

**ROOT-ZONE WATER STORAGE AND GROWTH OF  
*PINUS RADIATA* IN THE PRESENCE OF  
A BROOM UNDERSTOREY**

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### ABSTRACT

A simple water balance model was used to explain the difference in basal area growth over 3 years for 9- to 12-year-old *Pinus radiata* D. Don growing on a dryland site in the presence of a broom (*Cytisus scoparius* L.) understorey and where the understorey was removed. With an annual average rainfall of 600 mm, seasonal water deficits are characteristic of the well-drained, stony silt-loam soil. During the summer months, root-zone water content fell to approximately 90 mm, about 50% of the winter maximum. Modelled estimates of daily root-zone water storage in the two treatments were in close agreement with neutron probe measurements. *Pinus radiata* basal area increment over the experiment was approximately 9% higher in the treatment where the broom understorey was removed. Annual basal area increments for both treatments were highly correlated ( $r = 0.97$ ) with an annual integration of root-zone water deficits. The approach used in this study highlights the importance of root-zone water storage in regulating productivity at dry sites and confirms the success of water balance modelling to explain the impacts of understorey control on tree growth.

**Keywords:** plant competition; water balance; growth models; *Pinus radiata*; *Cytisus scoparius*.

### INTRODUCTION

*Pinus radiata* productivity is an important issue for plantation forest managers in New Zealand and many forest operations are directed at maintaining or increasing rates of production. The potential for tree growth is governed by the amount of intercepted solar radiation, but other factors, such as available soil water and fertility, control what is actually

achieved (Benson, Myers & Raison 1992). Experiments on dry sites that included irrigation and fertiliser (Benson, Landsberg & Borough 1992; Clinton *et al.* 1995; McMurtrie, Benson, Linder, Running, Talma, Crane & Myers 1990) have shown that root-zone water deficits limit tree growth by regulating the period during which tree growth is possible (Benson, Myers & Raison 1992). Furthermore, without sufficient water, trees are unable to utilise available nutrients.

Non-crop plant species can reduce tree growth by utilising resources (water, light, nutrients) that would otherwise be available for tree growth. Broom is one serious weed of New Zealand's *P. radiata* plantation forests. A number of studies have demonstrated that this nitrogen-fixing species can have a large negative influence on tree growth in the first few years after planting on both moist (Richardson *et al.* 1996) and dry sites (Clinton *et al.* 1995; Richardson *et al.* 1997). Weed control measures, often using herbicides, are routinely applied during the plantation establishment phase (Richardson 1993). These practices do not normally eliminate the target species, but simply delay their development. As a result, dense understoreys can develop beneath plantations.

A study on a moist, North Island site concluded that broom reduced tree growth by restricting light availability to tree crowns (Richardson *et al.* 1996, 1999). On sites of this type, it would be expected that competition for site resources would largely cease when tree crowns overtop the broom (i.e., when broom becomes an understorey species). Results from studies on drier sites have implicated water supply limitations in addition to light availability in the interaction between broom and *P. radiata* (Clinton *et al.* 1995; Richardson *et al.* 1997). On these sites it seems probable that resource competition would continue as long as the understorey is actively growing, unless the trees can access water deeper in the profile that is not available to broom. Understorey persistence is encouraged by *P. radiata* management practices that delay canopy closure, such as low crop stockings, pruning, and thinning.

Most studies designed to measure the size and duration of vegetation management treatment effects on crop growth have been undertaken during the tree establishment phase. However, a few have also demonstrated significant crop growth responses following the removal of understorey plant species later in the rotation (Oppenheimer *et al.* 1989; Clason 1993). Another study demonstrated that removal of an understorey species, salal (*Gaultheria shallon* Pursh), in a stand of Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), increased water use by the tree canopy (Kelliher *et al.* 1986). The implication was that salal used water that would otherwise be available to the tree crop. More information on the duration of competitive interactions between trees and neighbouring plants would help to model crop responses to weed control treatments. This ability would allow quantitative comparisons of alternative vegetation management regimes.

A simple empirical approach to quantifying effects of vegetation management treatments on crop growth (usually expressed in terms of height, diameter, basal area, or volume increment) has many advantages including relatively simple designs, treatments, measurements, and easy interpretation. However, one significant problem with studies of this nature is that results are dependent on site and environmental factors and plant species. This makes it difficult to extrapolate results to sites and situations with even slightly different characteristics. Process-oriented models have the potential for accommodating these differences but have often been criticised for being too complex and requiring detailed

parameterisation before they can be used. However, in recent years these models have been developed in ways that allow complex physiological processes to be described in a simplified manner (Battaglia & Sands 1997, 1998; Landsberg & Waring 1997; Whitehead *et al.* 2001). Furthermore, many of the parameter and variable values required are now available from published literature or from national databases.

The objective of the work described here was to adapt an existing root-zone water balance model to simulate interactions between *P. radiata* and a broom understorey for a site in Burnham Forest, in the South Island of New Zealand. The purpose was not to quantify growth differences in the presence or absence of broom but to find out whether water balance modelling could be used to explain any differences. The model was used to test the hypothesis that in a low rainfall climate, a broom understorey can reduce *P. radiata* productivity by using soil water that would otherwise be available for tree growth.

## METHODS

### Canopy Water Balance Model

Daily root-zone water storage,  $W$ , on the Day  $i$  is calculated from the water balance equation

$$W_i = W_{i-1} + P_i - \alpha(E_{ti} + E_{ui}) - E_{twi} - E_{uwi} - E_{gi} - F_i \quad (1)$$

where  $P_i$  is the daily rate of rainfall,  $E_{ti}$  transpiration from the tree canopy,  $E_{twi}$  evaporation of intercepted rainfall from the tree canopy,  $E_{ui}$  transpiration from the understorey canopy,  $E_{uwi}$  evaporation of intercepted rainfall from the understorey canopy,  $E_{gi}$  evaporation from the soil, and  $F_i$  drainage from the root zone. The value for the coefficient  $\alpha$  is set to 1 on days when there is no rainfall and 0.75 on days when rain occurs (Whitehead *et al.* 2001).

Transpiration from the tree canopy is calculated using the simple diffusion equation

$$E_t = \phi D g_{st} L_t \quad (2)$$

where  $D$  is the air saturation deficit,  $g_{st}$  is the average stomatal conductance for the canopy,  $L_t$  is the projected leaf area index, and  $\phi$  will be defined later. Stomatal conductance decreases in response to increasing air saturation deficit, following the response described by Lohammer *et al.* (1980)

$$g_{st} = g_{stmax} / (1 + D/D_{0t}) \quad (3)$$

where  $g_{stmax}$  is the maximum stomatal conductance at low air saturation deficit and  $D_{0t}$  describes the sensitivity of  $g_s$  to  $D$ . It was assumed that  $D$  was the same for both broom and *P. radiata* because the aerodynamically rough canopies ensured good mixing. Similar equations to (2) and (3) are used to describe stomatal conductance and transpiration for the understorey canopy with the definition of the terms  $g_{su}$ ,  $g_{sumax}$ ,  $L_u$ , and  $D_{0u}$ .

Evaporation from the wet tree  $E_{tw}$  ( $= f_{wt}P$ ) and understorey  $E_{uw}$  ( $= f_{wu}P$ ) canopies is calculated as a constant fraction,  $f_{wt}$  and  $f_{wu}$  respectively, of rainfall (Table 1) (Kelliher *et al.* 1992). Evaporation from the soil surface  $E_g$  is calculated from the available energy below the tree and understorey canopies  $G_g$  from

$$E_g = \phi \tau s G_g / [\lambda(s+\gamma)] \quad (4)$$

where the coefficient  $\tau$  ( $=1.4$ ) describes the degree of coupling of the soil surface with the air above the canopy (Kelliher *et al.* 1990),  $s$  is the slope of the relationship between saturated vapour pressure and temperature at a given temperature,  $\lambda$  is the latent heat of vaporisation,

TABLE 1—Values for parameters and site-specific variables in the model for the Burnham site. *See text for explanation of the symbols. The value for  $D_{0t}$  was taken from Whitehead *et al.* (1996) and, in the absence of data, the same value was given to  $D_{0u}$ .*

Parameter/Variable	Value	Units
$g_{stmax}$	100	mmol/m <sup>2</sup> /s
$D_{0t}$	0.6	kPa
$g_{sumax}$	150	mmol/m <sup>2</sup> /s
$D_{0u}$	0.6	kPa
$f_{wt}$	0.2	
$f_{wu}$	0.05	
$f_{\phi}$	0.1	
$r$	1000	mm
$\theta_r$ (control, broom removed)	0.15, 0.17	m <sup>3</sup> /m <sup>3</sup>
$\theta_m$ (control, broom removed)	0.09, 0.09	m <sup>3</sup> /m <sup>3</sup>
$L_t$	2	m <sup>2</sup> /m <sup>2</sup>
$L_u$	2	m <sup>2</sup> /m <sup>2</sup>

$\gamma$  is the psychrometric constant, and  $\phi$  will be defined later. Values for  $s$ ,  $\gamma$ , and  $\lambda$  are dependent on temperature and are calculated from standard meteorological tables.  $G_g$  is calculated from the available energy above the forest canopy,  $G_a$  (assumed to be equal to  $0.7 \times$  shortwave irradiance) using Beer's Law as  $[1 - e^{-k(L_t+L_u)}G_a]$  where  $k$  is the light extinction coefficient (given a value of 0.5 by assuming a random distribution of canopy foliage). Beer's Law is an approximation that is frequently used to estimate average values of irradiance reaching the forest floor on a daily basis.

Root-zone volumetric water content for the Day  $i$ ,  $\theta_i (= W_i/r)$ , is calculated from the water storage in the profile,  $W_i$ , and the root-zone depth,  $r$ . If  $\theta_r$  is the maximum root-zone water content at field capacity and  $\theta_m$  is the minimum root-zone water content, then the fraction of maximum water available for the  $i^{\text{th}}$  day is

$$\phi = [(\theta_i - \theta_m)/(\theta_r - \theta_m)] \quad (5)$$

Following McMurtrie, Rook, & Kelliher (1990), this expression is used to reduce transpiration from the trees and understorey and evaporation from the soil surface as the root-zone water content decreases.

Drainage from the root-zone,  $F_i$ , is assumed to be zero when  $\theta_i \leq \theta_r$ , and equal to net rainfall reaching the soil surface when  $\theta_i > \theta_r$ .

Daily weather data required for the model are solar irradiance, minimum and maximum air temperatures, and rainfall. Diurnal variations in irradiance, air temperature, and air saturation deficit are estimated from daily data and calculated five times each day, weighted using a Gaussian distribution, and summed to give daily totals using the procedures described by Goudriaan & van Laar (1994).

The model requires values for the seven parameters,  $g_{stmax}$ ,  $D_{0t}$ ,  $g_{sumax}$ ,  $D_{0u}$ ,  $f_{wt}$ ,  $f_{wu}$ ,  $f_{\phi}$ , and the site-specific variables  $r$ ,  $\theta_r$ ,  $\theta_m$ ,  $L_t$ , and  $L_u$  (Table 1).

## Site and Treatments

The model was used to estimate the daily water balance for a trial site located at Smiths Block (43°36'S, 172°18'E) in Burnham Forest, belonging to Selwyn Plantation Board. This

location is typical of flat, dry, low-fertility sites on the Canterbury Plains. The soil, classified as a Yellow-grey Earth belonging to the Lismore Series, is a free-draining very stony silt loam (NZ DSIR 1967). Seasonal water deficits are characteristic of these soils. The site has an average annual rainfall of around 600 mm and drains largely by percolation. Runoff flow from the site during extreme rainfall events was not observed during the period of this trial.

Smiths Block was the site of a land preparation trial described by Dyck *et al.* (1989) and Balneaves (1990). The area was planted in *P. radiata* (1250 stems/ha) in 1978 with herbicide (hexazinone) control of shrub weeds. Broom began to dominate the site by 1983 and pine canopy closure was delayed by thinning (to 610 stems/ha) and pruning (to 2.5 m) in 1985 (age 7 years). For the present study all measurements were confined to a single site-preparation treatment, windrowing by bulldozer, this being the then-preferred pre-establishment site treatment throughout Canterbury and in many South Island districts. Windrows were at 60 m spacing and plots were located midway between windrows.

Understorey broom was removed from half of the selected windrow plot in summer 1987 before measurements began, making two new plots of approximately 40 × 40 m. For the purpose of this paper, the treatments have been labelled +broom and –broom to indicate *P. radiata* growing in the presence and absence, respectively, of a broom understorey. Broom and herbaceous plant regrowth were prevented by herbicide treatment (terbuthylazine) as required. Measurements commenced in winter 1987 and continued through autumn 1990.

Scaffold platforms were erected to give crown access to a group of trees in approximately the centre of both plots. In the +broom treatment, the platform also gave access to the upper canopy of the broom without disturbing the soil surface or the natural form of the individual bushes. All growth and gas-exchange measurements were made in the tree and broom canopies accessed from the platforms.

### Measurements

Detailed climatic monitoring at the site was abandoned after the data logger and instruments were severely vandalised 5 months after installation in August 1987. Consequently, all meteorological data, except solar radiation, were obtained from a station located 14 km to the south-east at Lincoln University. Solar radiation data were taken from Christchurch airport (approximately 25 km from the site).

Thirteen alloy tubes were inserted in the gravelly, compacted soil to allow neutron probe (Campbell Pacific Hydroprobe 105) sampling for soil water around crop trees in both the +broom (seven tubes) and –broom (six tubes) treatments. Readings up to a depth of 1.3 m were taken at weekly intervals wherever possible, from October 1987 until March 1990. One additional measurement was taken in August 1990. Measurements were converted to soil water content using standard procedures. The maximum and minimum soil water contents observed for each treatment were used to define  $\theta_r$  and  $\theta_m$ . The total daily water deficit through the profile ( $\theta_r - \theta$ ) was calculated for each measurement time and treatment. These were accumulated for each of the three 12-month periods (commencing 1 July 1987) to give an integrated root-zone water deficit,  $S_w$ , using the method described by Arneith *et al.* (1998), itself a modification of the approach of Myers (1988).

Stem radial growth and height growth were measured at 2-weekly intervals on eight crop trees in each treatment, using dendrometer bands (positioned 1.4 m above the ground) and

a height pole, respectively. Stomatal conductance of *P. radiata* needles and broom leaves and stems was measured using a porometer (differential throughflow system using a LiCor 1600 coupled to a Binos CO<sub>2</sub> and H<sub>2</sub>O gas analyser). Eight sets of measurements were made periodically from October 1987 to September 1988. These measurements were limited to days of clear sky to ensure that any obvious seasonal and treatment differences were not obscured by physiologically limiting light conditions. Pre-dawn needle water potential was measured 10 times between July 1987 and September 1988 using a pressure chamber.

## RESULTS

### Climate

Local climate data were typical of coastal areas of the Canterbury Plains and similar to those recorded at Lincoln University 14 km east-south-east of the site (Fig. 1). During the 3 years of the experiment, summer temperatures occasionally exceeded 30°C. Such high temperatures are usually associated with north-west air-flows, which are often accompanied by high winds and low humidity, resulting in large vapour pressure deficits. Typically, these conditions oscillate with easterly sea breezes that bring cooler temperatures but humidity remains low. Annual rainfall in the first 2 years (1 July 1987 to 30 June 1989) was much lower than the average of 600 mm, with 470 mm in 1987/88 and 474 mm in 1988/89. In 1987/88 rainfall was evenly partitioned between summer and winter, but the following summer was particularly dry. Rainfall in the final year, 1989/90 was close to average (608 mm). Winters were cool with persistent and frequent frosts on open ground.

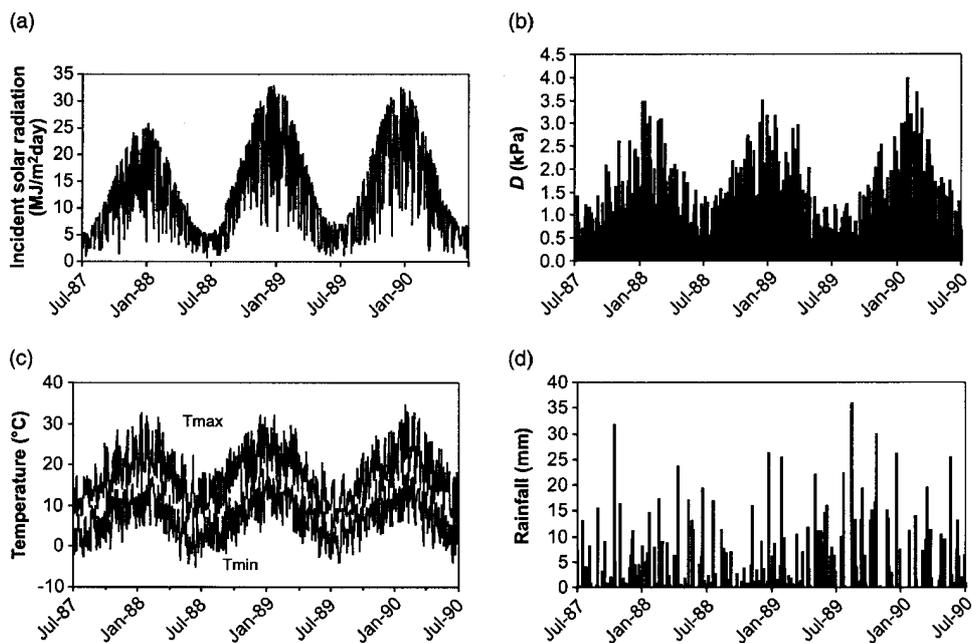


FIG. 1—Daily values of (a) incident solar radiation, (b) air saturation deficit, (c) maximum and minimum air temperatures, and (d) rainfall, taken from meteorological stations close to the Burnham site.

### Tree Growth

Tree height growth (Fig. 2) occurred during the late winter and spring of each year, with little recorded growth between December and May. Initial (July 1987) mean height of trees in the –broom treatment was 0.6 m less than that of those growing with broom. Over time this difference decreased and by November 1989 the height of –broom trees exceeded that of the +broom trees.

Distinct diameter growth periods, expressed as basal area per hectare (Fig. 3), occurred simultaneously in each treatment and at almost any time of year except over the coldest months of June–July. Growth in the summer of 1988/89 was not as persistent as other years,

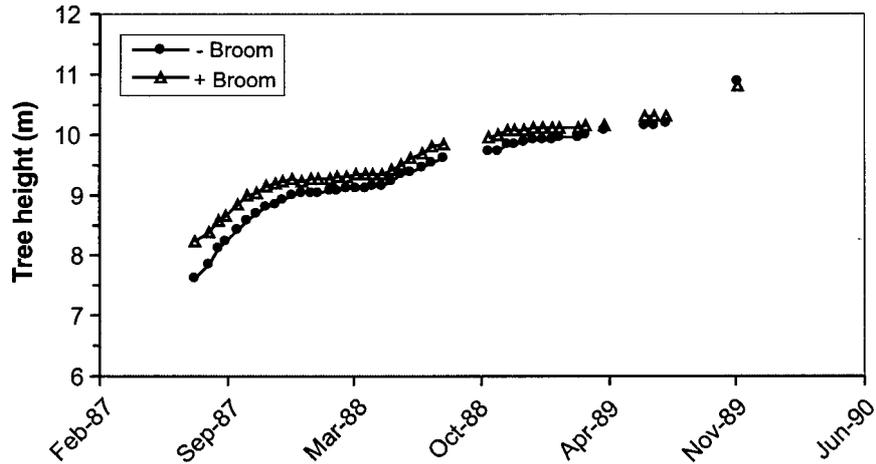


FIG. 2—Mean height of *P. radiata* growing in the presence (+broom) and absence (–broom) of a broom understorey.

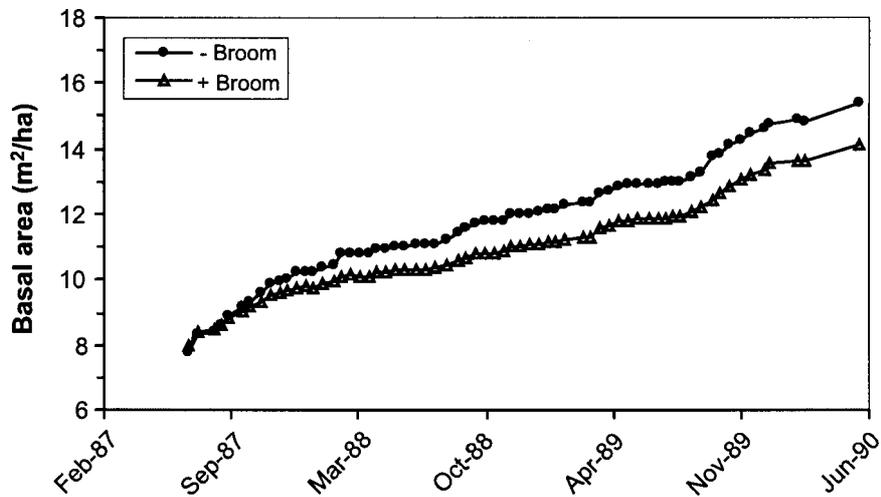


FIG. 3—Mean basal area of *P. radiata* growing in the presence (+broom) and absence (–broom) of a broom understorey.

coinciding with a period of very low rainfall. Such extremely dry conditions caused slight stem shrinkage over some measurement periods. Basal area of pine was marginally higher in the +broom plot at initial measurement. However, this was reversed during the first year of the experiment. After 3 years, *P. radiata* basal area in the –broom plot was 1.27 m<sup>2</sup>/ha (9%) higher than in the +broom plot.

While it is not possible to make a statistical comparison of treatment effects because there was no replication, the observed growth trends conform to what would be expected when comparing tree growth in the presence and absence of resource competition from weeds. Removal of broom resulted in increased tree height and diameter growth.

### Water Balance Model

Over most of the measurement period, there was a close match between modelled estimates of root-zone water storage and measurements (Fig. 4a, b). The difference in measured maximum water storage between the two plots was most likely associated with

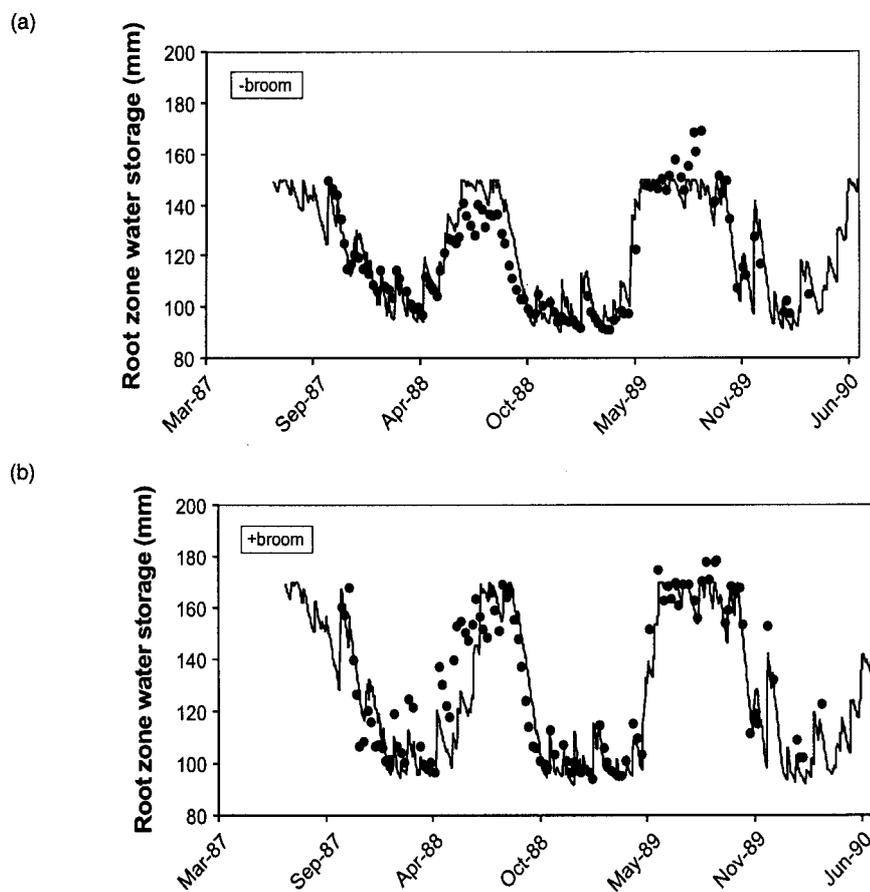


FIG. 4—Comparisons of modelled daily root-zone water storage (line) with measurements (solid circles) for plots containing (a) *P. radiata* on its own and (b) *P. radiata* with a broom understory.

subtle variation in soil characteristics. These differences were incorporated into the model. The high measured values for root-zone water storage in winter 1989 occurred because of flooding at the site.

The data show a clear summer–winter cycle of root-zone water depletion under both broom and open understory treatments. Depletion and treatment differences were most pronounced during summer months. Highest root-zone water content was recorded in winter, with depletion occurring by September and reaching near minimum levels by November of each year.

### Influence of Water Availability on Growth

Differences between the two treatments in pre-dawn needle water potential and root-zone water content clearly point to soil water as a major factor influencing growth. On this dry site, lowest mean pre-dawn water potentials were recorded in January with  $-1.7$  MPa in –broom trees and  $-2.0$  MPa in +broom trees. A paired t-test combining data from all measurement times indicated that there was a significant difference between the treatments ( $p = 0.02$ ) with mean values of  $-1.16$  and  $-1.35$  MPa for the –broom and +broom treatments.

Annual tree basal area increment was highly correlated (correlation coefficient = 0.97) with the annual integrated root-zone water deficit,  $S_w$ , irrespective of treatment (Fig. 5). Deficits ranged from 1024 to 2395 mm in the –broom treatment and 1245 to 3188 mm in the +broom treatment.

As  $S_w$  increased, growth increment decreased, illustrating the strong link at this site between root-zone water content, the presence or absence of broom, and tree growth. It

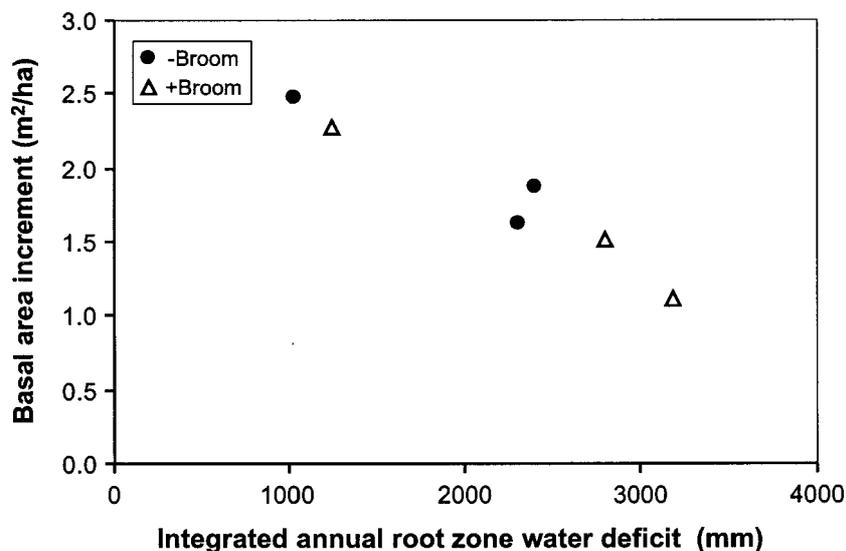


FIG. 5—Relationship between root-zone water deficit integrated over each year and annual basal area increment of *P. radiata* growing in the presence (+broom) and absence (–broom) of a broom understory.

should be noted that the representation in Fig. 5 is not ideal because tree size, as well as any treatment effects, influence growth increment over any period. At the start of the experiment tree basal area (Fig. 3) was almost identical for both treatments. This means that any differences in growth increment over the first year were almost certainly a treatment effect. At the start of the first and second year, however, trees in the –broom treatment were bigger than those in the +broom treatment. This means that growth increment over the next periods was influenced by differences in initial tree size as well as a possible treatment effect. Unfortunately, there were insufficient data from this study to model the treatment and tree size effects independently.

## DISCUSSION

It is well known that broom can have large negative effects on growth of newly planted or young *P. radiata* (Richardson *et al.* 1997, 1999). This study demonstrates that broom can also have a strong influence on tree growth when it is present as an understorey species in much older pine stands. Re-measurement of the trial in August 1994 revealed the trees from the –broom treatment had continued to outgrow those retaining a broom understorey and had 2.5 m<sup>2</sup>/ha greater basal area. By this time, crown closure had caused the complete demise of all broom in the plots so it is unlikely that treatment differences would increase beyond this time.

Measurements of root-zone water storage and needle water potential both strongly support the hypothesis that the presence of broom influenced tree growth at Burnham by reducing the relative availability of soil water. Although the differences between treatments in needle water potential were quite small, Myers (1988) showed that small differences maintained over long periods led to large changes in growth. The inference is that during drought the broom understorey caused a persistent loss of soil-water storage. In the absence of a broom understorey, pine was able to conserve soil water for gas exchange during those periods of the day when vapour pressure deficit was low.

The soil-water balance model effectively simulated these effects, with the predicted pattern of root-zone water content closely following the peaks and troughs obtained by measurements in both treatments. With the root-zone water deficit accounting for a large proportion of the variation in tree growth, this modelling approach provides a useful method for predicting the effect of understorey vegetation on tree growth on dry sites. This is reinforced by the fact that the model performed so well even though there was uncertainty on the precise value of leaf area for pines and broom ( $L_t$  and  $L_u$ , respectively). The value of 2 selected for both  $L_t$  and  $L_u$  accords reasonably well with values observed by B. Richardson (unpubl. data).

## Implications for Management

On the Burnham site, where water is a predominant growth-limiting factor, the water balance model effectively simulated differences in root-zone water content throughout the year for stands growing with or without an understorey. Root-zone water content was also highly correlated with tree growth. Therefore this modelling approach could be used to determine the effect of a wide range of vegetation management treatments on root-zone water content and consequently tree growth.

There are a number of steps that could be taken to make this modelling approach more useful to forest managers interested in predicting effects of vegetation management treatments on tree growth.

- (1) The first step would be to develop and test water balance models under a much wider range of conditions. On dry sites, calculations of root-zone water storage could then be directly used as an additional explanatory variable in an empirical growth model such as those described by Snowdon *et al.* (1998) and Woollons *et al.* (1997). This method combines the ability of process models to provide some level of responsiveness to changes in environmental conditions, in a biologically realistic way, with reliable estimates of growth and yield from conventional empirical models (Battaglia & Sands 1997, 1998).
- (2) On sites where resources other than water may be limiting growth, a slightly more complex approach would be required. One option is to further develop the model described by Richardson *et al.* (1999). Tree growth was modelled as a function of tree size and a competition modifier. The competition modifier is essentially a multiplier that reduces tree growth according to the degree of competition from another plant species. This was defined in terms of a competition index (Burton 1993) that effectively was a surrogate for the amount of light reaching tree crowns in the presence or absence of weed. A second term could be added to this model to account for the effects of non-crop plants on water availability. In the current study, broom was present only as an understorey species, so it clearly had no influence on the amount of light reaching tree crowns. However, a model that contained competition indices sensitive to both water and light availability would be extremely useful for evaluating the cost-benefit of alternative vegetation management.

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