A CALCULATION MODEL AND DESCRIPTIVE FORMULAS FOR THE EXTINCTION AND REFLECTION OF RADIATION IN LEAF CANOPIES

by

J. Goudriaan
Research Associate, Agricultural University,
Department for Theoretical Production Ecology,
De Dreijen 3, Wageningen, The Netherlands

Abstract

The model describes the interception and reflection of radiation by the components of the canopy. The angular distribution of the incoming and reflected radiation is taken into account. Repeated scattering is executed in wavebands where the leaves have a high scattering coefficient. It appears that in most cases the radiation profile may be approximated by an exponential extinction with leaf area index. Some formulas are given for a rapid calculation for the thus found extinction coefficients and for the reflection coefficients. Generally these formulas are sufficiently accurate, compared with the results of the model.

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1. Introduction

One of the major factors governing photosynthesis and transpiration of crops is the absorbed solar energy. In any realistic simulation model for plant growth it is calculated how much of the incoming radiation in the different wavebands is reflected by the canopy, and how the remaining part is distributed. In this paper a brief description will be given of the used model, which will be represented more extensively elsewhere 1). Because of the complexity and size of such a model it is desirable to summarize the results in relatively simple formulas for the purpose of application in a master model for crop growth.

2. Assumptions

The following assumptions are made in the calculation model. Leaves in subsequent layers do not have correlated positions. This is almost right for maize [2]. Within a layer of leaves there is no mutual shading. No property varies in a horizontal direction. The leaves do not have azimuthal preference. This is almost right for maize [10], moreover symmetrical deviations from this assumption do not have a serious effect 8. The individual leaves act as Lambertian radiators whenever they scatter radiation.

The following additional assumptions are necessary for the validity of the descriptive formulas. Leaf angle distribution and leaf scattering coefficient do not vary with height. Leaf transmission and reflection coefficient are equal.

3. Structure of canopy and radiation

The radiative flow field at each level of the leaf layers is characterized by nine contributions to the upward flux, and nine contributions to the downward flux. Each of these contributions refers to a ten degree class of inclination. As the leaves do not have azimuthal preference, the contribution of the entire azimuthal range is contained in an inclination class. The leaf angle distribution is also characterized by nine classes of inclination, as it is done in De Wit's model [13]. The projection of the leaves in each of these classes into each of the nine directions is calculated, employing Anderson's formulas [1]. A weighted addition according to the leaf angle distribution gives the average projection of the leaves into each of the nine directions.

1) Proceedings of The Royal Netherlands Academy of Sciences, Series B, North-Holland Publishing Company, Amsterdam.

The main improvements with respect to De Wit's model [13] are:

a. Scattered radiation is not necessarily isotropic. A scattering layer as a whole is not a Lambertian radiator, in spite of the Lambertian components. The effectiveness of radiation into a certain direction is the same as the effectiveness of intercepting radiation from that direction. This depends on the leaf angle distribution. As a consequence, reflected radiation is not isotropic either. For the radiation reflected from the soil surface, however, isotropic reflection was assumed.

b. Repeated scattering is possible, as many times as necessary, to obtain a self consistent flow field of radiation. The solution of the 18 equations at each level is done by calculating first from top to bottom, beginning with the incoming radiation. The upward components are still zero. Scattered radiation coming from downward radiation is directly added. Arriving at the bottom, the reflection from the soil is calculated and going from bottom to top, the upward components are calculated, while adding contributions of scattering coming from both upward and downward radiation. If necessary the procedure is repeated, until a self consistent flow field is obtained. The number of necessary iterations ranges from 1 for a scattering coefficient of 0.1 to 20 for a scattering coefficient of 1.

4. Results

The model yields reflection coefficients of the canopy, some being given in table 1 for various conditions. The model yields also profiles of downward, upward and net radiation. Net radiation means here downward minus upward radiation, both within a considered waveband for which the scattering coefficient is constant. Like in figure 1, these profiles are in general not fully exponential. This means that the extinction coefficient K with respect to the leaf area index LAI in the expression

$$I = I_o \, e^{-K.LAI} \qquad (1)$$

varies with depth. This variation is often so small that it is justified to use a constant extinction coefficient. Some of these values for the net radiation are given in table 2 for various conditions.

A detailed analysis of the model-generated data shows that these may be summarized in some simple descriptive rules and formulas, which are valid in most situations and do not require extensive computations. These will be discussed in the next sections.

5. Reciprocity

An interesting result of the model from a theoretical point of view is the property of reciprocity of reflection. It appears that the brightness of a reflection surface in direction β, when light is incident from direction ϕ, is the same as in direction ϕ, when light is incident from direction β, provided the flux through a horizontal surface is the same. This property is unaffected by the leaf inclination distribution, or scattering coefficient. It is also unaffected by variation of these properties with height.

It can be derived that as a consequence of the reciprocity π times the brightness Ω of a reflecting surface under diffuse illumination (uniform overcast distribution) has the same dependency on the angle of view, as the reflection coefficient on the angle of incidence, when illuminated by direct light. In the figures 3, 4 and 5 this property is used. For the reason given above $\pi x \Omega$ is set along the vertical axis.

6. Descriptive formulas

It would be convenient if some relatively simple formulas could be found to describe the dependency of outputs as profiles and reflection on inputs as scattering coefficient, inclination distribution of the incoming radiation, and leaf angle distribution.

a. Horizontal leaves

It can be derived that extinction is always exponential, with an extinction coefficient

$$K = (1-Sc)^{0.5} \qquad (2)$$

valid when the leaves are sufficiently small.
The scattering coefficient Sc is the sum of reflection and transmission coefficient, whereby in this case they are assumed to be equal. For the same situation it can be derived that the reflection coefficient of a canopy with a sufficiently large LAI is:

$$Refl = (1-(1-Sc)^{0.5})/(1+(1-Sc)^{0.5}) \qquad (3)$$

b. Other leaf angle distributions

Although extinction is generally not exponential, it makes sense to define the extinction coefficient as the coefficient of the closest fitting exponential curve, provided the maximum deviation never exceeds a pre-set error. It was attempted to approximate these values by the following formulas. For incoming direct radiation the formulas are:

$$Kf(I) = (1-Sc)^{0.5}\ Kbl(I) \qquad (4)$$

where Kbl(I) is the extinction coefficient for radiation incident on black leaves, and I is the number of the inclination class of the incoming radiation. Kbl is calculated from the average projection of the leaves in the various directions, whereby a correction is added for the leaf area index per layer, called S by De Wit [13] . Kf(I) is assumed to be valid for a profile of net radiation, only within the considered waveband.
The value for diffuse radiation Kdf in that waveband is then calculated by

$$e^{-Kdf.LAI} = \sum_{I=1}^{9} B(I).\ e^{-Kf(I).LAI} \qquad (5)$$

where B(I) is the relative contribution of class I to the incoming diffuse radiation. According to this formula Kdf depends on LAI.

The model-generated values of K, Km, were plotted against those calculated by the above formulas in figure 2. The regression equation is

$$Km = 0.03533 + 0.94623.Kf \qquad (6)$$

To evaluate the confidence of this equation, it is rewritten as

$$Km = 0.75413 + 0.94623.(Kf - 0.75965) \qquad (7)$$

in which the origin is shifted to the centre of gravity of the 200 considered points. The standard deviation of the mean of Km is 0.0077, and the one of the slope is 0.0081. This means that there is 95 % probability that the value found by the model is within 2 % of Kf for Kf $>$ 0.75. For Kf less than 0.75 range increases to 10 % for Kf as small as 0.1.

A similar procedure is followed for the reflection coefficient. The following formulas are used for approximation for direct light.

$$Rf(I) = 1.- e^{-RR} \qquad (8)$$

$$RR = 2.Refl.(1.+S.Kdf/(1.+Kdf)).Kbl(I)/(1.+Kbl(I)) \qquad (9)$$

Refl is calculated by 3 . There is a small influence of S, raising the reflection when the canopy density becomes larger. Kdf is found by 5 , taking the value 1 for LAI. Correlation of Rf with values found by the model gives the following regression equation:

$$Rm = 0.20570 + 1.1170 .(Rf - 0.19414) \qquad (10)$$

Here the mean of Rm has a standard deviation of 0.0022 and the slope one of 0.0097. The 95 % confidence limit of Rm is within 2 % of the value found by the formula Rf.

Reflection coefficients for diffuse light are found by weighted addition over the nine inclination classes of the incoming radiation.

7. Discussion

The discussed model is so intricate that a simple theory is not sufficient to cover each detail. Deviations from the presumed relatively simple formulas may be interpreted as stochastic, because the sources of the deviations cannot be caught within the framework of those formulas. This sort of relationship also exists between any scientific theory and reality. Therefore running the model and comparing the results to a simple theory may be called experimentation with the model. There are different levels of understanding, the discussed model being closer to reality than the descriptive formulas. The scatter of the results of the model round those of the formulas, however, is mostly so small compared to the scatter of the values in reality, irrespective whether this is due to incomplete understanding or to inadequate measurements, that one may safely replace the model by the formulas. Only under conditions as indicated by a dash in table 2, this is not allowed.

It is not attempted to give a thorough validation of the relation between the described model and reality. Data from literature, however, support the results of the model. Brown [3] found an extinction coefficient of 0.53 for net radiation (total) in maize. Separate employment of the model for the different wavebands, assuming a clear sky and the sun at 45 degrees, gives after addition of the profiles an extinction coefficient of 0.48 for a spherical leaf angle distribution. Qualitatively and quantitatively the increase of the reflection and extinction coefficient with decreasing height of the sun agrees well with measurements described in literature [2] , [6] , [7] , [9] .

Rodskjer [11] found a linear relationship between the logarithm of the relative transmission in the canopy of near infrared and that of visible radiation. The slope between them can be interpreted as the ratio of the extinction coefficients. According to 4 its value is $((1-Scn)/(1-Scv))^{0.5}$, where Scn is the scattering coefficient for near infrared radiation and Scv for visible radiation. This ratio is independent on canopy structure and height of the sun, at least within the range of the scatter as shown in fig. 2. Realistic values as Scn=0.82 and Scv=0.25 yield the ratio 0.48, which Rodskjer measured.

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Table 1. Reflection coefficients of leaf canopies under some conditions

Sc	5	15	25	35	45	55	65	75	85	diffuse
					direct radiation					
					horizontal leaves (5 degrees)					
0.3	.0928	.0928	.0928	.0928	.0928	.0928	.0928	.0928	.0928	.0928
0.8	.387	.387	.387	.387	.387	.387	.387	.387	.387	.387
					leaves under 45 degrees					
0.3	.146	.110	.0905	.0790	.0736	.0736	.0736	.0736	.0736	.0794
0.8	.517	.438	.386	.350	.332	.332	.332	.332	.332	.350
					vertical leaves (85 degrees)					
0.3	.151	.111	.0897	.0745	.0617	.0499	.0381	.0255	.0138	.0590
0.8	.526	.443	.388	.342	.297	.251	.199	.138	.0764	.275
					spherical or isotropic leaf angle distribution					
0.3	.148	.111	.0922	.0801	.0720	.0664	.0626	.0603	.0591	.0781
0.8	.522	.445	.396	.360	.334	.315	.302	.294	.290	.350

Table 2. Best fitting extinction coefficient K for net radiation. The maximum deviation is less than 3 %, for the numbers with an asterix it is less than 5 %, a dash indicates larger deviations.

Sc	5	15	25	35	45	55	65	75	85	diffuse
					horizontal leaves (5 degrees)					
0.	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
0.3	.872	.872	.872	.872	.872	.872	.872	.872	.872	.872
0.8	.44	.44	.44	.44	.44	.44	.44	.44	.44	.44
					leaves under 45 degrees					
0.	7.29	1.91	1.13	.843	.734	.734	.734	.734	.734	.829
0.3	-	1.47	.939	.722	.638	.638	.638	.638	.638	.708
0.8	-	-	.458*	.385	.351	.351	.351	.351	.351	.376*
					vertical leaves (85 degrees)					
0.	12.9	2.70	1.46	.951	.658	.458	.306	.181	.0876	-
0.3	-	2.05	1.20	.820	.586	.417	.282	.169	.083	-
0.8	-	-	-	.435*	.340	.256	.179	.109	.054	.261*
					spherical leaf angle distribution					
0.	8.55	2.15	1.26	.911	.733	.629	.568		.515	.81*
0.3	-	1.64	1.03	.774	.636	.556	.504		.461	.684
0.8	-	-	.48*	.422	.37	.34	.32		.30	.38

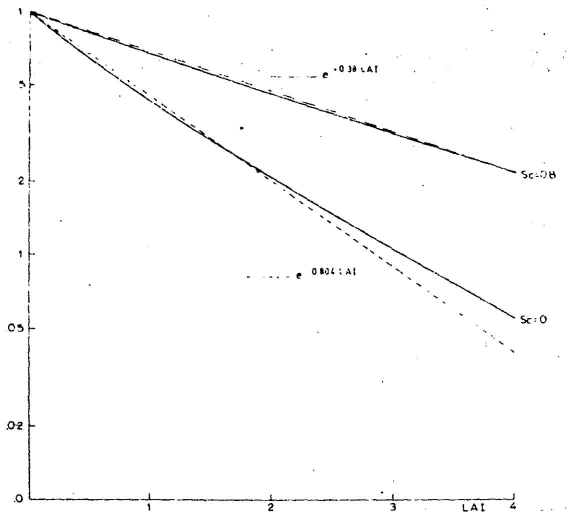

Fig. 1. Profiles of net radiation for two scattering coefficients in a canopy with a spherical leaf angle distribution under a diffuse illumination.

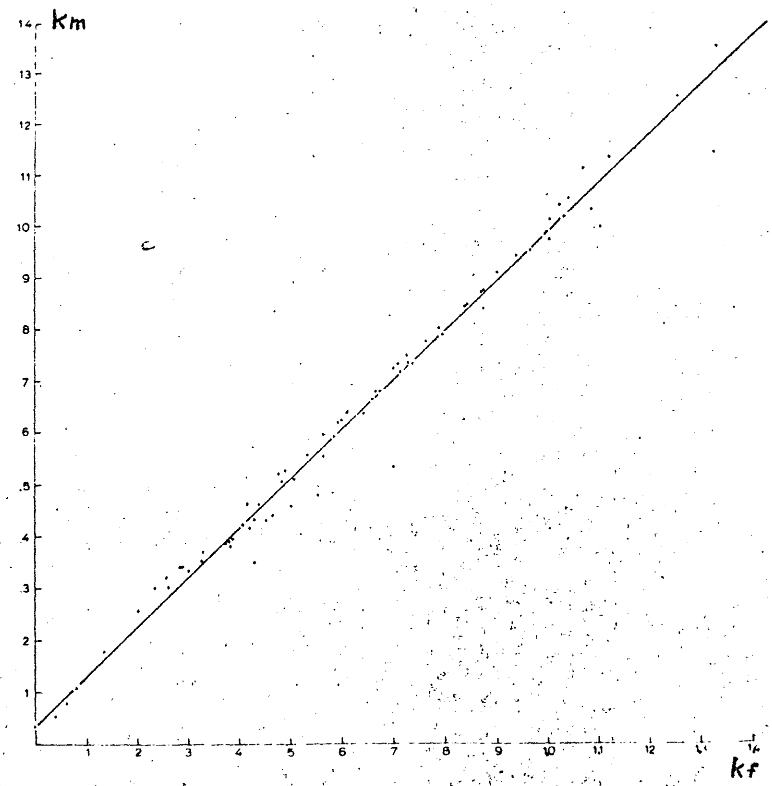

Fig. 2. Extinction coefficients found by the model aginst those found by the descriptive formulas for various circumstances. The solid line is the regression line.

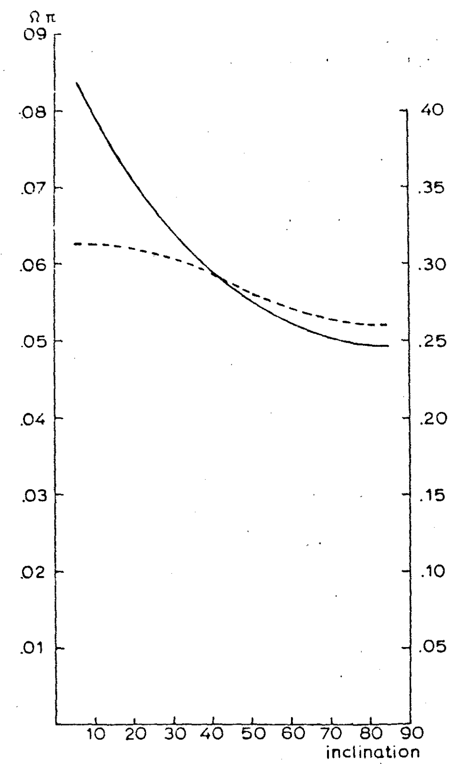

fig. 3

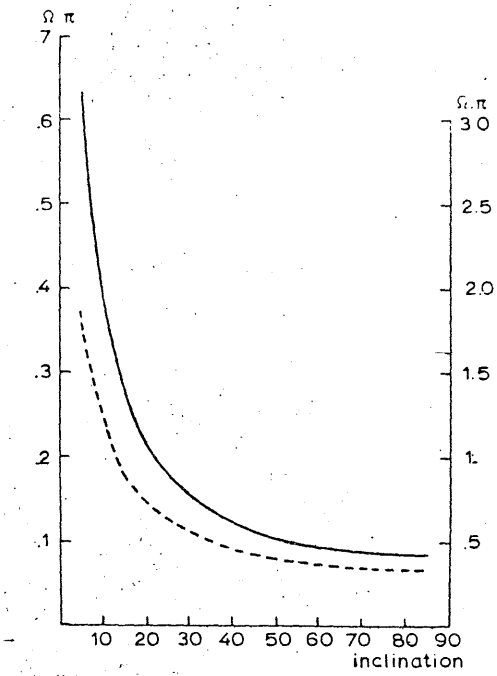

fig.4

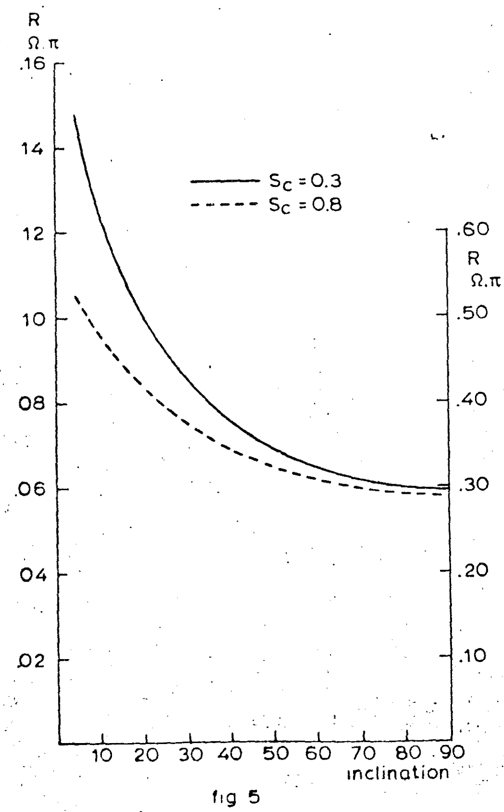

fig 5

Fig. 3, 4 and 5

In the figures 3, 4 and 5 the relations are given between brightness Ω and the angle of view for a scattering coefficient 0.3 (solid line), and one of 0.8 (dashed line). Figure 3 is valid for direct light incident under an inclination of 85 degrees, figure 4 for 5 degrees, and fig. 5 for diffuse incident light. Because of reciprocity the figures 3 and 4 also represent the brightness under an angle of 85 and 5 degrees respectively as dependent on the angle of incidence. Figure 5 also gives the reflection coefficient R for direct light as dependent on the angle of incidence. The scale for the solid line (Sc=0.3) is given on the left hand axis, and for the dashed line (Sc=0.8) is given on the right hand axis.