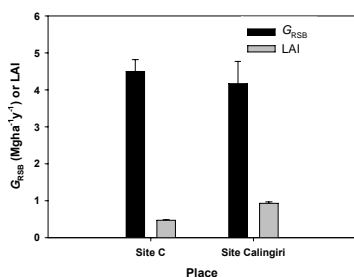


Fig. 1. Annual growth rate ( $G_{\text{RSB}}$ ) and LAI for the fifth year after planting at Site C and Site Calingiri. The error bar is standard error.

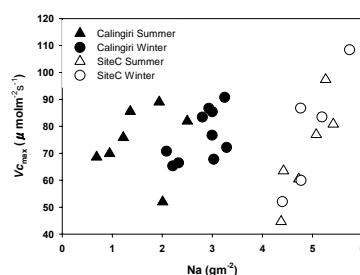


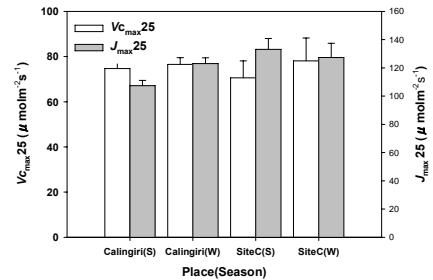
Fig. 2.  $N_a$  vs.  $V_{c_{\max}}$  at Site C and Site Calingiri in summer (triangles) and winter (circles).

sites ( $p>0.1$ ). Na at Site Calingiri varied with season, and the mean Na at Site Calingiri is smaller than at Site C ( $p<0.01$ , **Fig. 2**). These differences result from variations in the LMA. The same variations in Na and LMA were recognized in natural-growth *E. camaldulensis* (Utsugi *et al.*, 2006).  $V_{c_{max}25}$  and  $J_{max}25$  did not differ between sites nor between the seasons ( $p>0.1$ , **Fig. 3**). The average  $V_{c_{max}25}$  and  $J_{max}25$  were  $77.4 \pm 2.1 \mu\text{mol m}^{-2} \text{s}^{-1}$  and  $120.0 \pm 2.9 \mu\text{mol m}^{-2} \text{s}^{-1}$ , respectively. Among the tree species for which  $V_{c_{max}25}$  and  $J_{max}25$  have been determined, the mean  $V_{c_{max}25}$  for *E. camaldulensis* determined in this study is 86% that for the tree species with the highest  $V_{c_{max}25}$  (excluding the outlier, *E. pauciflora*) (**Fig. 4**), and the mean  $J_{max}25$  of *E. camaldulensis* was 54% that for the tree species with the highest mean  $J_{max}25$  (**Fig. 5**).  $V_{c_{max}}$  is the maximum rate of RuBP carboxylation under saturated light at low intercellular  $\text{CO}_2$  concentration. Higher  $V_{c_{max}25}$  indicates that *E. camaldulensis* is highly light-demanding for a  $\text{C}_3$  tree species.  $J_{max}$  is the maximum rate of electron transport, which represents the potential quantum yield from photosynthesis. The  $J_{max}25$  for *E. camaldulensis* puts it near the median among  $\text{C}_3$  tree species. This indicates that the leaves under shade condition cannot have a higher photosynthetic rate than species having higher  $J_{max}25$ . The higher LAI in *E. camaldulensis* forest hinders photosynthetic production per unit leaf area at the stand level, because of self-shading of leaves.

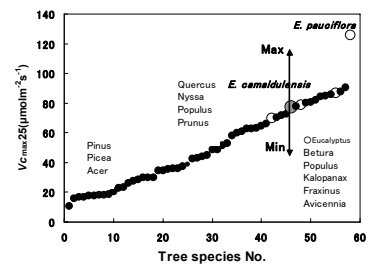
We assume that predawn leaf water potential is equal to soil water potential. There are pronounced seasonal patterns in parameter  $m$  and  $G_{s_{min}}$ , as shown by Equation (1). The parameters decrease when predawn leaf water potential decreases in the range of  $-0.5$  to  $-3.5$  MPa (**Figs. 6 and 7**). In contrast, in a study of Mediterranean blue oak,  $m$  remained constant even when the predawn leaf water potential decreased (Xu and Baldocchi, 2003); however, in studies of other Mediterranean trees (e.g. Sala and Tenhunen, 1996),  $m$  did vary with changes in predawn leaf water potential. Despite the different water conditions among Site C, Site LP and Site Calingiri, the relations in Equation (1) seem to be approximated with one power function (**Figs. 6 and 7**). These findings indicate that the response of stomata to water stress in *E. camaldulensis* does not differ even when the planting density differs. In managing the stand planting of *E. camaldulensis* under shade condition, where photosynthesis is highly light-demanding and inefficient, we should focus on preventing the self-shading of leaves. The standard planting density in semi-arid condition should be set such that the leaf area index does not exceed 1. At such a planting density, stem and branch biomass production is about  $3\sim 5 \text{ Mg ha}^{-1} \text{ y}^{-1}$ .

#### 4. Conclusions

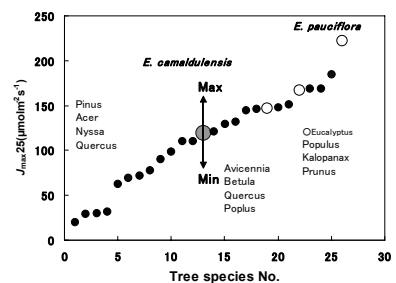
*E. camaldulensis* planted on an irrigated semi-arid site (Site C) and on a non-irrigated plantation site



**Fig. 3.**  $V_{c_{max}25}$  (white bars) and  $J_{max}25$  (gray bars) at Site C and Site Calingiri for the summer(S) and winter(W) seasons.



**Fig. 4.**  $V_{c_{max}}$  values of tree species investigated so far. Black circles are  $V_{c_{max}}$  value of each species put in low order from left side. White circles are those of other eucalypts.



**Fig. 5.**  $J_{max}$  values of tree species investigated so far. Black circles are  $J_{max}$  value of each species put in low order from left side. White circles are those of other eucalypts.

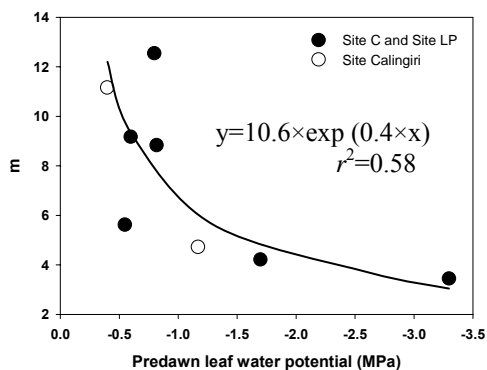


Fig. 6.  $m$  vs. predawn leaf water potential. The “ $m$ ” is determined in Equation (1).

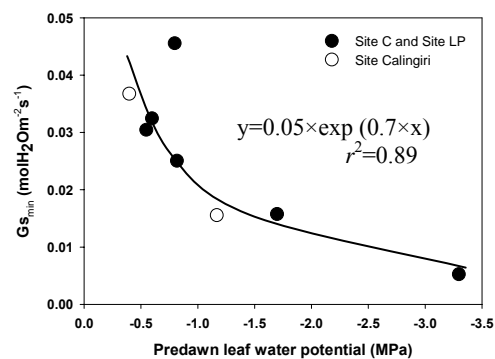


Fig. 7.  $G_{s_{min}}$  vs. predawn leaf water potential. The “ $G_{s_{min}}$ ” is determined in Equation (1).

(Site Calingiri) were compared in terms of stem and branch growth rate ( $G_{RSB}$ ) and photosynthetic properties. Planting density and LAI (LAI=1) were higher for Site Calingiri than for Site C.  $G_{RSB}$  and photosynthetic capacity ( $V_{c_{max}25}$  and  $J_{max}25$ ) did not differ significantly between the sites. *E. camaldulensis* is highly light-demanding, showing high  $V_{c_{max}}$  (86% of the  $V_{c_{max}}$  for the  $C_3$  tree species with the highest mean  $V_{c_{max}}$ ). The response of stomatal conductance to soil water content does not differ greatly between the sites. These findings indicate that silvicultural techniques for afforestation of *E. camaldulensis* in semi-arid areas should keep the LAI below 1, because this will prevent the self-shading of leaves. Under such LAI, the  $G_{RSB}$  is estimated to range from 3 to 5  $Mg\ ha^{-1}\ y^{-1}$ .

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