

# MODELLING THE INTERCEPTION OF SOLAR RADIANT ENERGY IN INTENSIVELY MANAGED STANDS

J. C. GRACE

Ministry of Forestry, Forest Research Institute, Private Bag, Rotorua, New Zealand

P. G. JARVIS

Department of Forestry and Natural Resources, University of Edinburgh,  
Edinburgh, Scotland EH9 3JU

J. M. NORMAN

Department of Agronomy, University of Nebraska, Lincoln, Nebraska,  
United States 68583

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## ABSTRACT

A model has been constructed for predicting the interception of solar radiant energy by an array of plants with ellipsoidal crowns. The applicability of the model to stands of *Pinus radiata* D. Don was investigated by comparing model predictions with measurements of instantaneous irradiance below tree crowns in a 9-year-old stand. The agreement between actual and predicted transmittances was generally good. However, small errors in measuring crown shape and leaf area can cause large variations in predicted instantaneous transmittances. When predicting the interception of solar radiant energy on a daily basis, small errors in measuring crown shape or leaf area did not cause large variations in intercepted radiant energy.

Model simulations indicated that there is a linear relationship between intercepted photosynthetically active radiant energy (PAR) and above-ground dry matter production in stands of *P. radiata* growing on a fertile site. This relationship was unaffected by thinning and light pruning. Assuming that the relationship is unaffected by more extreme thinnings and prunings, simulations indicated that unthinned-pruned stands can intercept up to 25% more PAR than unpruned-thinned stands with the same leaf area index.

**Keywords:** light interception; solar radiant energy; modelling; *Pinus radiata*.

## INTRODUCTION

The growth rate of several agricultural crops has been shown to increase linearly with increasing intercepted solar radiant energy (e.g., Monteith 1972). However, the solar radiant energy intercepted by plants is dependent on both the incident solar radiant energy and the optical and geometrical properties of the plants (Ross 1981). Therefore, radiative transfer models, which are a mathematical formulation of the structure of plant canopies and the attenuation of radiant energy passing through them, are needed to understand the effect of plant structure on growth.

Many radiative transfer models have been developed with varying levels of complexity (*see, e.g., review by Norman 1975*). The main difference between models is in the treatment of canopy structure. For example, the canopy can be assumed to be continuous in the horizontal plane, with the foliage either randomly or non-randomly distributed throughout the canopy space (*e.g., Norman & Jarvis 1975*). Measurements of penetration of solar radiant energy have shown that, provided the canopy is continuous, the assumption of random foliage distribution does not produce excessive errors even when the foliage is non-randomly distributed. However, absurd results are obtained if plants are widely spaced (*Jarvis & Leverenz 1983*). In this situation an alternative is to assume that the canopy is made up of blocks of foliage of a given shape. For crops where plants are closely spaced within rows and rows are widely spaced, an appropriate model would be one that assumes a row of plants constitutes one block of foliage (*e.g., Allen 1974*). When plants are widely spaced both within and between rows an appropriate model would need to treat the foliage of each plant as a separate block (*e.g., Whitfield et al. 1982; Norman & Welles 1983*).

In New Zealand, trees are often widely spaced both between and within rows – for example, in newly planted or heavily thinned plantations, or in agroforestry systems where different planting patterns can be used. Therefore, a suitable radiative transfer model for such intensively managed plantations should consider the foliage of individual trees to be discrete blocks. It should also be able to investigate the effect of alternative spacing patterns. The model of Norman & Welles (1983) fulfilled these criteria and was selected for consideration as a model for predicting radiative transfer in New Zealand forests.

This paper reports improvements to increase the flexibility of the model of Norman & Welles (1983), including a procedure for estimating annual intercepted radiant energy. The suitability of the model for estimating radiative transfer in stands of *Pinus radiata* was tested by comparing field measurements of radiant energy beneath tree crowns with model estimates. The sensitivity of the model to small changes in the input parameters was also examined. The relationship between model estimates of annual intercepted photosynthetically active radiant energy (PAR) and estimates of annual above-ground dry matter production in stands of *P. radiata* growing at Puruki (38° 26' S, 176° 13' E), a fertile site about 30 km from Rotorua, was examined. The model was used to investigate the likely effects of thinning and pruning on intercepted PAR and hence on above-ground dry matter production.

### MAIN FEATURES OF THE MODIFIED MODEL

In the model a forest stand is represented by a plot of up to 100 trees spaced in any desired manner. The tree co-ordinates are specified in three dimensions to allow the effects of slope, aspect, and different planting patterns to be investigated. The plot is replicated eight times by translation (*Fig. 1*) so that errors are not introduced by insufficient attenuation of incoming radiant energy at high zenith angles. This technique is also used in forest growth models to account for competition at the plot edge (*e.g., Monserud & Ek 1974*).

The crown structure of each tree is individually specified and represented by an ellipsoid. A specified length of the crown, from the base of the crown upwards, may

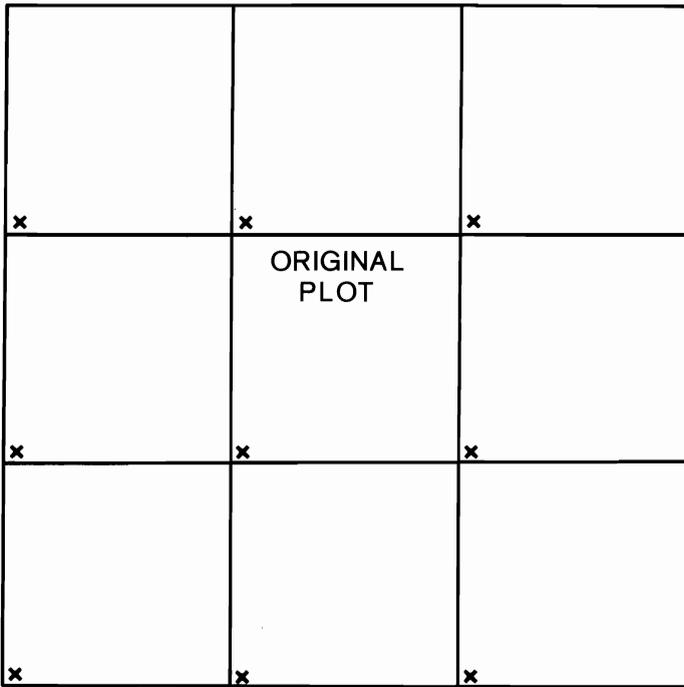


FIG. 1—Original plot and location of the eight plots produced by translations. The cross marks the position of one tree in the original plot and its position in other plots.

be removed. This allows green pruning regimes to be simulated. Within the ellipsoid crown, three other ellipsoids are now defined. The only limitation to their shape is that they must be within each other (Fig. 2). The amount of foliage associated with each of the shells formed by the four ellipsoids is specified. This allows for non-random distribution of the foliage within the whole crown and allows the effects of defoliation to be simulated.

Within each shell the foliage is assumed to be randomly distributed with no preferred azimuthal direction. The inclination angles of the foliage are assumed to be distributed according to the spherical leaf angle distribution, unless another distribution is input.

Subroutines have been added which calculate times of sunrise and sunset, and zenith and azimuth angles for the sun from date, longitude, and latitude using equations given by Barkstrom (1981) and Usher (1970).

Although the theory for calculating the attenuation of solar radiant energy is unchanged from Norman & Welles (1983), details are given here for clarity.

From measured incoming solar radiant energy, the model calculates, on an hourly basis, the attenuation of beam radiant energy and sky diffuse radiant energy in the photosynthetically active (PAR) (400–700 nm) and near infra-red (NIR) (700–

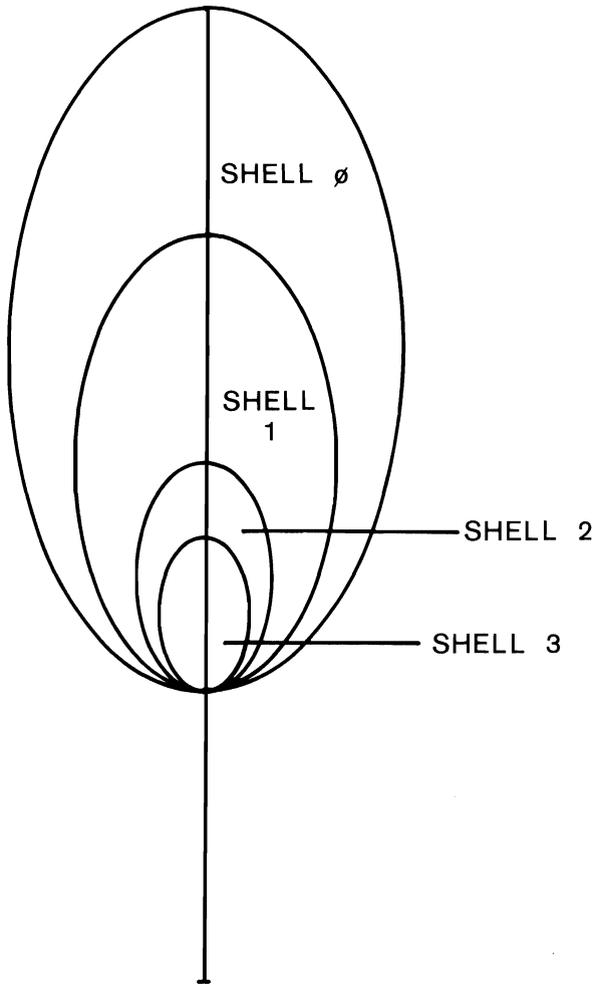


FIG. 2—Structure of a tree crown.

3000 nm) wavebands, by assuming that 48% of the incoming radiant energy is PAR. These two wavebands are considered separately as foliage transmits and reflects PAR and NIR differently. The fraction of incoming radiant energy that is beam is calculated from the zenith angle of the sun or, if sunshine data are available, from the zenith angle of the sun and the fraction of each hour that the sun is shining (using equations given by Revfeim 1981).

The probability that the solar beam passes unintercepted from its source to any point within or below the canopy is given by:

$$p = \exp(-k\rho S) \text{-----} (1)$$

where:  $p$  is the probability that the beam is not intercepted

$k$  is the fraction of the "one-sided" foliage area projected on a plane normal to the solar beam

$\rho$  is the "one-sided" foliage area density

S is the distance that the beam passes through tree crowns.

The probability that diffuse radiant energy passes unintercepted from above the canopy to a specified point, within or below the canopy, is calculated by numerically averaging the results of the above equation over a hemisphere.

Scattering of solar radiant energy is calculated using the method given by Norman & Welles (1983).

Outputs from the model are hourly and daily intercepted and absorbed PAR and NIR averaged over a grid of points in a horizontal plane either below or within the canopy.

## PROCEDURE FOR PREDICTING ANNUAL INTERCEPTED RADIANT ENERGY

### Method

To predict annual intercepted radiant energy, the model should ideally be run for each day of the year. However, this is expensive in computer time. An alternative is to run the model on selected days covering the range of weather conditions and to develop equations for predicting daily intercepted radiant energy from daily incoming radiant energy.

For a given value of daily incident radiant energy, the fraction intercepted will vary with time of year. Reasons for this are that a given value of incident radiant energy will be made up of different proportions of beam and diffuse radiant energy at different times of the year, that these wavebands have different patterns of attenuation, and that the daily path of the sun varies throughout the year. Hence it would not be applicable to derive one equation for predicting daily intercepted radiant energy from daily incident radiant energy. Therefore the year was split into three groups, by month, in which the solar path would be similar. The groups were:

- (1) November, December, January, February
- (2) March, April, September, October
- (3) May, June, July, August

Since the rate of photosynthesis is related to the intercepted PAR rather than intercepted solar radiant energy, the feasibility of using the above approach to estimate daily intercepted PAR from incoming PAR was investigated using the stand structure of a 7-year-old stand of *P. radiata* growing at Puruki (Table 1). From solar radiant energy data collected at Puruki, 8 to 12 days were chosen from each of the above

TABLE 1—Stand structure used in calculating radiant energy intercepted by a 7-year-old *Pinus radiata* stand

Stems/ha	496
LAI	2.6
Tree height (m)	9.0
Height to base of crown (m)	2.6
Crown width (m)	3.4

periods covering the range of daily incoming radiant energy. Approximately the same number of days were chosen from each month and care was taken to ensure that they were not grouped together. The model was then run for these days. For each group, daily intercepted PAR was plotted against incoming PAR to determine the shape of the relationship between the two variables, and an appropriate regression equation was derived. This equation was then used to estimate intercepted PAR from daily incoming PAR for each day of each month. Results were summed according to month and compared with estimates of monthly intercepted PAR obtained by running the model for each day between 1 January and 30 June.

### Results

Graphs of daily intercepted PAR against incoming PAR indicated that the relationship between these two variables was either linear or slightly curvilinear tending towards an asymptote. Hence the following regressions were fitted to each data set:

$$Y = a X \text{ ..... (2)}$$

$$Y = a X + b X^2 \text{ ..... (3)}$$

where Y is the intercepted PAR,

X is the incoming PAR

a and b are regression coefficients.

Equation 3 was chosen in preference to a non-linear model because the coefficients could be calculated automatically. Non-linear regression models require initial estimates for the regression coefficients. A zero intercept was considered realistic. Using the more appropriate of the above two regression equations, estimates of monthly intercepted PAR were within 5% of the estimates obtained by running the model for each day of the month (Table 2). The estimate of intercepted PAR obtained using the regression equation was within  $\pm 10\%$  of the estimate obtained by running the model for that day, apart from 5 days with low incoming PAR, when the percentage difference was within  $\pm 12\%$ .

These results suggest that yearly intercepted PAR can be estimated using this procedure provided that the model is suitable for estimating intercepted PAR.

TABLE 2—Monthly intercepted PAR for a 7-year-old *Pinus radiata* stand; data obtained by running the model for each day, and by running the model for selected days and then using a regression equation to derive daily intercepted PAR from incoming PAR (stand structure given in Table 1)

Month	Intercepted PAR (MJ/m <sup>2</sup> /month)		Error (%)
	Running model for each day	Using regression equation	
Jan	240	241	-0.3
Feb	159	154	3.4
Mar	128	132	-3.4
Apr	129	129	0.2
May	84	83	0.9
Jun	68	67	1.7

## FIELD TEST

### Method

The model described above estimates hourly and daily intercepted radiant energy. However, the underlying theory is concerned with instantaneous transmission of solar radiant energy. Hence to determine the applicability of the model one needs to compare model estimates of instantaneous transmittance with field measurements.

Measurements to determine the applicability of this model for calculating intercepted PAR in stands of *P. radiata* were collected at Puruki during the spring of 1982. The forest was planted in 1973 at a nominal stocking of 2200 stems/ha with a spacing of  $1.83 \times 2.44$  m. Within Puruki, there are three sub-catchments which have received different silvicultural treatments. The measurements were taken in subcatchment Toru which had been thinned to a nominal stocking of 550 stems/ha during the winter of 1981. In winter 1982, the mean height of trees in assessment plots close to where the measurements were taken was 12.8 m. The basal area was  $71 \text{ m}^2/\text{ha}$ .

Two sample trees were subjectively selected for different amounts of foliage within the crown. The forest canopy surrounding each tree was closed and the nearest tree to each sample tree was 2.1 m and 2.6 m away respectively. Measurements of PAR were taken at selected grid points below the forest canopy. The grid points were sited so that the solar beam passed through the crown of only the sample tree. Concurrent measurements of PAR in a nearby field were assumed to give PAR above the canopy. As the foliage area was measured only for the sample trees, the measurements of PAR were taken on cloudless days so that the amount of diffuse radiant energy passing through the surrounding trees was minimised.

Quantum sensors (LI-190SB), were used to measure PAR. Three sensors were placed on top of posts located at three of the selected grid points. A fourth sensor was placed in the open. It took about 1 min to obtain readings from the four sensors. Measurements were taken continuously and the sensors were moved to new positions every 15 min.

The location, height, and crown shape of the sample trees and six to eight surrounding trees were measured. The two sample trees were harvested, the foliage was weighed, and the weight was converted to surface area using the method of Beets (1977). These data were used as input to the radiative transfer model together with measured values of incoming PAR. It was assumed that the foliage was randomly distributed throughout the whole crown and that the leaf inclination angles were distributed according to the spherical leaf angle distribution. The predicted values of PAR reaching the grid points were compared with the measured values.

As well as using the measured crown shapes and leaf areas for the sample trees, the model was run with adjusted sizes for the sample trees as follows:

- (1) Each crown radius increased by 0.1 m and leaf area increased by 15%;
- (2) Each crown radius increased by 0.1 m and leaf area decreased by 15%;
- (3) Each crown radius decreased by 0.1 m and leaf area increased by 15%;
- (4) Each crown radius decreased by 0.1 m and leaf area decreased by 15%.

For each instantaneous transmittance measured, the range ( $r$ ) in predicted transmittances was calculated. This is the difference between maximum and minimum predicted instantaneous transmittance. The mean, minimum, and maximum values of  $r$  were then calculated for each tree.

### Results

The measured crown shape and foliage area for each sample tree are given in Table 3. Timing of measurements, and maximum and minimum values of PAR above and below the canopy are given in Table 4. For each pair of actual and predicted instantaneous transmittances a residual transmittance was calculated from:

$$R = (A - E) / Q \text{ ..... (4)}$$

where R is the residual transmittance

A is the measured PAR below the canopy

E is the estimated PAR below the canopy

Q is the measured PAR above the canopy.

TABLE 3—Structural parameters of the two sample trees from a 9-year-old stand of *Pinus radiata* with 550 stems/ha

	Tree 1	Tree 2
Height (m)	14.4	13.8
Crown shape — radii for ellipsoid (m)		
(a) (horizontal)	2.1	2.2
(b) (horizontal)	1.4	2.1
(c) (vertical)	4.1	5.3
One-sided leaf area (m <sup>2</sup> )	76	126
Leaf area density (m <sup>2</sup> /m <sup>3</sup> )	1.5	1.2

TABLE 4—Timing of measurements, and maximum and minimum measured PAR below tree crowns in a 9-year-old stand of *Pinus radiata* with 550 stems/ha

	Minimum	Maximum
Time (h)	10.73	13.68
Incoming PAR (W/m <sup>2</sup> )	388	583
PAR at grid points below canopy (W/m <sup>2</sup> )	8	291

The results are presented in terms of transmittances because the irradiance reaching a point is a function of both the leaf area above that point and the incoming irradiance. For each sample tree the mean residual transmittance, variance, and 95% confidence interval were calculated. The results (Table 5) indicate that the mean residual transmittance is not significantly different from zero.

At some grid points, changing the crown width by  $\pm 0.1$  m and the leaf area by  $\pm 15\%$  caused large variations in the estimated transmittance, as can be seen by the maximum values of r (Table 6). However, for Tree 1 over 80% of the residuals, R, and for Tree 2 over 90%, were less than the mean value of r (Table 6).

Since the above variations in crown shape and leaf area are considered to be realistic estimates of measurement errors, it is concluded that the large differences between measured and predicted instantaneous transmittances are likely to have been caused by errors in measuring crown shape or leaf area.

TABLE 5—Mean, variance, and 95% confidence intervals for the residuals derived from model predictions and field measurements of instantaneous transmittance of PAR

	Tree 1	Tree 2
Number of observations	266	854
Mean residual transmittance	-0.018	-0.0028
Variance	0.038	0.0019
95% confidence interval	0.023	0.0029

TABLE 6—Range (*r*) in predicted instantaneous transmittances of PAR at the selected grid points below the tree crown, obtained by running the model with measured crown shape and leaf area and by changing the crown radii by  $\pm 0.1$  m and leaf area by  $\pm 15\%$ 

	Tree 1	Tree 2
Number of observations	266	854
Minimum <i>r</i>	0.03	0.01
Maximum <i>r</i>	0.93	0.81
Mean <i>r</i>	0.16	0.06

## MODEL SENSITIVITY

### Method

Although the previous section showed that model estimates of instantaneous transmittances can vary widely with changes to crown shape and leaf area, the model will be used to estimate interception over longer time periods. Here we investigate the sensitivity of daily estimates of transmittance to measurement error in the data input to the model, using a coefficient of sensitivity for mathematical models (Huson 1984).

Given a base set of input data and output for the model, and probability distributions for the error associated with each input variable, random sets of input data are calculated and the model is run to give corresponding sets of output. The sensitivity coefficient is defined as the proportion of generated model results which lie outside a boundary centred on the original output. For example, if the boundary is defined as  $\pm 10\%$  of the original output, then this is defined as a 10% sensitivity coefficient. The coefficient is bounded between zero and one, making it easy to compare the sensitivity of different models.

In the model described in this paper there are many parameters which can be varied – e.g., whether trees are all the same size, the size of each tree, whether the spacing is regular or random, optical properties, and distribution of the foliage. In calculating a sensitivity coefficient for the model it has been assumed that all trees are the same size, regularly spaced, with the foliage randomly distributed throughout the whole crown. The input parameters which have been varied are the three lengths which define the shape of the ellipsoidal crown and the amount of foliage within the crown. It has been assumed that the error in measuring any of the three lengths is

uniformly distributed between  $\pm 0.5$  m of true value, and that the foliage area can be measured to within  $\pm 15\%$ . A uniform distribution was assumed for the error in measuring foliage area. Each variable was assumed to be independent.

Using 25 sets of input data generated using the above error ranges, a sensitivity coefficient for daily intercepted PAR/m<sup>2</sup> was calculated for two different spacing arrangements (499 stems/ha and 2003 stems/ha) in which trees were assigned the same crown shape and foliage area per tree. In order to compare the variability in model predictions with the variability in input data, a sensitivity coefficient was derived for the input data.

### Results

The value of the sensitivity coefficient for daily intercepted PAR is less than the corresponding sensitivity coefficient for the input data (Table 7) indicating that small errors in measuring crown shape or leaf area will not cause the model to give unrealistic estimates of daily intercepted PAR.

TABLE 7—Sensitivity coefficients for the model to changes in the input parameters of crown shape and foliage area per tree, assuming that the standard crown length and width are 6.8 m and 2.5 m respectively, and the one-sided leaf area per tree is 38.33 m<sup>2</sup>

	Plot 1	Plot 2
	2003	499
Stems/ha		
Sensitivity coefficients for input data		
10% level	0.53	0.53
15% level	0.29	0.29
20% level	0.24	0.24
Sensitivity coefficients for daily intercepted PAR		
10% level	0.12	0.48
15% level	0.04	0.28
20% level	0.04	0.12

The sensitivity coefficients for daily intercepted PAR are larger at 499 stems/ha than at 2003 stems/ha. A reason for this is that at 2003 stems/ha the leaf area index is high and the canopy almost closed. A small change in the crown shape or foliage area will have only a small effect on the radiant energy reaching the ground since the probability of radiant energy passing through a tree crown unintercepted decreases exponentially with increasing foliage within the crown.

## COMPARISON OF INTERCEPTED PAR AND ABOVE-GROUND DRY MATTER PRODUCTION AT PURUKI

### Method

Data presented by Linder (1985) indicated that there was a linear relationship between above-ground dry matter production and intercepted PAR in stands of

*Eucalyptus globulus* Labill. generated by a radiative transfer model which did not take stand structure into account. In this section we examine the relationship between above-ground dry matter production and modelled intercepted PAR in stands of *P. radiata* growing at Puruki.

Using the procedure to estimate yearly intercepted PAR, we calculated yearly intercepted PAR for stands of *P. radiata* at Puruki, with different crown shapes and numbers of stems per hectare (Table 8). Stands with more than 1000 stems/ha were unthinned but the rest of the stands had been thinned once or twice and pruned to 2.2 m at the time of first thinning. In the simulation, leaf area index and crown shape were held constant during the year. Meteorological data from Puruki (R. Brownlie, unpubl. data) were used to drive the model. Values of yearly intercepted PAR were plotted against estimates of above-ground dry matter production (Beets & Pollock 1987), and a regression equation between the two variables was derived.

TABLE 8—Details of stands of *Pinus radiata* at Puruki for which yearly intercepted PAR has been estimated

Stand No.	Sub-catchment	Age (years)	Stems/ha	Leaf area index	Crown width (m)	Crown length (m)
1	Tahi	2–3	1970	0.6	0.6	1.2
2	Tahi	3–4	1960	1.3	1.2	2.3
3	Rua	3–4	1840	1.2	1.1	2.0
4	Toru	4–5	2170	2.1	1.8	3.5
5	Tahi	5–6	1950	6.4	2.4	4.8
6	Tahi	7–8	495	2.6	3.4	6.4
7	Toru	7–8	1960	5.9	2.4	6.8
8	Tahi	9–10	495	5.6	4.8	10.9
9	Toru	9–10	540	2.8	3.8	9.0
10	Toru	10–11	540	4.6	4.3	9.9
11	Tahi	11–12	160	2.0	6.8	15.4

## Results

The relationship between intercepted PAR and above-ground dry matter production at Puruki appeared to be linear (Fig. 3). Analysis of the data indicated that a linear regression with zero intercept was appropriate. The slope of the regression equation with zero intercept was 1.34 g/MJ (PAR). Using this regression equation, the value of the residual was not affected by whether the stand had been thinned and pruned. Also, the percentage difference between estimates of above-ground dry matter production from the regression equation and from Beets & Pollock (1987) was of a comparable size to the sampling errors for estimating production (Grace & Madgwick 1987) suggesting that scatter around the regression line is likely to be due to sampling errors.

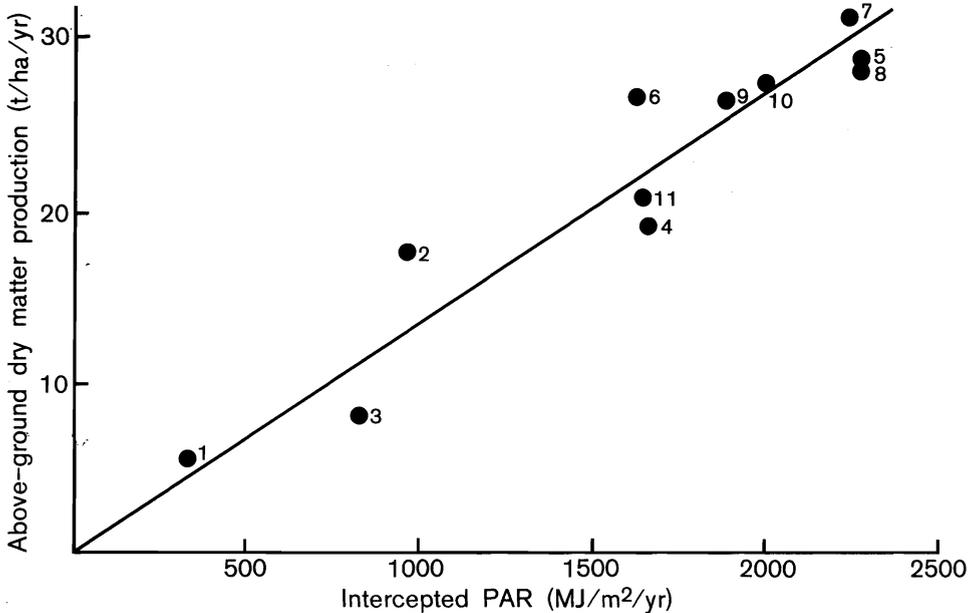


FIG. 3—Relationship between above-ground dry matter production and intercepted PAR for stands of *Pinus radiata* growing at Puruki (numbers correspond with Table 8).

## EFFECT OF PRUNING AND THINNING ON DRY MATTER PRODUCTION

### Method

Assuming that above-ground dry matter production is linearly related to intercepted PAR on fertile sites, and that the slope of the relationship is unaffected by thinning or pruning, the model can be used to investigate the effects of thinning and pruning on dry matter production.

A stand at 1840 stems/ha was theoretically thinned to 900, 600, and 300 stems/ha. The leaf area of the stand was also reduced to be equivalent to that in the thinned stands by pruning the crown of each tree. Similarly, a stand at 495 stems/ha was thinned to 300 and 100 stems/ha, and pruned to give equivalent leaf areas. The stand structures used are given in Table 9. Annual intercepted PAR was calculated for each of these stands and was plotted against both "one-sided" leaf area index and crown length per hectare (the sum of the crown lengths of all the trees in a hectare of forest (West *et al.* 1982)).

### Results

For a given leaf area index, an unthinned-pruned stand intercepts more PAR than an unpruned-thinned stand (Fig. 4). Hence, unthinned-pruned stands should have greater above-ground dry matter production than unpruned-thinned stands. The increase in intercepted PAR can be at least 20%. The relationship between leaf area index and

TABLE 9—Details of stands used to simulate the effects of thinning and pruning

Stand	Stems/ha	Leaf area index	Crown width (m)	Crown length (m)
1	300	3.45	4.80	11.60
2	495	3.45	4.80	6.65
3	100	1.15	4.80	11.60
4	495	1.15	4.37	3.30
5	900	2.59	2.50	9.10
6	1840	2.59	2.50	4.50
7	600	1.73	2.50	9.10
8	1840	1.73	2.43	3.50
9	300	0.86	2.50	9.10
10	1840	0.86	1.75	2.30

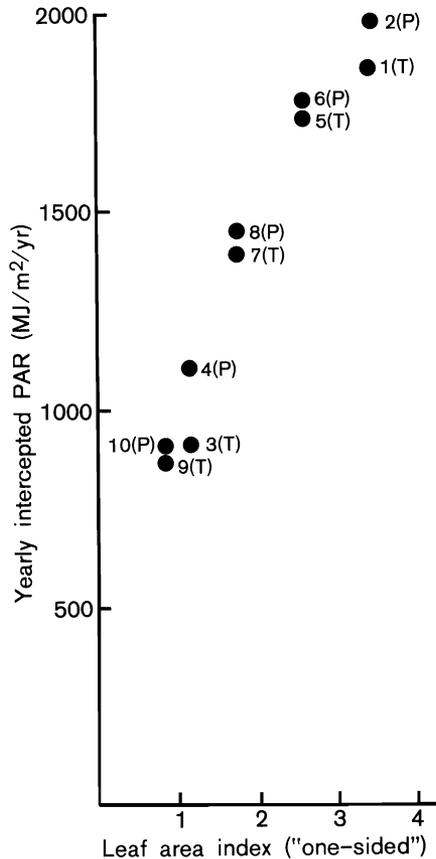


FIG. 4—Annual intercepted PAR for pairs of simulated stands with the same leaf area index but which have been achieved by either thinning or pruning (T implies a thinning; P a pruning) (numbers correspond with Table 9).

intercepted PAR is not affected by the initial structure of the stand. However, if crown length per hectare is used as the dependent variable, then the initial structure of the stand (spacing, tree size, etc.) becomes important (Fig. 5).

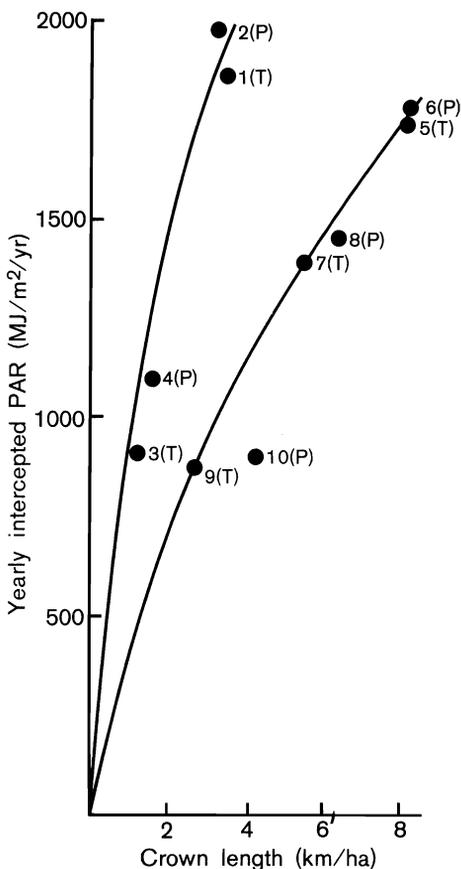


FIG. 5—Annual intercepted PAR for simulated stands v. crown length per hectare. Simulated stands are in pairs with same leaf area index achieved by either thinning (T) or pruning (P) (numbers correspond with Table 9).

## DISCUSSION

The radiative transfer model described in this paper simulates the transmission of solar radiant energy through a plant canopy. Although it predicts hourly intercepted radiant energy from hourly incoming radiant energy, the model is theoretically calculating instantaneous transmission of solar radiant energy through the canopy. Hence, it is appropriate to test the validity of the model on the basis of instantaneous transmittance of solar radiant energy, rather than on average transmittances over a long time period.

Though there were large differences between measured and predicted PAR beneath the tree crown, simulation runs indicated that these differences could be accounted for

by measurement error in crown shape and leaf area. This indicates that the theory is appropriate for estimating the transmittance of PAR in *P. radiata* stands. The theory of radiative transfer applies to radiant energy in any wavebands; hence, it is appropriate to use the model to estimate the transmission of radiant energy in any waveband provided that one knows how foliage transmits and reflects radiant energy in that waveband.

On a daily basis, small errors in measuring crown shape and leaf area are unlikely to cause large changes in the estimate of intercepted PAR. The percentage difference in intercepted PAR is likely to be smaller than the percentage difference between actual and measured crown shape and leaf area.

Several authors have compared field measurements of irradiance in coniferous stands with predictions from radiative transfer models (Norman & Jarvis 1975; Kellomäki & Oker-Blom 1983). However, they used different models and assumed that the foliage is clumped. The differences between measured and predicted values of transmittance in those two studies appear to be of a comparable size to the differences found in this study. In our model we did not assume that foliage was clumped within the crown. Hence, the above suggests that it is reasonable to assume that foliage is randomly distributed throughout discrete ellipsoidal crowns in stands of *P. radiata*.

To reduce computing costs, the possibility of running the model for selected days (rather than for each day of the year) and deriving equations to predict daily intercepted PAR from daily incoming PAR was investigated. The results (Table 2) indicate that this procedure would be unlikely to cause an error of more than 5% in the estimate of yearly intercepted PAR. Because it results in about a 10-fold reduction in computing costs, a 5% difference in results is considered acceptable. The above procedure has been used in all the calculations of yearly intercepted PAR presented in this paper.

Computer simulations of yearly intercepted PAR indicated that a linear relationship (Eqn. 2) between intercepted PAR and incoming PAR was realistic when the forest canopy was almost closed, and also during winter months in more open stands. In the other cases it was more appropriate to use a curvilinear regression equation (Eqn. 3).

There is a linear relationship between intercepted PAR and dry matter production at Puruki (Fig. 3). A zero intercept is considered realistic since above-ground dry matter production occurs throughout the year at Puruki (D. Santantonio, unpubl. data). While such a relationship is useful for predicting above-ground dry matter production, it is an empirical relationship and should be used with caution outside the range of data used in deriving the relationship.

Assuming that the relationship between intercepted PAR and above-ground dry matter production does not change with more drastic silvicultural treatments than those considered, the model was used to investigate the effects of thinning and pruning on intercepted PAR and hence dry matter production. For a given leaf area index, an unthinned-pruned stand will intercept more PAR (Fig. 4), and hence have greater above-ground dry matter production than an unpruned-thinned stand. This result will be due to the greater ground area shaded by tree crowns in the unthinned-pruned stands. The initial number of stems per hectare is not important; however, when crown length per hectare rather than leaf area index is used as the dependent variable, the

points tend to fall on two curves depending on the initial number of stems per hectare. The intercepted PAR, and hence above-ground dry matter production for a heavily pruned stand with a high stocking (Stand 10) was less than might have been expected. This result is not unrealistic since West *et al.* (1982) found that the basal area increment for such stands tended to fall below the general relationship of basal area increment to crown length per hectare. Since the data points in Fig. 4 are less scattered than those in Fig. 5, it appears that leaf area index would be a better variable than crown length per hectare for estimating growth.

One of the main advantages of the radiative transfer model described in this paper is that it can be used to calculate the interception of solar radiant energy under a wide range of conditions. Specifying the tree co-ordinates in three dimensions allows one to investigate how slope affects the interception of solar radiant energy. Since the position of each tree is specified, the model can be used to investigate the effects of alternative tree arrangements on intercepted radiant energy, and the amount reaching the forest floor. Being able to specify the amount of foliage within shells, and being able to remove foliage from the base of the crown will allow the effects of defoliation by insects or pathogens to be investigated.

The radiative transfer model described in this paper need not be a stand-alone model. Routines for predicting net photosynthesis have been added (Grace *et al.* 1987). The addition of routines for respiration, allocation of carbon from photosynthesis, and tree dimensional growth will improve our understanding of the factors controlling tree growth.

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