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Development and validation of a simple approach to modelling tree shading in agroforestry systems

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Abstract. There have been a number of models developed which attempt to predict the shading patterns beneath individual tree or forest canopies. We describe a computer-based model which is able to estimate shading patterns through a discontinuous canopy of pruned trees. The model is designed to assist in the layout and management of agroforestry systems with widely spaced trees. The model was tested against data collected from a seven-year-old agroforestry system involving radiata pine, located near Canberra, Australia. The model was shown to slightly but consistently underestimate light penetration at ground level beneath the trees. However, the extent of bias (0.7% to 5%) was so small as to be of little significance in practice.

Introduction

Many studies of the relationship between pasture productivity and the growth of widely spaced trees in agroforestry systems indicate a high degree of competition between the pasture and trees [1, 3, 6, 7].

Models describing the relationship between pasture and trees have generally adopted some measure of tree crown cover in order to predict pasture production [3, 6]. For intensively managed agroforestry involving radiata pine (*P. radiata*), Percival et al. [7] established a relationship between pasture yield, total green crown length and mean green crown length per hectare.

The availability of light at ground level beneath a discontinuous canopy of trees is directly related to the size, shape and nature of the tree canopy, the number of trees, and their arrangement. Total transmission of light through the forest canopy is equal to the sum of the light which misses the trees completely and the amount of light which can pass through the canopies of the individual trees [4]. The latter is dependent on the depth of the forest canopy and the density of the leaves, branches and trunks. Light availability under the tree crop is therefore likely to be closely related to the two crown variables, total green crown length and mean green crown length per hectare, adopted by Percival et al. [7].

Structure of an agroforestry system

Factors affecting the physical structure of an agroforestry system include the species involved, the age of the stand, the initial espacement and the silvicultural management. With few exceptions, agroforestry in Australia and New Zealand has involved plantings of a single tree species. In most cases, homogeneity of tree growth has been further enhanced by the planting of improved stock, such as superior clones of poplar or radiata pine. Initial espacement is most commonly based on a rectangular grid for agroforestry. The trees are also regularly pruned of lower branches in order to improve timber quality. Agroforestry systems are therefore typically planted and managed so as to minimize variability in tree size and shape as well as in the espacement.

The evenly spaced stand of pruned trees forms a discontinuous canopy under which some type of agricultural production is undertaken. This situation lends itself to the development of a simple mathematical model to describe the penetration of direct solar radiation or light, in particular.

The single tree model developed by Satterlund [10] was used as the basis for constructing a model for widely-spaced pruned trees. Satterlund's model depicts tree shape (Fig. 1) as being made up of a cone atop a cylinder which itself is balanced upon a cylindrical bole and allows a wide range of crown sizes to be explored. Quesada et al. [8] developed a model to calculate the periods of shadow beneath a discontinuous canopy which considered the shadow cast by trees with crowns of the following types: spherical, hemispherical, ellipsoidal, hemi-ellipsoidal and conical. Crowns were assumed to be opaque and shade cast by the trunk was ignored. Their model can accommodate sloping sites and attempts to model shading patterns and represents the most advanced computer-based model relating to light penetration in a very irregular flow of work that goes back to that of Brown and Merritt [2], relating to gap size for natural regeneration.

Our model, developed independently, allows for the shadow cast by the trunk and direct radiation passing through the canopy. It can also provide a 'picture' of the shadow pattern for any time of the day.

Light penetration

Direct light penetrates a discontinuous forest canopy by (a) passing through the gaps in the tree foliage and (b) passing between individual trees. For light that passes through the gaps in the foliage it is necessary to determine to what degree the direct light is intercepted by the crown. The vertical and horizontal crown densities measure the proportion of direct light intercepted by the crown. An assumption often made is that a tree crown is made up of a large number of small, randomly inclined and orientated leaves, distributed with equal probability throughout the volume of its canopy. The assumption of an equal probability of distribution of light-intercepting material can also

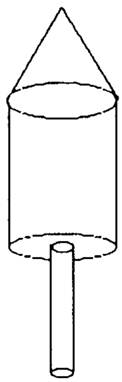


Fig. 1. Satterlund's model of tree shape.

account for the irregularities in tree shape and an uneven distribution of foliage. Satterlund's model involves the estimation of the angular crown density for light passing through the crown at an angle to the vertical and horizontal.

The angular crown density (k) is calculated from the horizontal and vertical crown densities and the solar altitude:

$$k = C + (C' - C) \sin \phi \tag{1}$$

where:

k denotes the angular crown density;

ϕ denotes the solar altitude above the horizon;

C denotes the crown density from the horizontal;

and

C' denotes the crown density from the vertical.

Satterlund [10] assumed a random spatial distribution of trees within a stand, being the simplest situation in which to calculate light interception by the canopy of a natural forest. This is inappropriate for agroforestry, where a more realistic assumption is that of uniformly distributed trees set out on a rectangular grid of known dimensions and orientation.

Slope and aspect vary across many agroforestry sites. It is therefore also desirable to stratify the site into uniform areas so that the effects of slope and aspect can be taken into account.

This 'TREE-SHADE' model of light penetration developed for agroforestry systems is therefore dependent on user-supplied estimates of variables shown in Table 1.

Table 1. Input variables required for TREE-SHADE model.

Variable	Code-name	Definition
Site variables		
Latitude	ALAT	Latitude of site (deg)
Longitude	ALONG	Longitude of site (deg)
Slope	SLOPE	Slope of site (deg)
Aspect	SAZI	Aspect from north (deg)
Time zone	IZONE	Time zone from 1 to 6 for zones from New Zealand to Western Australia
Tree variables		
Diameter	DB	Average tree diameter (cm) at breast height (1.3 m)
Height	HT	Average tree height (m)
Pruned height	PB	Average height of pruned bole (m)
Crown diameter	DC	Average diameter of lower crown (m)
Conical angle	ANG	Half the average angle (degrees) of the conical tip of the trees
Crown density:		
Horizontal	HORK	Average light transmission (decimal)
Vertical	VERTK	
Times and dates		
Starting time	STIME	All times on 24 hour clock,
Finishing time	FTIME	minutes being distinguished from hours by a decimal point
Time interval	TINT	Measurement interval during day (min)
Starting Date	SDATE	Dates described as month day
Finishing Date	FDATE	
Day interval	IDINT	Measurement interval between days
Points	NOS	Number of random points

The model projects the shadow of a single tree of average dimensions on any given slope, at any time, and on any particular day of the year, in order to estimate light penetration to ground level beneath the discontinuous canopy of an agroforestry system.

Basis of the model

The true position of the sun (declination, altitude and azimuth) at any standard time is determined by correcting for local time and the equation of time. The angle of incidence of the sun's rays onto the ground is then determined by considering the slope and aspect of the site.

The estimation of light penetration in the tree community was done by considering a single tree of average dimensions on the basis of the assumption of a rectangular grid and uniformity among the trees. Because all the trees in the stand are identical and the slope of the site is considered constant, the rectangular area between any four trees on the grid will be covered by a shadow of exactly the same shape as all the other grid cells in the forest (Fig. 2). It is therefore only necessary to estimate light penetration in this rectangle. This assumes, of course, that the area planted to trees is reasonably large relative to the height of the trees and thus the external boundary zone effects are negligible.

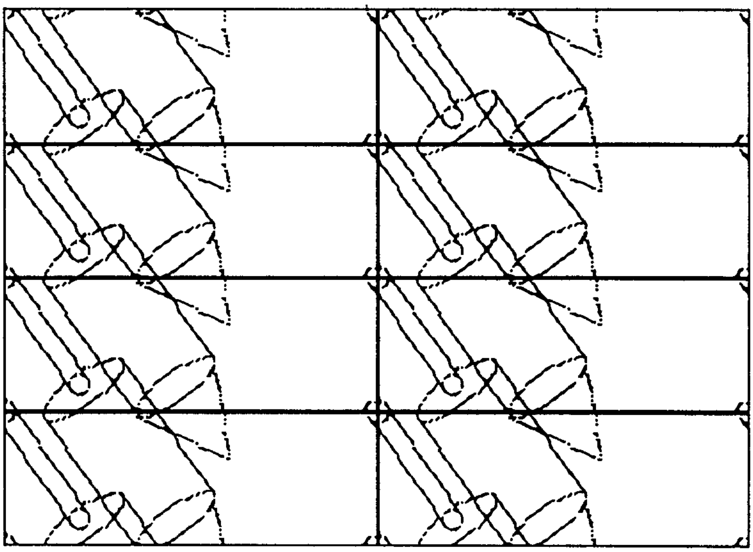


Fig. 2. Sample of tree shadow outlines.

A Monte Carlo process [9] is used to estimate light penetration within the rectangle bounded by the grid of four trees, thereby avoiding complex integrations that would otherwise be needed (e.g. Satterlund [10]). A sample of points are randomly selected within the rectangle concerned and evaluated with respect to light penetration. If a point is found to be situated within the ground shadow of a bole, it is recorded as being in a shadow. If a point is found to be situated within the shadow of a tree crown or crowns, a stochastic simulation is initiated according to the angular crown density (suitably adjusted according to the number of overlapping crown shadows) to determine whether or not the point occurs within a sun fleck or in a shadow. The sample average provides an estimate of the mean value of light penetration, the precision of this estimate being to a large extent controllable by the sample size that the user defines.

By repeating the process of estimation at intervals over the day, the changes in light penetration can be traced over the day. Similarly, repeating the process over days of the year enables comparisons of light penetration over a year to be made. A copy of the program, which is written in FORTRAN 77, may be obtained from the authors.

Validation

Testing of the model was undertaken at the Pinebank Agroforestry Trial on the Southern Tablelands of New South Wales. Established in 1978, the trial involves the integration of radiata pine and improved pasture for the joint production of wood and animal products.

Due to limited resources it was possible to collect data from only two plots on site characteristics, tree dimensions and the resulting light penetration, so as to enable comparison with estimates of light penetration from the model.

Plots four and six were selected. They carried healthy trees at even stocking rates of 300 and 200 stems per hectare respectively. For both plots the initial planting had been in north-south rows 8 m apart so as to achieve an initial stocking rate of 500 stems per hectare and 312 per hectare respectively. Thinning at an age of 3 years reduced these initial stockings to their present levels. In doing so, thinning also changed the nature of the espacement from the initial rectangular grid, aside from occasional failures, to a less regular basis.

The pruning history of each plot was similar with two previous prunings resulting in the branches being removed from the stem up to just over 2 m. The third pruning, undertaken during the field survey, was aimed at removing all limbs from the stem up to a bole diameter of 10 cm with some corrective pruning of the larger limbs above this point. This lifted the average pruning height for both plots to over 3 m, with many of the larger trees being pruned to over 5 m. This represents a further deviation from the presumed uniformity in the computer model.

Two measurement plots were established within each of the two trial plots:

(i) a small rectangular light penetration plot (33 × 25 m) was placed at near the centre of each trial plot and aligned across the rows;
(ii) a rectangular tree measurement plot (56 × 39 m) surrounded the light penetration plot.

Due consideration was given to the dimensions of the larger tree measurement plot to include virtually all trees whose shadows would affect the inner light interception plot between 8.00 am and 4.00 pm. Similarly, care was taken in the design of the plot layout to ensure that the internal plots were representative of the light penetration through the trees of the larger trial plot.

Both plots were measured before and immediately after the third pruning providing four treatments with which to test the computer model.

Conical angle and crown density measurements were determined from a series of photographs of ten randomly selected trees from each treatment. At least two colour slides were taken of each randomly selected sample tree. Crown images were photographed from two distinct angles (measured with a clinometer) so as to allow the vertical and horizontal crown densities to be derived from simultaneous equations.

The method developed for field measurement of light penetration involved the systematic marking of 72 points on the ground within the internal plot on a rectangular grid pattern of 5 × 3 m. The points were assessed as to whether or not they were shaded and the percentage of the area under shade calculated.

Table 2. Data from Pinebank Agroforestry Trial.

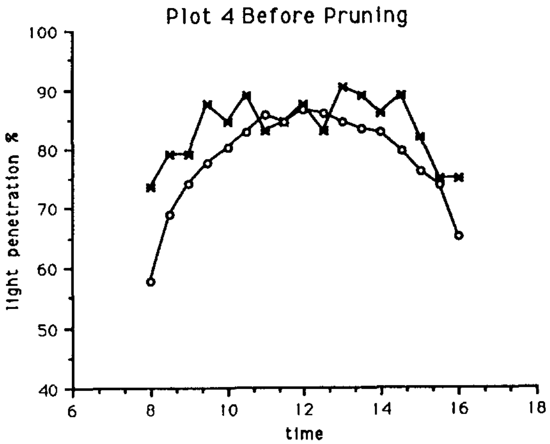
	Plot 4		Plot 6	
	Before pruning	After pruning	Before pruning	After pruning
Site variables				
Latitude (deg)	−35.1	−35.1	−35.1	−35.1
Longitude (deg)	149.7	149.7	149.7	149.7
Slope (deg)	7.5	7.5	4.5	4.5
Aspect (deg)	315.0	315.0	340.0	340.0
Time Zone	3	3	3	3
Tree variables				
Bole diameter (m)	0.0678	0.0678	0.0786	0.0786
Crown diameter (m)	2.02	1.70	2.26	1.78
Tree height (m)	6.74	6.74	7.47	7.47
Pruned height (m)	2.22	3.38	2.83	3.97
Conical angle (deg)	32.14	34.88	28.22	27.92
Crown Density				
Vertical	0.56	0.55	0.56	0.54
Horizontal	0.71	0.61	0.73	0.57
Stand variables				
Ros spacing (m)	8.00	8.00	8.00	8.00
Tree spacing (m)	4.79	4.79	6.35	6.35
Row orientation (deg)	0	0	0	0
Dates and times				
Date (day/month)	28/8	1/9	28/8	1/9
Starting time	8.00	8.00	7.45	7.45
Time interval (min)	30	30	30	30
Finishing time	16.30	16.30	16.45	16.45

The two plots were tested at half hour intervals from 7.45 or 8.00 am until 3.45 or 4.00 pm on two sunny relatively still days before and after pruning.

Results

The data collected are summarized in Table 2.

The TREE-SHADE model was run for the four treatments and the predictions of available sunlight compared with the observed results (Figs. 3 and 4).



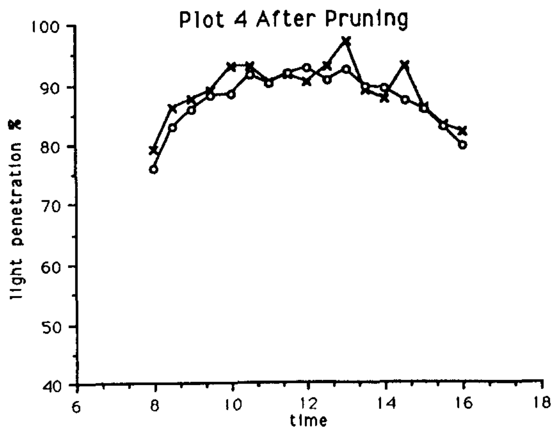


Fig. 3. Actual (x) and predicted (0) values of light penetration for plot 4.

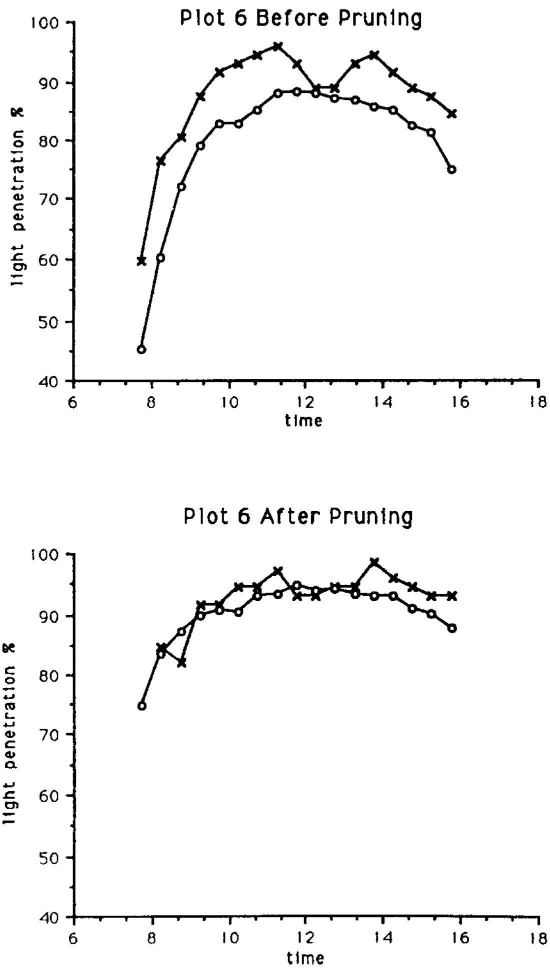


Fig. 4. Actual (x) and predicted (0) values of light penetration for plot 6.

Paired *t* tests were used to compare the actual and estimated values for light penetration between 9.00 am and 3.00 pm. For all treatments, the estimated values were significantly less than the actual, the differences before pruning (4.96% for plot 6 and 2.20% for plot 4) being greater than after pruning (1.53% for plot 6 and 0.66% for plot 4). However the differences were small and the trends very consistent.

The effect of assuming regular tree espacement was tested by modifying the model to reflect actual tree spacings, as measured on site. Such a process is unlikely to be practicable for general usage, because of the additional field measurements required and the increase in computing time. Nevertheless, it enabled the effect of irregular spacing to be gauged. The results indicated that the irregular tree spacing along the rows, due to previous thinning, explained up to 35% of the difference between the actual values and the estimates from the standard model.

Conclusions

The small bias in the predictions is not likely to be of practical importance and thus this approach to modelling light penetration has potential as an aid to management in agroforestry. The TREE-SHADE model enables comparisons to be made for different sites, stockings, and pruning options with only a fairly modest input of equipment and time.

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