A simple method to estimate radiation interception by nursery stock conifers: a case study of eastern white cedar

A.A. Pronk[1,*], J. Goudriaan[2], E. Stilma[2] and H. Challa[3,†]

[1] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, NL-6700 AA Wageningen, The Netherlands
[2] Plant Production Systems Group, Wageningen University, Wageningen, The Netherlands
[3] Farm Technology Group, Wageningen University, Wageningen, The Netherlands
† Deceased before publication.
* Corresponding author (tel: +31-317-475793; fax: +31-317-423110; e-mail: annette.pronk@wur.nl)

Received 6 December 2002; accepted 12 May 2003

Abstract

A simple method was developed to estimate the fraction radiation intercepted by small eastern white cedar plants (*Thuja occidentalis* 'Brabant'). The method, which describes the crop canopy as rows of cuboids, was compared with methods used for estimating radiation interception by crops with homogeneous canopies and crops grown in rows. The extinction coefficient k was determined at different plant arrangements and an average k-value of 0.48 ± 0.03 (R^2 = 0.89) was used in the calculations. Effects of changing plant characteristics and inter- and intra-row plant distances were explored. The fraction radiation intercepted that was estimated with the method for rows of cuboids was up to 20% and for row crops up to 8% lower than estimated with the method for homogeneous canopies at low plant densities and a LAI of 1. The fraction radiation intercepted by small plants of *Thuja occidentalis* 'Brabant' was best estimated by the simple method described in this paper.

Additional keywords: clustering factor, extinction coefficient, *Thuja occidentalis* 'Brabant', row crops, rows of cuboids

Introduction

The amount of radiation intercepted by plants depends on plant canopy structure. The estimation of intercepted radiation becomes increasingly complicated with increasing heterogeneity of the plant canopy structure. To estimate radiation interception several methods are available, each of which is suitable for the specific canopy involved (Monsi & Saeki, 1953; De Wit, 1965; Ross & Nilson, 1966; Miller, 1967). However, these methods generally assume a homogeneous distribution of leaves within the crop canopy and interception of radiation by the photosynthetically active surface, i.e., by the leaves only. Such conditions are not met by field-grown nursery stock planted at low densities where foliage is clustered into individual plant crowns and where also stems may contribute to radiation interception. Discontinuous canopies and clustered foliage require a more detailed description of radiation interception by the leaves as more radiation reaches the soil surface and is not used for dry matter production in comparison with situations where leaves are homogeneously distributed.

Norman & Welles (1983) and Bartelink (1996) developed detailed, complex methods to estimate radiation interception of discontinuous canopies with grouped foliage, mainly for individual tree crowns or for forests. However, conditions of individual trees and forests differ considerably from those of conifers in production nurseries. For example, *Thuja occidentalis* 'Brabant' (eastern white cedar) is planted in rows with a low leaf area index (LAI). This allows a more simple approach to estimate the fraction of radiation intercepted: the row crop approach (Goudriaan, 1977), a method successfully used for other row crops (Palmer, 1989; Wagenmakers, 1995; Heuvelink, 1996). However, the row crop approach assumes continuous rows, a condition not always met in field-grown nursery stock. For instance, during the first year of the two-year nursery period of transplanted conifers, the bare intra-row area interrupts the canopy in a similar way as the bare area between rows (Figure 1). The reduction of intercepted radiation due to the bare intra-row area may be included in the row crop approach. To estimate this reduction in row crops the bare intra-row area can be treated in the same way as the bare inter-row area. In other words, the plant row can be considered as an array of cuboids.

The objective of this study was to use this approach and develop a simple method to estimate radiation interception in crops consisting of rows of cuboids. In this study the conifer eastern white cedar (*Thuja occidentalis* 'Brabant') was used because this crop is

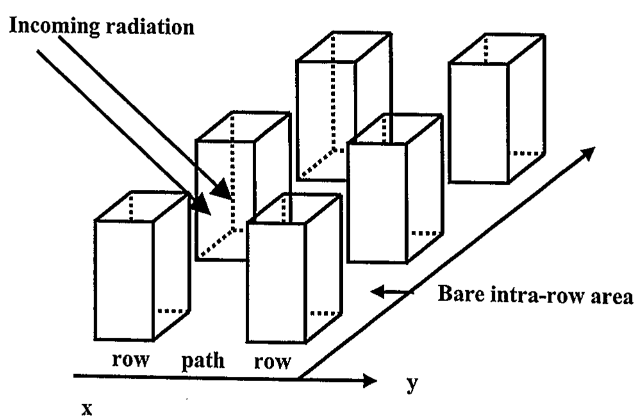

Figure 1. Schematic representation of radiation interception by a crop consisting of rows of cuboids. The y-axis is in the direction of the row; x-axis is perpendicular to the row.

planted in the field in rows with bare intra-row areas during much of the two-year nursery period. The extinction coefficient k was determined experimentally and was used to investigate effects of LAI, plant height and plant width on the calculated fraction of radiation intercepted by a homogeneous canopy, a row crop and a row of cuboids.

Theory of radiation interception by crop canopies

Homogeneous canopy versus row crop

In a homogeneous crop canopy the fraction of radiation intercepted (F_{int}) is described as an exponential extinction function of LAI (Monsi & Saeki, 1953):

$$I = I_o * e^{-k*LAI} \quad (1)$$

where
I = the radiation intensity below the plant canopy,
I_o = the radiation intensity above the plant canopy,
k = the radiation extinction coefficient, and
LAI = the leaf area index.

So F_{int} by the canopy (ignoring reflection by the canopy) is:

$$F_{int} = 1 - e^{-k*LAI} \quad (2)$$

In Equation 2, F_{int} is the complement ($1- e^{-k*LAI}$) of the fraction transmitted to the soil surface, assuming that the leaf area is homogeneously distributed over the entire area.

In a row crop, paths and rows alternate. Total leaf areas being the same, the leaves are concentrated in the plant rows and absent between the rows: the paths. This heterogeneity of the crop canopy normally tends to reduce canopy radiation interception because the leaves shade each other more strongly and most of the radiation in the path will fall onto the soil surface. The description of this heterogeneity could be simplified by considering a crop to consist of two parts: a homogeneous part with the 'compressed' leaf area and a bare, leafless part. If all rows would be pushed together, the compressed leaf area index (LAI_{comp}) is given by the following equation:

$$LAI_{comp} = LAI * \frac{(W + P)}{W} \quad (3)$$

where W is the width of the plant row and P the width of the bare path (Figure 1). The radiation level transmitted to the soil (I_{comp}) below the LAI_{comp} then becomes:

$$I_{comp} = I_o * e^{-k*LAI_{comp}} \quad (4)$$

In such a compressed canopy the fraction of soil area covered by the crop is $W/(W+P)$. Consequently, the fraction of radiation intercepted, $F_{int,comp}$, averaged over the whole area, becomes:

$$F_{int,comp} = \frac{W}{(W+P)} * (1 - e^{-k*LAIcomp}) \qquad (5)$$

and the fraction of soil area that is bare and receives full radiation becomes: $P/(W+P)$.

Direct and diffuse radiation

In this study it was assumed that on a daily basis direct or diffuse radiation does not affect the average fraction of radiation intercepted (Goudriaan, 1977; 1988). The simplest description for diffuse radiation is that of isotropy, i.e., homogeneous radiance from the entire sky. This assumption enables easy spatial integration over all directions without the need to consider time of day or day of year.

Transmission for row systems with 'black' and 'non-infinite' LAI

Rows with a non-infinite leaf area index transmit radiation either to the soil surface or to the adjacent plant row. To calculate the fraction of transmitted radiation, the theoretical case of a 'black' row (infinite LAI) not transmitting any radiation is considered first. The only radiation reaching the soil surface is then passing through the space of the paths. It can be calculated for a known path width, plant row width and plant row height. This fraction – radiation level at a horizontal surface element of the path divided by the radiation level above the canopy – is called the *view factor* of the sky. The *view factor* for any horizontal surface is identical to the vertical projection of the unobstructed portions of the sky dome, relative to the total vertical projection of the sky dome (Figure 2). Since the radiance from the sky dome is assumed to be homogeneous, the contribution of any element of the sky to the radiation that reaches the soil surface is proportional to the sine of the angle of incidence of the radiation coming from that sky element. The vertical projection of the sky view of the path is given by the difference of the cosines (Figure 3).

If spatially integrated over the path the relative radiation onto the path, IP_{black}, is (Goudriaan, 1977):

$$IP_{black} = \frac{\sqrt{H^2 + P^2} - H}{P} \qquad (6)$$

where H is the plant height and P the bare path width between the rows.

At non-infinite LAI, however, the row transmits radiation, increasing the level of IP_{black}. Depending on the angle of incidence, radiation from lateral directions will have passed through one or more adjacent rows before reaching the path. The number of rows through which radiation passes can be estimated according to Gijzen & Goudriaan (1989), but here a simplifying approach is followed. On average the radiation

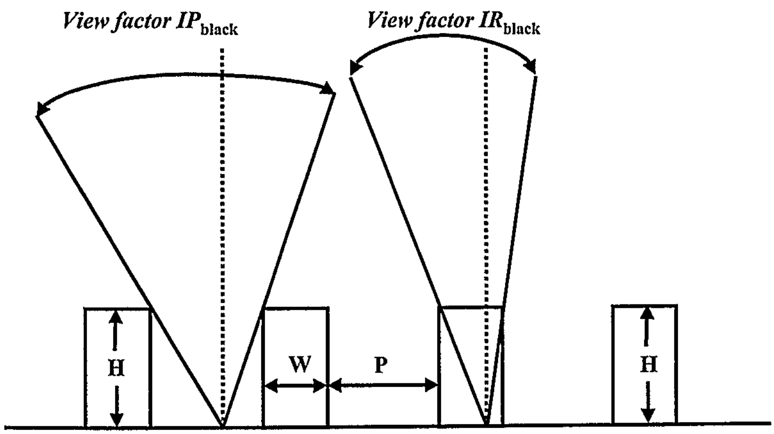

Figure 2. Boundaries of part of the sky seen from a point at the bottom of the inter-row space (*view factor* IP_{black}) and from a point in the plant row (*view factor* IR_{black}) with infinitive leaf area index (after Goudriaan, 1977). H = plant height, W = plant row width, and P = bare path width.

transmitted by the row equals I/I_o (Equation 1), as in a homogeneous canopy. Its *view factor* is the complement of that for the path, IP_{black}, and so the resulting expression for radiation levels in the path at soil level with non-infinite *LAI* (SP_{ni}) is:

$$SP_{ni} = IP_{black} + (1 - IP_{black}) * e^{-k*LAI} \quad (7)$$

For the radiation level at the soil surface below the row, SR_{ni}, a similar geometrical approach is followed. First the *view factor* of the row itself is determined, IR_{black}, in the same way as IP_{black} (Equation 6 but with *P* replaced by *W*). In analogy to the equations for SP_{ni}, SR_{ni} would be given by $IR_{black} + (1 - IR_{black}) * I/I_o$. However, this would result in an overestimation as in the first term with the *view factor* IR_{black} one still needs to account for the radiation extinction in the overhead row itself. The best approximation for this *view factor* is the transmission value in the case that the rows would be pushed

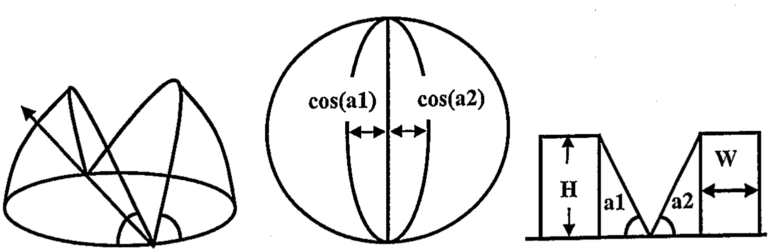

Figure 3. The vertical projection of the *view factor* of the path. H = plant height, W = plant row width, and a1 and a2 are the inclinations of the incident rays in the normal polar co-ordinate system. The single arrow points in the direction of the plant row.

together, termed I_{comp}/I_o (Equation 4). So the final expression for SR_{ni} will be:

$$SR_{ni} = IR_{black} * \frac{I_{comp}}{I_o} + (1 - IR_{black})*e^{-k*LAI} \quad (8)$$

Fraction of radiation intercepted by the plant canopy

For a plant canopy with a given total leaf area index and a given plant height, the degree of heterogeneity varies with plant row and path widths relative to canopy height. For plant row and path widths that are much smaller than canopy height, the canopy will be indistinguishable from a homogeneous canopy and Equation 1 can be used. On the other hand, if path and plant row widths are very large in comparison with canopy height, the situation will be virtually as presented by Equations 3, 4 and 5.

The approach followed below is that in intermediate cases the relative difference between the radiation at the soil surface below plant row and path will serve to characterize the degree of heterogeneity. This relative difference is given by the ratio $(SP_{ni} - SR_{ni})/(1 - I_{comp}/I_o)$. In homogeneous canopies SP_{ni} and SR_{ni} will be identical so that this relative difference becomes zero.

The approximating equation for the total fraction of radiation intercepted by the plant canopy will be:

$$(F_{int,row\_crop} = F_{int} - \frac{(F_{int} - F_{int,comp}) * (SP_{ni} - SR_{ni})}{(1 - \frac{I_{comp}}{I_o})} \quad (9)$$

Rows of cuboids

Although plants are planted in rows, rows most often are not continuous as assumed above, at least not during part of the growing period (Figure 1). The above-presented procedure for estimating radiation interception by crops grown in rows could be followed for crops that can be represented by arrays of cuboids. The compressed leaf area index for rows of cuboids, $LAI_{comp,cub}$, is not only related to P, but also to the bare soil between the plants within the row, B (Figure 4). Analogous to Equation 5, the fraction radiation intercepted for the compressed leaf area index for rows of cuboids, $F_{int,comp,cub}$, is calculated. The *view factor* of the bare soil between plants in the row (for infinite LAI), IB_{black}, can be defined by replacing P in Equation 6 by B, and SB_{ni} can be calculated (Equation 7). The bare area between P and B, BP, is not yet included (Figure 4). The *view factor* IBP_{black} for BP is related to the *view factors* for P and B according to the following equation:

$$IBP_{black} = \frac{(IP_{black} * P * W + IB_{black} * B * W + IBP_{black} * P * B)}{(W * P + W * B + P * B)} \quad (10)$$

Adding the transmitted radiation reaching the soil surface in case of a non-infinite leaf area index gives:

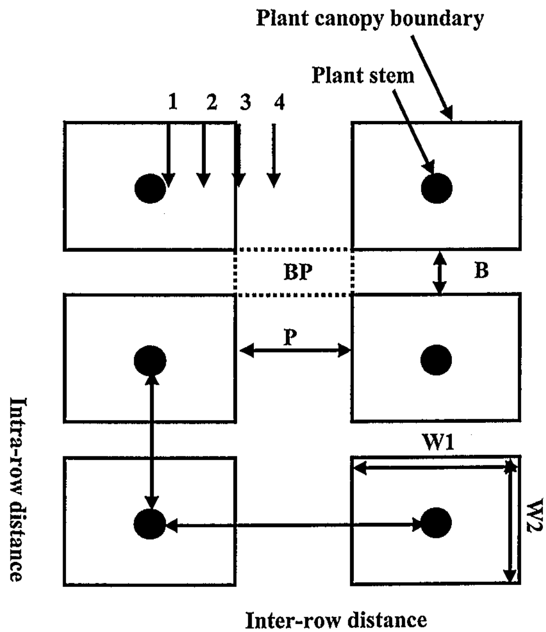

Figure 4. Layout of the experiment for measuring radiation interception. P = bare path width, B = bare intra-row area, BP = bare area between B and P, W1 = plant width across the plant row, and W2 = plant width in the plant row. 1–4 = points where radiation was measured.

$$SBP_{ni} = IBP_{black} + (1 - IBP_{black})*e^{-k*LAI} \quad (11)$$

Finally, the approximating equation for the total fraction of radiation intercepted by the plant canopy of rows of cuboids will be:

$$F_{int,cub} = F_{int} - \frac{(F_{int} - F_{int,comp,cub}) * (SBP_{ni} - SR_{ni})}{(1 - \frac{I_{comp,cub}}{I_o})} \quad (12)$$

If B decreases to zero (a continuous row), the fraction radiation intercepted becomes identical to that given by Equation 9.

Materials and methods

Mid-March 2001, 100 small (height: 0.25–0.35 m) and 100 large (height: 0.6–0.8 m) plants of *Thuja occidentalis* 'Brabant' were transplanted to nursery containers and placed in an unheated greenhouse. The plants were used to form two experimental groups.

On an overcast day, 26 April 2001, 20 small and 20 large, uniform plants were selected and placed outdoors at the Applied Plant Research Nursery Stock unit in Boskoop in two plots consisting of 4 rows of 5 plants each (Group 1). Inter- and intra-row plant distances were varied to create different plant arrangements (Table 1). Light interception was measured the same day on 6 plants in the middle of each plot, using a Licor LAI-2000 Plant Canopy Analyzer (Lincoln, NB, USA). The recordings were carried out facing south with a 270° viewcap (Nackaerts *et al.*, 2000). A reference reading was taken above the plant canopy, followed by 4 readings at soil level at equidistant intervals between the stem base and the middle of the path (Figure 4). Light interception was calculated from these 5 readings according to the Licor LAI-2000 Plant Canopy Analyzer Reference Manual (Anon., 1991). The average amount of light intercepted per plant per plot was considered the light interception estimate of that particular plot. The light interception of each plot was measured twice (2 replicates), or three times (3 replicates) if LAI < 0.2 to account for a larger variability at lower LAI. The day after light interception was measured (27 April 2001), plant height (H) and plant width (across the row: W1 and in the row: W2) were recorded. The leaves (defined as the green parts of the plant) of the 6 small and 6 large plants were removed and the one-sided projected area of the leaves was measured with a LI-COR 3100 area meter (Lincoln, Nebraska, USA). The radiation interception recordings were repeated for the defoliated plants in the two plots with the highest plant density (arrangement 1) and for the generally used plant density for field-grown *Thuja* (arrangement 3) (Table 1).

Table 1. Plant arrangements for the small and large plants in the two experimental groups.

Plant arrangement	Small plants[1]		Large plants[1]	
	Row distance	Intra-row distance	Row distance	Intra-row distance
	(m)			
Group 1				
1	0.19	0.19	0.23	0.23
2	0.40	0.40	0.40	0.40
3	0.50	0.40	0.50	0.40
4	0.75	0.40	0.75	0.40
Group 2				
5	0.30	0.19	0.30	0.23
6	0.30	0.30	0.30	0.30
7	n.d.[2]	n.d.	0.40	0.40
8	n.d.	n.d.	0.50	0.23
9	n.d.	n.d.	0.50	0.30

[1] See Table 2 for specification.

[2] n.d. = not determined.

The Licor LAI-2000 Plant Canopy Analyzer not being sensitive enough, the one-sided projected area of the stems of the small plants was measured with the LI-COR 3100 area meter.

On 1 May 2001 (an overcast day), another 20 small and 20 large plants were selected and placed outdoors at the same location, and light interception was measured as described above for a different series of plant arrangements (Table 1, Group 2). The next day, the 6 small and 6 large record plants were destructively harvested, following the same procedure as described for Group 1.

LAI (m^2 leaf per m^2 soil) was calculated from the destructively determined leaf area for each of the plant densities, assuming a homogeneous crop canopy. LAI_{comp} was calculated according to Equation 3 and $LAI_{comp,cub}$ as proposed in the section 'Rows of cuboids'. The extinction coefficient k was calculated fitting Equation 1 to the recorded data by using the statistical programme GENSTAT 6, release 1 and the fraction radiation intercepted was calculated using Equations 2, 9 and 12. Although k theoretically consists of many different values, depending on the orientation of the leaves and on the direction of the incoming radiation (Goudriaan & Van Laar, 1994), one value of k was fitted. The clustering factor was calculated as the ratio between the actual k and the theoretical value k_{bl} [0.72 ($0.8 * \sqrt{(1-\sigma)}$; where σ = the scattering coefficient (0.2)] (Goudriaan & Van Laar, 1994).

Results

Extinction coefficient

The one-sided projected area of the stems of the small plants was 14 cm^2 on 26 April (Group 1) and 17 cm^2 on 1 May 2001 (Group 2), which was less than 4% of that of the leaves (Table 2). The contribution of this stem area to the leaf area index was low and within the standard error of the leaf area measurements.

The fraction radiation intercepted by the stem area, F_{stem}, of the larger plants was 0.13 for plant arrangement 1 and 0.09 for plant arrangement 3 (Table 3), whereas the fraction radiation intercepted at the same plant arrangements for stems plus leaves was 0.98 and 0.60, respectively (Figure 9). F_{stem} was therefore 3.3 and 8.1%, respectively, of the interception by the plant canopy $[-\ln(1-F_{stem})/k)/(LAI + (-\ln(1-F_{stem})/k]$.

The leaf area index of some plant arrangements was less than 0.5 (Table 3). The extinction coefficient k decreased with increasing *LAI* (Table 3) but was stable at *LAI* values of 1.5 and higher. The best fitting value of k for all interception measurements was 0.48 ± 0.03 (R^2 = 0.89, Figure 5A).

Radiation interception predicted for different plant arrangements

The leaf area index calculated on the basis of the entire area (*LAI*) was lower than LAI_{comp}, which in turn was lower than $LAI_{comp,cub}$, depending on path width and intra-row gaps (Table 3). Plant width exceeded row distance for small plants at plant arrangement 1 and for large plants at arrangements 1, 5 and 6. Therefore P was zero,

Table 2. Plant height, plant width across the row (W1), plant width in the row (W2), and leaf and stem area of the small and large plants in the two experimental groups. Averages of 6 plants. Standard error of the mean in parentheses.

	Plant size	Height	W1	W2	Leaf area	Stem area
		(m)			(cm² per plant)	
Group 1	Small	0.46 (0.3)	0.20 (1.2)	0.15 (1.0)	391 (14)	14 (0.6)
	Large	0.85 (1.4)	0.39 (1.2)	0.33 (1.1)	4478 (290)	n.d.[1]
Group 2	Small	0.45 (0.5)	0.19 (1.0)	0.13 (1.4)	490 (33)	17 (1.3)
	Large	0.92 (1.4)	0.33 (1.2)	0.27 (1.5)	5488 (416)	n.d.

[1] n.d. = not determined.

Table 3. Measured fraction of radiation intercepted by the stems (F_{stem}), LAI (based on entire ground area), LAI_{comp}, $LAI_{comp,cub}$, estimated k value, and relative difference (%) between F_{int} (Equation 2) and $F_{int,row\text{-}crop}$ (Equation 9) and between F_{int} and $F_{int,cub}$ (Equation 12) for different plant arrangements and plant sizes in the two experimental groups. See text for the various symbols.

Plant arrangement	Plant size[1]	F_{stem}	LAI	LAI_{comp}	$LAI_{comp,cub}$	k	Relative difference	
							$F_{int,row\text{-}crop}$	$F_{int,cub}$
Group 1								
1	Small	n.d.[2]	1.08	1.08	1.40	0.71	0.0	0.3
2		n.d.	0.24	0.49	1.34	0.87	1.2	5.1
3		n.d.	0.20	0.49	1.34	1.26	1.7	5.4
4		n.d.	0.13	0.49	1.34	1.47	2.3	5.9
1	Large	0.13	8.46	8.46	8.46	0.45	0.0	0.0
2		n.d.	2.80	2.91	3.52	0.38	0.0	0.6
3		0.09	2.24	2.91	3.52	0.42	1.0	2.0
4		n.d.	1.49	2.91	3.52	0.38	5.1	6.5
Group 2								
5	Small	n.d.	0.86	1.37	2.08	0.69	1.5	3.6
6		n.d	0.54	0.87	2.08	0.97	1.0	5.6
5	Large	n.d.	7.95	7.95	7.95	0.36	0.0	0.0
6		n.d	6.10	6.10	6.80	0.43	0.0	0.0
7		n.d.	3.43	4.16	6.19	0.51	0.6	2.8
8		n.d.	4.77	7.24	7.24	0.40	2.8	2.8
9		n.d.	3.66	5.55	6.19	0.39	2.6	3.1

[1] See Table 2 for specification.

[2] n.d. = not determined.

LAI was equal to LAI_{comp}, and $(W+P)/W$ was equal to 1 (Table 3). The same occurred along the rows for large plants at plant arrangements 1, 5 and 8: $LAI_{comp,cub}$ was equal to LAI_{comp} because W2 exceeded the intra-row distance (Table 3). The differences between *LAI* and LAI_{comp} and between *LAI* and $LAI_{comp,cub}$ were larger for narrower

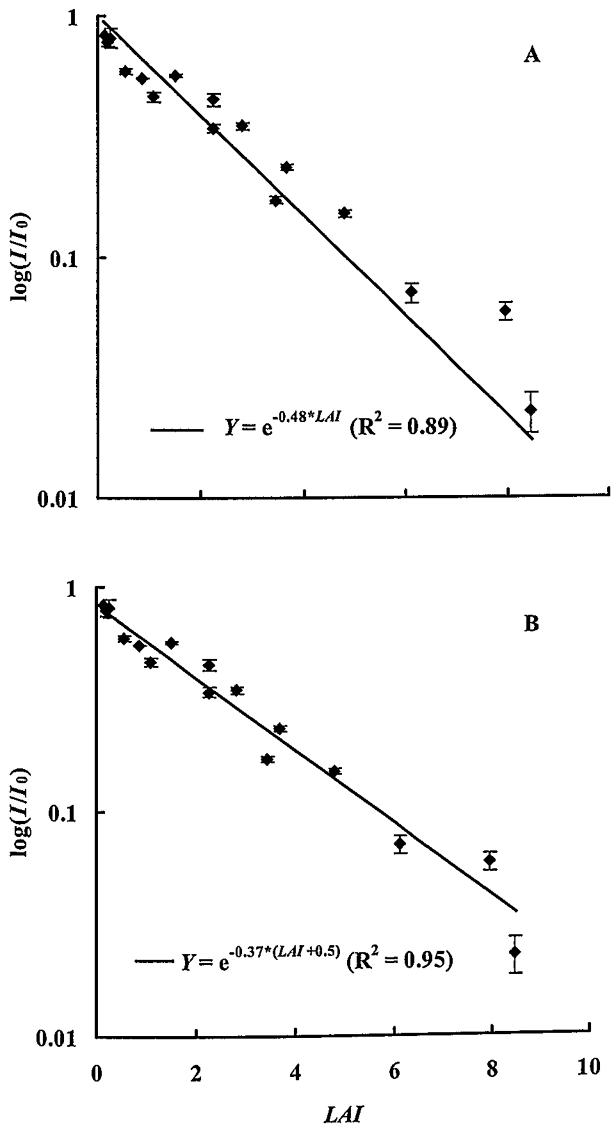

Figure 5. Intercepted fraction of radiation (logarithmic scale) by small and large *Thuja occidentalis* 'Brabant' plants at different *LAI* at the start of the experiment. A: for measured *LAI* values; B: for measured *LAI* values + 0.5 to account for the large interception of radiation with grazing incidence from the sky zone just above the horizon. Error bars indicate standard error of means.

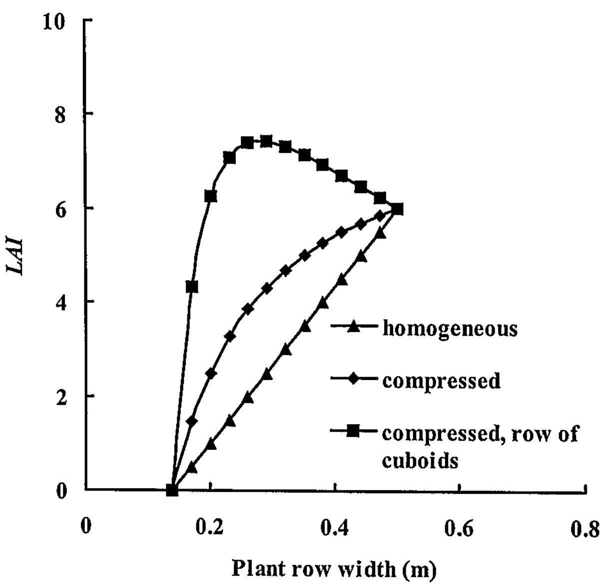

Figure 6. Effect of plant row width on *LAI* of a homogeneous canopy, LAI_{comp} and $LAI_{comp,cub}$ at an inter-row and intra-row distance of 0.5 m. Plant row width varies simultaneously with *LAI* (based on the entire area) from 0.14 m for $LAI = 0.0$ to 0.5 m for $LAI = 6.0$.

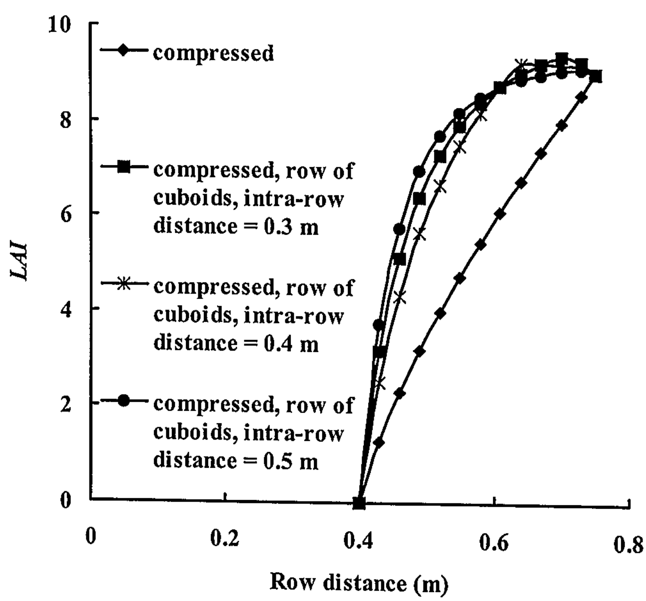

Figure 7: Effect of inter-row distance on $LAI_{comp,cub}$ at different intra-row distances, and on LAI_{comp} both at W1 = W2 = 0.25 m.

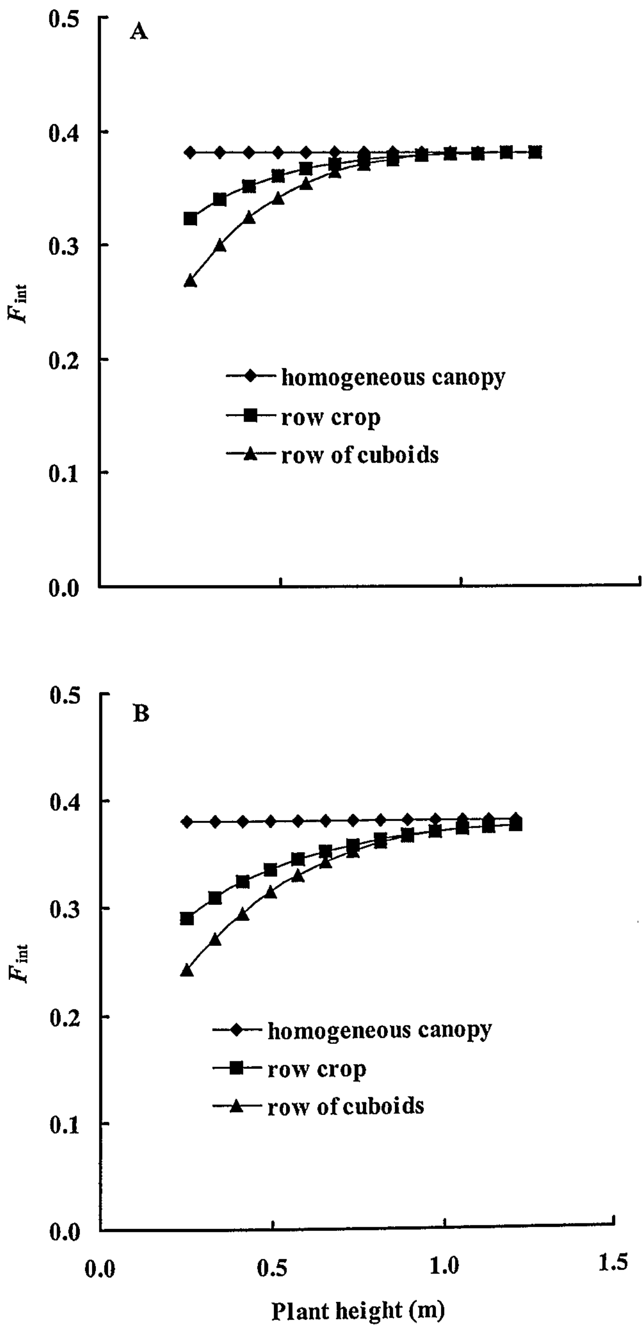

Figure 8. Effect of plant height on the calculated fraction radiation intercepted (F_{int}) at $LAI = 1$ and plant row distances of 0.5 (A) and 0.75 m (B) for different plant arrangements.

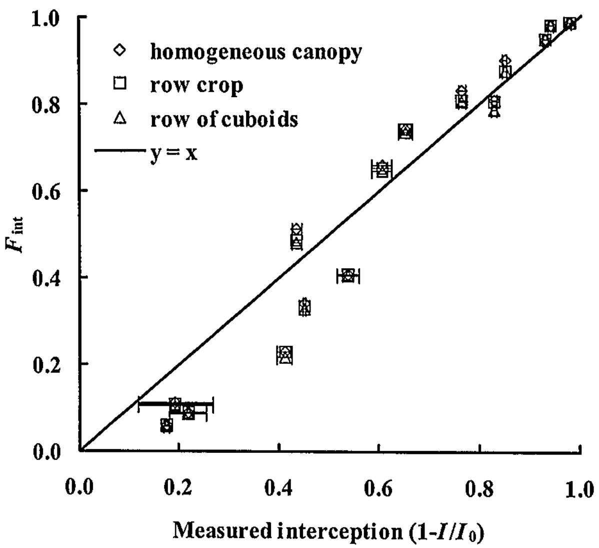

Figure 9. Calculated F_{int} in comparison with measured fraction of intercepted radiation for different plant arrangements. Error bars indicate standard error of means.

plants (larger bare inter- and intra-row areas), and leaf area increased (Figures 6 and 7). So in comparison with $F_{int,row\text{-}crop}$ and $F_{int,cub}$, F_{int} was mostly overestimated at low plant densities with a high LAI (Table 3).

The fraction radiation intercepted was also related to plant height. At the standard row distance of 0.5 m, an intra-row distance of 0.4 m and a leaf area index of 1, the fraction radiation intercepted was smaller for the row-of-cuboids system than for a homogeneous canopy (Figure 8A). The fraction radiation intercepted that was calculated with the simple exponential formula for radiation extinction (Equation 1) was 0.38. When $F_{int,row\text{-}crop}$ was used, the fraction radiation intercepted at low plant heights was much lower due to the row effect. It was even lower when $F_{int,cub}$ was used. The effect of plant height increased at larger distances between plant rows (cf. Figure 8A and B). However, in practice the differences between measured interception and F_{int}, $F_{int,row\text{-}crop}$ or $F_{int,cub}$ were small (Figure 9). The differences between the measured and the calculated fraction of radiation intercepted at low LAI did not improve with either of the methods used (Figure 9). F_{int} was already smaller than the measured fraction of radiation intercepted. $F_{int,row\text{-}crop}$ and $F_{int,cub}$ were even smaller and therefore the discrepancy between the measured and the calculated radiation intercepted was larger. The relative difference between F_{int} and $F_{int,row\text{-}crop}$ or $F_{int,cub}$ varied between 0 and 6.6%, depending on plant arrangement (Table 3).

Discussion and conclusions

The very low *LAI* values at some plant arrangements are realistic for one-year old transplants in spring. Leaf area index increases throughout the first growing season and values close to 1 are reached by the end of the summer (Pronk *et al.*, 2003). *LAI* values between 1 and 6 have been observed in the field in the second growing season and the plant arrangements investigated represent the range of leaf area indices generally found in cropping systems in practice.

Interception recordings for estimating *k* should be corrected for the interception by the stems because *k* is based on leaf area only. However, for the small plants in our investigation such a correction was not considered necessary because the average data on leaf-intercepted radiation varied by 12%, whereas the contribution of the stem area (4%) to the radiation-intercepting area at a *LAI* =1 was smaller than this variation. At plant arrangements 1 and 3 the fraction of radiation intercepted by the bare stems of the large plants was 3.3 and 8.1%, respectively, of the radiation intercepted by the plant canopy. Also these percentages were within the variations of the measurements and no correction was made either.

A *k*-value of 0.48 for *Thuja occidentalis* 'Brabant' is considerably lower than the theoretical k_{bl} value of black leaves with a spherical leaf angle distribution (Goudriaan & Van Laar, 1994). The resulting clustering factor was 1.5, which is smaller than the ones found for other coniferous crops: 1.72 for Scots pine (Stenberg, 1994) and 1.61 for Douglas fir (Smith *et al.* 1993). However, the large *k*-values (> 1) found at low *LAI*

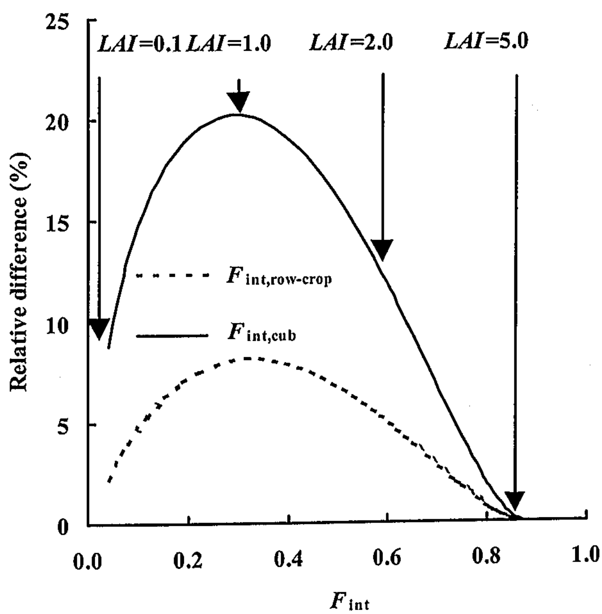

Figure 10. Relative difference between F_{int} and $F_{int,row\text{-}crop}$ or $F_{int,cub}$ for plants of different size (*LAI* = 0.1–5; plant height = 0.25–1.10 m; W1 and W2 = 0.13–0.5 m).

are an indication of a large radiation interception with grazing incidence from the sky zone just above the horizon. If *LAI* increases, this fraction of radiation is already intercepted and so k becomes smaller with increasing *LAI*. To account for this effect in a practical way, the measured *LAI* was increased by a factor of 0.5 (SE = 0.09) for the whole range of interception assessments. The factor 0.5 was found by means of the FITNONLINEAR procedure of the statistical programme GENSTAT 6, release 1, fitting $I/I_0 = e^{-k*(LAI + a)}$. Using this equation with a = 0.5, a better fit between k and the interception measurements was found (R^2 = 0. 95 against R^2 = 0.89 earlier) whereas k was now smaller: 0.37 ± 0.02 (Figure 5B).

Although the differences between $F_{int,row\text{-}crop}$ and $F_{int,cub}$ in relation to F_{int} are small for the plant arrangements investigated (Table 3), calculations with increasing plant height (0.2–1.10 m), row width and intra-row width (0.1 –0.5 m) and *LAI* (0–5) show that $F_{int,row\text{-}crop}$ and $F_{int,cub}$ are overestimated by up to 8 and 20%, respectively (Figure 10).

The row crop approach has been investigated for other row cropping systems (Palmer, 1989; Wagenmakers, 1995; Heuvelink, 1996). In these studies additional adjustments for rows of cuboids did not seem necessary because intra-row plant distances were usually small (no bare intra-row area) and *LAI* increased rapidly. For field-grown nursery stock, however, the bare area between plants is considerable (Petersen & Hill, 1985), indicating relatively large path widths and large bare intra-row areas. An overestimate of the fraction radiation intercepted by 20% on a daily basis leads to a substantial surplus of total radiation intercepted during the growing season and subsequently to an overestimate of dry matter production. After one growing season the total amount of overestimated dry matter may almost double due to a positive feedback of increasing dry matter production on *LAI*. The fraction radiation intercepted by the canopy of field-grown conifers is therefore best estimated by the method that describes the canopy as rows of cuboids.

References

Anonymous, 1991. LAI-2000 Plant Canopy Analyzer: Instruction Manual. LI–COR Inc., Lincoln, Nebraska, 76 pp.

Bartelink, H.H., 1996. Simulation of Radiation Interception and Transmission in Forest Stands. Model Documentation and Examples. Hinkeloord Reports No 19, Department of Forestry, Wageningen Agricultural University, Wageningen, 38 pp.

De Wit, C.T., 1965. Photosynthesis of Leaf Canopies. Agricultural Research Report No 663. Pudoc, Wageningen, 57 pp.

Gijzen, H. & J. Goudriaan, 1989. A flexible and explanatory model of light distribution and photosynthesis in row crops. *Agricultural and Forest Meteorology* 48: 1–20.

Goudriaan, J., 1977. Crop Micrometeorology: a Simulation Study. Simulation Monographs, Pudoc, Wageningen, 249 pp.

Goudriaan, J., 1988. The bare bones of leaf-angle distribution in radiation models for canopy photosynthesis and energy exchange. *Agricultural and Forest Meteorology* 43: 155–169.

Goudriaan, J. & H.H. Van Laar, 1994. Modelling Potential Crop Growth Processes. Textbook with Exer-

cises. Kluwer Academic Publishers, Dordrecht, 238 pp.
Heuvelink, E., 1996. Tomato growth and yield: quantitative analysis and synthesis. PhD thesis Wageningen Agricultural University, Wageningen, 326 pp.
Miller, J.B., 1967. A formula for average foliage density. *Australian Journal of Botany* 15: 141–144.
Monsi, M. & T. Saeki, 1953. Über den Lichtfaktor in den Planzengesellschaften und seine Bedeutung für die Stoffproduction. *Japanese Journal of Botany* 14: 22–52.
Nackaerts, K., P. Coppin, B. Muys & M. Hermy, 2000. Sampling methodology for LAI measurements with LAI-2000 in small forest stands. *Agricultural and Forest Meteorology* 101: 247–250.
Norman, J.M. & J.M. Welles, 1983. Radiation transfer in an array of canopies. *Agronomy Journal* 75: 481–488.
Palmer, J.W., 1989. The effect of row orientation, tree height, time of year and latitude on light interception and distribution in model apple hedgerow canopies. *Journal of Horticultural Science* 64: 137–145.
Petersen, M.P. & R.W. Hill, 1985. Evapotranspiration of small conifers. *Journal of Irrigation and Drainage Engineering* 4: 341–351.
Pronk, A.A., E. Heuvelink & H. Challa, 2003. Dry matter production and leaf area development of field grown ornamental conifers: measurements and simulation. *Journal of Agricultural Systems* 78: 337–353.
Ross, J. & T.A. Nilson, 1966. A mathematical model of the radiance regime of vegetation. In: V.K. Pyldmaa (Ed.), Actinometry and Atmospheric Optics, pp. 253–270. (Translated by Israel Program of Scientific Translations, Jerusalem, 1971)
Smith, N.J., J.M. Chen & T.A. Black, 1993. Effects of clumping on estimates of stand leaf area index using the LI-COR LAI-2000. *Canadian Journal of Forest Research* 23: 1940–1943.
Stenberg, P., S. Linder, H. Smolander & J. Flower-Ellis, 1994. Performance of the LAI-2000 plant canopy analyzer in estimating leaf area index of some Scots pine stands. *Tree Physiology* 14: 981–995.
Wagenmakers, P., 1995. Light relations in orchard systems. PhD thesis Wageningen Agricultural University, Wageningen, 151 pp.