

## Water use by *Pinus radiata* trees in a plantation

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**Summary** We used the heat-pulse velocity technique to estimate transpirational water use of trees in an experimental 16-year-old *Pinus radiata* D. Don plantation in South Australia during a 4-month period from November 1993 to March 1994 (spring–summer). Fertilization and other silvicultural treatments during the first 8 years of the plantation produced trees ranging in diameter at a height of 1.3 m from 0.251 to 0.436 m, with leaf areas ranging from 83 to 337 m<sup>2</sup>. Daily water use was greater for large trees than for small trees, but transpiration per unit leaf area was nearly identical. Daily transpiration was highly correlated with available soil water in the upper 1 m of soil and weakly correlated with irradiance and air temperature. For the stand (0.4 ha), estimated rates of transpiration ranged from 6.8 to 1.4 mm day<sup>-1</sup> in wet and dry soil conditions, respectively. Total water use by the plantation during the 4-month study period was 346 mm. Water transpired by the trees was about three times that extracted from the upper 1 m of soil. Large trees extracted water from the same soil volume as small trees and did not exhibit a greater potential to extract water from deeper soil when the upper horizons become dry.

**Keywords:** heat-pulse velocity, leaf area, sapwood area, soil water, transpiration.

### Introduction

With appropriate silviculture and fertilization, the mean annual increment (MAI) of *Pinus radiata* D. Don plantations in south-east South Australia and southwest Victoria is generally in the range of 20 to 30 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> over 40 years (Smethurst and Nambiar 1990). On the best sites, MAI can exceed 35 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> over the same period (Boardman 1988). These productivities are high compared with those of other forests receiving similar amounts of rainfall (800 mm year<sup>-1</sup>) (Nambiar 1995). One possible explanation is that the trees have access to an appreciable amount of groundwater.

The unconfined aquifer in the region at depths of 8 to 10 m could be accessed by roots penetrating through the sandy soils. Anecdotal information indicates that tap and sinker roots of *P. radiata* can extend to these depths. Furthermore, based on measurements of soil water and precipitation, Mitchell and Correll (1987) calculated that a young *P. radiata* plantation in this region used more water than was available in rainfall, and they observed that the water table depth dropped substantially

as the stand developed. It has been demonstrated that even 2-year-old seedlings can extract water from 2 m depths (Sands and Nambiar 1984).

We examined the relationship between soil water availability and transpirational water loss. We assumed that a close coupling between the soil water content in the upper meter of soil and transpirational water loss would indicate that most transpired water was coming from the soil rather than groundwater, whereas a poor correlation between soil water content in the upper horizons and transpired water would be indicative of substantial water use from lower soil depths. Other objectives of the study were to: (1) measure water use by *P. radiata* trees in a plantation that had developed its maximum leaf area; (2) determine if, on a proportional basis, larger trees use more water than smaller trees; and (3) develop relationships based on microclimate and stand characteristics that could be used to estimate transpirational water loss from the plantation.

### Materials and methods

#### Study description

The study was located in a 16-year-old *P. radiata* plantation located near Wandilo, approximately 10 km north of Mt. Gambier, South Australia. The climate is Mediterranean with cool wet winters and warm dry summers. The average annual rainfall is 714 mm of which about 80% falls in the winter. Monthly mean maximum and minimum air temperatures vary from 25.2 and 10.8 °C in January (summer) to 13.0 and 4.9 °C in July (Australian Bureau of Meteorology). The soil is a deep podsolized sand. The experimental plantation was established in 1978 after clear-felling the previous *P. radiata* stand. At planting, all trees received fertilizer with macro- and micronutrients, and weed control with herbicides. Three nitrogen treatments were established: N0, no additional nitrogen applied; N1, 766 kg N ha<sup>-1</sup> applied over the first 8 years (1978–1986); and N2, 1900 kg ha<sup>-1</sup> applied over the same time period. In addition phosphorus was applied at three rates: P0, no addition; P1, 94 kg P ha<sup>-1</sup>; and P2, 205 kg P ha<sup>-1</sup>. Some other treatments were applied to the plantation either before planting (soil sterilization, lime amendments, tillage) or at the time of planting (addition of mycorrhizal symbionts, application of insecticide), but after 16 years of growth, the effects of these additional treatments were not apparent. The site had been thinned

twice, at ages 4 and 11 years.

For this experiment, we chose to use trees in three fertilizer combinations: N0P0, N1P0 and N1P1. These represented the slowest and fastest growing trees in the plantation as well as an intermediate rate of growth. Mean diameters at a height of 1.3 m of experimental trees ranged from 0.25 m in the N0P0 treatment to 0.42 m in the N1P1 treatment. For unknown reasons, the N2 and P2 treatments had resulted in an intermediate rate of growth.

### Measurements

Heat pulse velocity probes (Greenspan Technology Pty. Ltd., Warwick, Queensland, Australia) were used to estimate whole-tree transpiration. The probes consisted of two thermistors, one 10 mm upstream and one 5 mm downstream from a heater. Thermistors and heater were enclosed in 2-mm diameter stainless steel tubing. Two probes were placed at a height of 1 m, each at a different depth, in the sapwood of each tree. Following the procedure outlined by Hatton et al. (1990), the depth for each probe was calculated so that the thermistors were at the center of equal annuli of sapwood area. To determine the radius of heartwood and sapwood, each measurement tree was cored with an increment borer. Heat pulse velocity was calculated as outlined by Dye et al. (1992) and corrected for wound effects (Swanson and Whitfield 1981). Sap velocity was calculated from heat pulse velocity based on the known volume fraction of wood and water. Sap velocity was converted to sap flux by multiplying by the sapwood area at the positions of the probes and applying a correction for the radial sap velocity profile relative to that measured by the probes. This approach produced good agreement between the estimate of sap flux from the sensors and actual sap flux from a cut tree (Figure 1).

Three trees, one of each size class, were measured each week during the summer (October 26, 1993 to February 28,

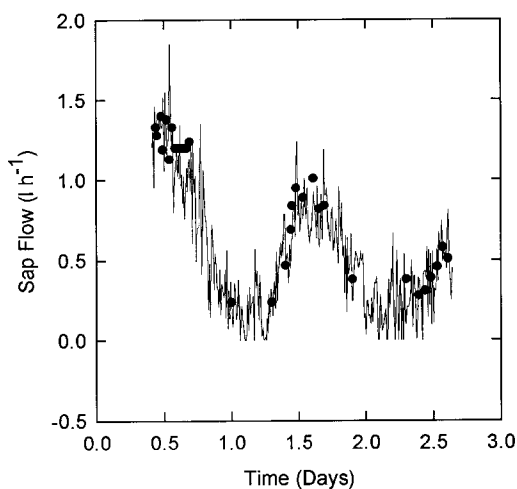


Figure 1. Comparison of estimated and actual rates of water uptake in a 0.18-m diameter *P. radiata* tree. Sap flow calculated from heat pulse velocity is shown by the line. The circles represent measured rates of water uptake from a cut tree placed in water. The heat pulse probes were placed approximately 0.1 m above the cut end of the stem.

1994). Heat pulse velocity measurements were made and recorded automatically every 10 min. These values were integrated separately for each tree to provide an estimate of its daily transpirational water use.

The sampled trees were distributed throughout a 0.4-ha area and were used to calculate total daily rates of transpiration. At the end of the study, leaf area, which was assumed to have remained constant during the study period, was estimated by destructive sampling of the crowns of the sample trees. A relationship between projected leaf area and basal area was developed and used to estimate the projected leaf area of the stand. Foliage was also collected concurrently from five whorls, equally spaced from the top to the bottom of the canopy, and dried for nutrient analysis as described by Sheriff and Nambiar (1991).

A relationship between transpiration per unit leaf area and microenvironment was developed by multiple linear regression analysis. Environmental measurements of photosynthetically active radiation ( $Q$ ) (quantum sensor, Li-Cor Inc., Lincoln, NE), air temperature (platinum RTD probe, Temperature Controls, Leichhardt, NSW, Australia) and dew point (Dew 10, General Eastern Corp., Waterton, MA) were made at 5-min intervals and recorded as hourly means with a DT 100F data logger (Data Electronics, Boronia, Victoria, Australia). Both the air temperature and dew point sensors were aspirated and shielded. Rainfall was measured after each rain event with a rain gauge in an open field. Volumetric soil water was sampled monthly with a 50-mm diameter sampling tube to a depth of 1 m. Five soil water samples were taken, and each sample was divided into 0.2-m increments for gravimetric calculation of water content. Between sampling intervals, water content of the soil was estimated by an empirical relationship of the form:

$$\text{Soil water content} = W_s(a + be^{cd}), \quad (1)$$

where  $W_s$  is the mean volumetric soil water content (0 to 1 m) at Day 1 of a drying cycle,  $a = 0.3$ ,  $b = 0.8$ ,  $c = -0.06$  and  $d = \text{day}$ , where the initial day of the drying cycle = 1. There were three major (> 5 mm) rainfall events during the measurement period. The increase in soil water content after each of these was calculated from the amount of precipitation minus interception losses from canopy and litter. An estimate of 29% interception loss from measurements in a 7-year-old *P. radiata* plantation was used (Kelliher et al. 1992).

### Statistical analysis

Multiple linear regression was used to develop a model for estimating daily rates of transpiration with environmental factors as the independent variables. These calculations were performed using SigmaStat statistical software (Jandel Scientific, San Raphael, CA).

### Results

Stem diameter of the nine trees at a height of 1.3 m ranged from 0.251 to 0.427 m, basal area from 0.0495 to 0.1492 m<sup>2</sup>, and leaf

area from 64.0 to 337.3 m<sup>2</sup> (Table 1). There were no significant differences between trees for any of the foliar nutrient concentrations measured (Table 2). When the daily transpiration rates of trees of different diameters were compared, it was evident that larger diameter trees used much more water than smaller diameter trees (Figure 2). However, when transpiration rates of these trees were divided by their respective leaf areas, differences were no longer apparent (Figure 3) indicating that transpirational water use by different sized trees within the plantation was proportional to their leaf area.

Transpiration rate calculated on a unit leaf area basis varied from day to day and also appeared to be highest in the spring and lowest toward the end of the summer (Figure 3). A multiple linear regression was used to determine if environmental factors correlated with these patterns of water use. Daily measures of photosynthetically active radiation, air temperature and vapor pressure deficit in the forms of mean, sum, maximum and minimum values, as well as daily soil water content, calculated from Equation 1, were used in the regression. In addition, various transformations of each variable that might describe the relationships being modeled were attempted. The best model was ( $R^2 = 0.84$ ):

$$\ln E = -2.14 + 32.845W_s + 0.0007577Q + 0.016T_a \quad (2)$$

where  $\ln E$  is the natural log of daily transpiration (liter day<sup>-1</sup> m<sup>-2</sup>),  $W_s$  is the mean volumetric soil water content in the upper 1 m of soil (m<sup>3</sup> m<sup>-3</sup>),  $Q$  is the mean daily photosynthetically

active radiation ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), and  $T_a$  is the mean daily air temperature ( $^{\circ}\text{C}$ ). Vapor pressure deficit was not a significant variable in this model. Examining the partial  $R^2$  for each variable showed that  $W_s$  was the most important factor, accounting for 80% of the variation in daily transpiration, whereas  $Q$  accounted for 3% and air temperature for 1%.

Based on Equation 2, transpiration was calculated for the entire measurement period and compared with the measured

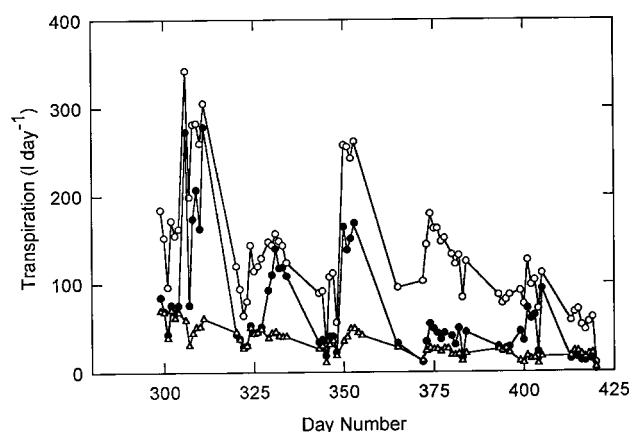


Figure 2. A comparison of daily rates of whole-tree transpiration for small ( $\Delta$ ), medium ( $\bullet$ ) and large diameter ( $\circ$ ) trees. Each point represents the transpiration rate of an individual tree. Day 1 was January 1.

Table 1. Aboveground biometric characteristics of the *P. radiata* trees used for the sap velocity measurements.

Tree no.	Diameter (m)	Height (m)	Basal area (m <sup>2</sup> )	Sapwood area (m <sup>2</sup> )	Projected leaf area (m <sup>2</sup> )
1	0.251	22.4	0.0495	0.0364	83.33
2	0.254	22.5	0.0506	0.0307	63.96
3	0.269	23.7	0.0568	0.0438	91.98
4	0.288	23.9	0.0652	0.0467	93.32
5	0.297	24.2	0.0692	0.0493	127.98
6	0.322	24.5	0.0814	0.0593	164.56
7	0.410	24.7	0.1320	0.1025	259.00
8	0.415	24.7	0.1352	0.1081	305.25
9	0.436	25.2	0.1492	0.1161	337.25

Table 2. Mean nutrient concentrations (mg g<sup>-1</sup>) in the foliage of the nine study trees. Tree numbers correspond to those in Table 1. The number in parenthesis is 1 SE. There were no statistically significant differences among trees in the concentration of each nutrient at  $P = 0.05$ .

Tree no.	N	P	K	Ca	Mg
1	11.382 (0.999)	1.358 (0.165)	6.614 (0.363)	3.888 (0.397)	1.976 (0.268)
2	12.501 (0.729)	1.556 (0.239)	6.210 (0.324)	4.746 (0.584)	2.630 (0.158)
3	13.109 (1.119)	1.840 (0.580)	7.026 (0.936)	4.536 (1.109)	2.352 (0.201)
4	11.393 (1.108)	1.898 (0.257)	7.508 (0.478)	4.408 (0.742)	1.404 (0.202)
5	11.187 (0.711)	1.820 (0.170)	8.984 (0.434)	4.094 (0.938)	1.758 (0.275)
6	12.885 (1.349)	1.956 (0.407)	6.702 (0.293)	4.408 (0.793)	1.978 (0.302)
7	11.682 (1.083)	1.480 (0.223)	8.410 (0.584)	3.384 (0.762)	1.350 (0.214)
8	11.313 (0.425)	1.916 (0.227)	7.916 (0.684)	3.410 (0.654)	1.710 (0.074)
9	11.563 (0.693)	1.862 (0.391)	8.434 (0.860)	3.362 (0.858)	1.970 (0.234)

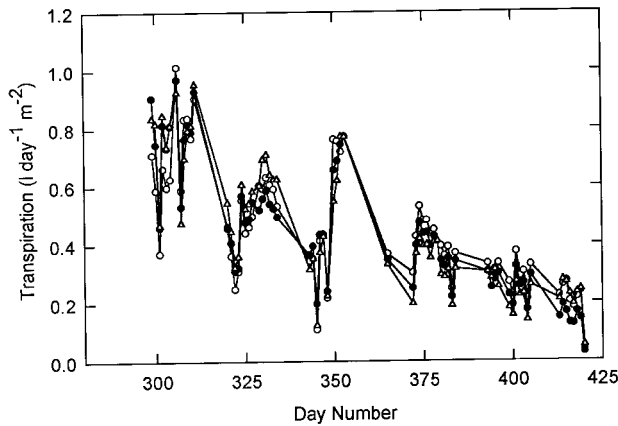


Figure 3. A comparison of daily rates of transpiration calculated on a leaf area basis for the same small ( $\Delta$ ), medium ( $\bullet$ ) and large diameter ( $\circ$ ) trees shown in Figure 2. The total daily rate of transpiration of each tree (shown in Figure 2) was divided by its individual leaf area. Day 1 was January 1.

values (Figure 4). Although the model was not sensitive enough to estimate the highest and lowest rates of transpiration accurately, overall, it appeared to fit the data well, as might be expected from the high  $R^2$ .

Estimated daily water use ( $\text{liter m}^{-2} \text{day}^{-1}$ ) and information on the biometric characteristics of the stand were used to estimate stand transpirational water use. For the nine measurement trees, there was a clear relationship between sapwood area and basal area (Figure 5). The intercept of this relationship did not cross zero, presumably because the relationship between sapwood area and basal area changes after *P. radiata* begins to develop heartwood. There was a linear relationship between leaf area and sapwood area of the trees (Figure 6A), and because sapwood area and basal area were linearly related, leaf area and basal area were also linearly related (Figure 6B).

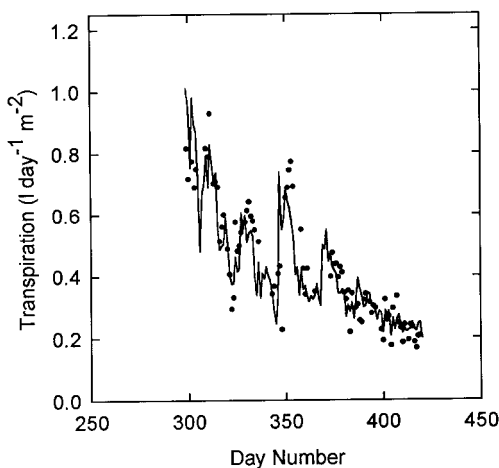


Figure 4. Comparison of measured ( $\bullet$ ) and modeled (line) daily rates of transpiration on a unit leaf area basis. Each data point represents the mean of three trees, one small, one medium and one large in diameter. Overall, the average standard error was 0.026, with a minimum of 0.015 and maximum of 0.057. Day 1 was January 1.

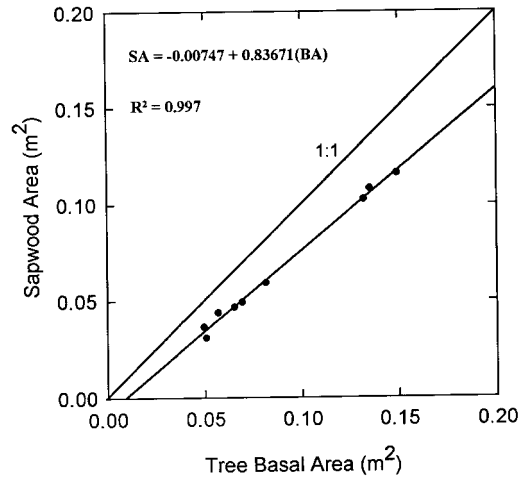


Figure 5. Relationship between sapwood area (SA) and basal area (BA) for the nine trees used for measurements of sap velocity.

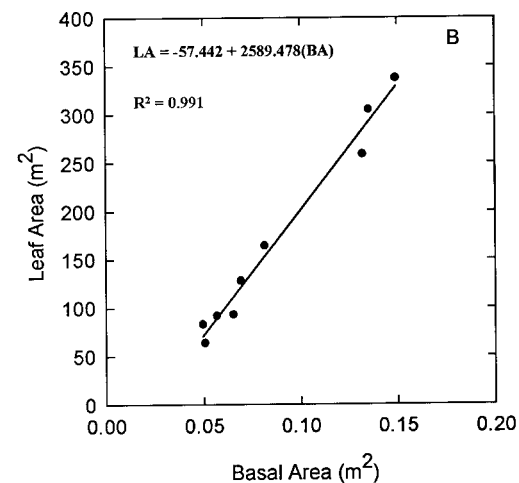
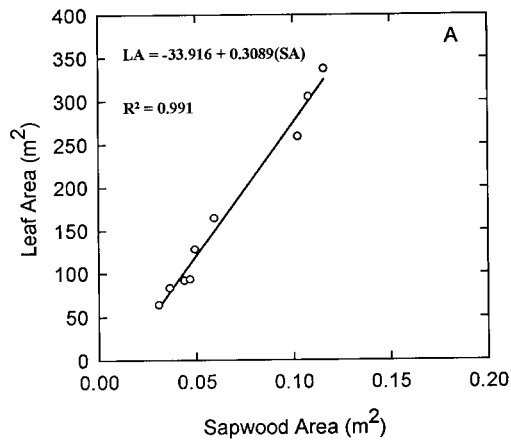


Figure 6. (A) Relationships between leaf area (LA) and sapwood area (SA), and (B) leaf area and basal area (BA) for the nine trees used for measurements of sap velocity.

Trees in the stand were grouped into 10 basal area classes ranging from 0.048 m<sup>2</sup> to 0.156 m<sup>2</sup> (Figure 7). The relationship between leaf area and basal area (Figure 6B) was used to estimate the total leaf area of trees in each basal area class (Figure 8). By summing the leaf areas of all 10 basal area classes and dividing by 0.4 ha, the area occupied by the stand, the leaf area index of the stand was estimated to be 6.6.

Daily stand transpiration was estimated from the daily values of transpiration per m<sup>2</sup> of foliage and from stand leaf area. It was calculated in both liter ha<sup>-1</sup> day<sup>-1</sup> and mm day<sup>-1</sup> (Figure 9). Because the leaf area of the stand did not change during this period, the pattern of stand transpiration followed that of transpiration calculated on a unit area of foliage basis. Transpiration ranged from 6.82 mm day<sup>-1</sup> (68,286 liter ha<sup>-1</sup> day<sup>-1</sup>) in late spring to 1.41 mm day<sup>-1</sup> (14,173 liter ha<sup>-1</sup> day<sup>-1</sup>) at the end of the summer. Total water use and total withdrawal from the top 1 m of the soil profile during this 120-day period were 346.4 and 110.4 mm, respectively.

## Discussion

Hatton and Vertessy (1990) used the heat pulse technique to estimate water use by a 9-year-old *P. radiata* plantation on 4 days in October and found that it varied from 5.31 to 3.06 mm day<sup>-1</sup>. Although these values are lower than our highest value (6.8 mm day<sup>-1</sup>), measured in the first week of the study, they are closely comparable to the values we obtained in the remainder of the study: 5.4 to 1.4 mm day<sup>-1</sup> (Figure 9). Whitehead and Kelliher (1991) used a modeling approach incorporating the Penman-Monteith equation (Monteith 1965) to estimate transpiration by a 13-year-old *P. radiata* stand in New Zealand. Transpiration in that stand, which had a projected leaf area index of 4.9, ranged from approximately 5 to 1 mm day<sup>-1</sup> with an estimated total water use during the 4-month period from November through February of 370 mm, which is comparable with our estimate of 346 mm for the same period. Whitehead and Kelliher (1991) estimated that the total annual water use of the stand was 704 mm. The transpiration rates

measured in our study were also within the range of summer-time transpiration rates reported for other temperate coniferous stands (see reviews by Whitehead and Jarvis 1981 and McNaughton and Jarvis 1983).

Water use by individual trees was proportional to their leaf area. Part of the reason for this was that nutrient concentrations per unit area of foliage were not significantly different in trees of different sizes. Even though the trees had received different amounts of fertilizer, nutritional effects on stomatal conductance were not evident (Sheriff et al. 1986). Presumably, over time, differences in foliar nutrient concentration were diminished by tree growth and crown development. Fertilizer not absorbed by trees is readily leached from the sandy soil on this site during the first winter after fertilizer application. Thus there is no long-term reserve of soil nutrients from applied fertilizer. Similarity in transpiration per unit leaf area in trees of different sizes also indicates that although larger trees were using more water, they were unable to exploit water available

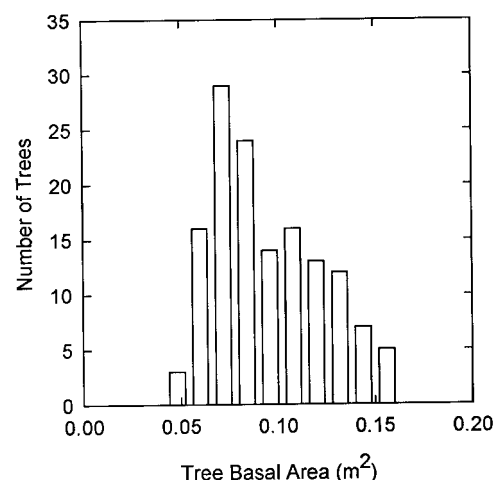


Figure 7. The number of trees in the plantation in each of 10 basal area classes.

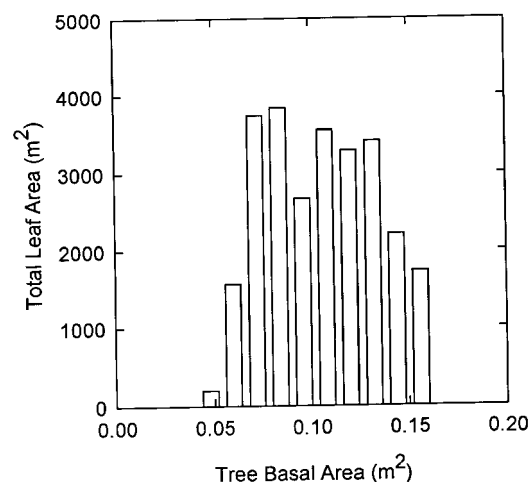


Figure 8. Total leaf area for each of the basal area classes.

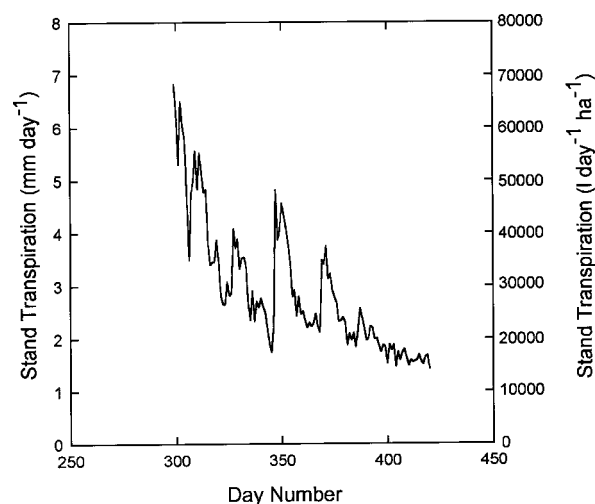


Figure 9. Total daily stand transpiration in units of mm day<sup>-1</sup> and liter ha<sup>-1</sup> day<sup>-1</sup> during the measurement period. Day 1 was January 1.

at depth or in the aquifer any more effectively than smaller trees, which suggests that roots of large and small trees occupied a similar soil volume. Proportional water use by large and small trees, relative to their leaf areas, may not apply in stands that are rapidly changing, e.g., before canopy closure or shortly after thinning or fertilization. However, in this stand, which was thinned 5 years before the start of the experiment and last fertilized 8 years earlier, it appears that relative water use by individual trees can be predicted from their leaf area.

The large differences in daily water use during the summer could be explained by fluctuations in the environmental factors, especially soil water, that regulate water uptake by roots and water loss through stomata. Because the sandy soils at the site have low water-holding capacity, soil water was rapidly depleted under the forest canopy, resulting in rapid changes in water use during drying cycles. Close correspondence between rates of evapotranspiration and soil water content during a drying cycle has been demonstrated for young *P. radiata* (Ruiter 1987), *Eucalyptus nitens* Maiden and *E. delegatensis* R.T. Bak. (Honeysett et al. 1992). The high correlation between soil water in the upper meter of soil and daily stand water use indicates a strong effect of water availability in the upper soil horizons on transpiration. The mechanism underlying this response could result from two effects acting singly or together. (1) If the root system transported large amounts of water from the aquifer to the atmosphere, appreciable decoupling of transpiration from soil water would be expected, especially during dry periods. Our results indicate that the plantation was not using large amounts of water from deep water sources. (2) Drying of soil around all (e.g., Turner 1986), or only a portion (e.g., Blackman and Davies 1985), of a plant's roots has been found to reduce stomatal conductance, even at full leaf turgor (e.g., Gollan et al. 1986) in many species. This root to shoot communication, which is mediated by hormones (e.g., Schulze 1986), may have caused stomata to close when the upper meter of soil dried, even though water was accessible at lower depths.

During the 4-month study, the stand transpired about 3.14 times more water than it withdrew from the top 1 m of the soil profile. This estimate includes water present in the soil at the beginning of the experiment and that added to the soil by rain during the experiment. We do not know how much water was available in the soil below 1 m, but lack of organic matter and higher bulk density of deeper sand generally means that deeper soil has a lower water-holding capacity than soil nearer the surface. Over the 4-month study period, of the total transpirational water use of 345 mm, 110 mm can be accounted for in the upper 1 m of soil and rainfall, leaving 235 mm unaccounted for. An appreciable amount of water must have been obtained from soil depths lower than 1 m or the aquifer, or both. Water available at depth may be used only when water availability in the upper 1 m of soil is limited, or it may be used whenever there is uptake into the trees. Because the aquifer was at a depth of 8 to 10 m at the site, water raised to the surface would have a pressure potential of more than  $-0.1$  MPa. Predawn water potentials (considered to be the highest during the day) at a nearby site averaged  $-0.6$  MPa in winter and  $-1.0$  MPa in

summer (Sheriff and Nambiar 1995). Thus water potentials of the trees were always low enough to lift water from depth. At the end of the summer, the upper 1 m of soil was very dry ( $< 0.02 \text{ m}^3 \text{ m}^{-3}$  mean volumetric soil water content). If the mean minimum transpiration rate at this time,  $1.7 \text{ mm day}^{-1}$ , is taken as the daily contribution to transpiration from lower soil depths or the aquifer, or both, this would account for almost all of the additional water extracted (204 of 235 mm). When the soil water content is high in the upper 1 m, the relative contribution from roots at depth would be less than 25% of daily water use, but it would rise to nearly 100% when the upper horizons are dry. Before the use of deep water by *P. radiata* in regions with unconfined aquifers can be fully resolved, further investigation, including a yearly water balance, is required to assess whether there is sufficient recharge of soil water to meet annual evapotranspiration by these plantations.

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