2 Radiation in plant canopies

2.1 Introduction

In simulation models of plant growth, the absorption of radiation by the leaves of a canopy is a major factor governing photosynthesis and transpiration. During the last few years there have been several publications on this subject. Lemeur & Blad (1974) gave an excellent review of these light models, so that it suffices here to give a short survey of the work done.
In 1953 Monsi & Saeki introduced the idea of the exponential extinction of radiation in a canopy. In 1959, de Wit first used an analytical method to calculate the light distribution, but applied later in 1965 an entirely numerical method. Some extensions to this work were presented by Anderson (1966), Cowan (1968), Lemeur (1971) and Ross & Nilson (1966). They used primarily analytical methods, but sometimes computer programs as well. Cowan's analytical method is only applicable to a canopy with horizontal leaves. Ross & Nilson used a more general, but also a more complicated and laborious method.
An attempt was made to design models, sufficiently general to be realistic, and to formulate their results in terms sufficiently simple to be applicable without excessive effort.
First the basic elements of the model are presented (Section 2.2). Subsequently an analytical study is made for canopies with horizontal leaves (Section 2.3.1). In Section 2.3.2 the more general case of non-horizontal leaf angle distributions is studied by an extension of de Wit's numerical method to multiple scattering. The results of this numerical model are summarized in Section 2.3.3, mainly by generalizing the earlier results for horizontal leaves. In Section 2.3.4, the results obtained so far are evaluated by checking with experimental data, largely from literature. The model presented is also used for the treatment of thermal radiation. In Section 2.4 some model extensions are given. The first one concerns the case of individual elements with a very high scattering coefficient. In the next extension the constraint is

removed that the leaf reflection should equal the leaf transmission coefficient. Subsequently leaf positionings other than random are considered. The radiation field in plant stands, cultivated in rows, deserves special attention and is treated in Section 2.4.4.

2.2 Basic elements

2.2.1 Geometry

The canopy is supposed to be homogeneous in a horizontal plane so that there is no horizontal clustering of leaves. The leaf area density is height dependent with the dimension m^2 leaf per m^3 air. The number of leaves expected in a layer is equal to the leaf area density multiplied by the air volume of this layer and divided by the area per leaf. In maize the actual number of leaves in a volume element can be described by a Poisson distribution (Sinclair & Lemon, 1974), but in this model only the expection values of leaf area and radiant fluxes are considered. This is allowed if the horizontal extension of the layers is sufficiently large. Thus there is no correlation between the positions of leaves in subsequent layers and the horizontal layers are considered continuous. Each layer has a leaf area L_s per unit of ground area. L_s is made so small that mutual shading within such a layer can be neglected. For this purpose a value for L_s of 0.1 is sufficiently small. The total number of layers equals leaf area index *LAI* divided by L_s.
The leaves may have different inclinations, given by the leaf angle distribution, which may be a function of height and consists of nine classes of ten degrees each. Absence of azimuthal preference is assumed. The average projection of leaves with inclination λ in a direction with inclination β can then be calculated.
The sine of the angle of incidence θ on a leaf was given by de Wit (1965).

$$\sin\theta = \sin\beta \cos\lambda + \cos\beta \sin\lambda \sin\alpha \qquad (2.1)$$

where α is the difference in azimuth between the leaf's normal and the incident ray.
The mean projection of the leaves can be found by averaging over α:

$$O(\beta,\lambda) = \frac{\int_0^{\pi/2} \sin\theta \, d\alpha}{\int_0^{\pi/2} d\alpha} \tag{2.2}$$

As the interception of the rays by the under and the upper side of a leaf has the same effect, the absolute value of $\sin\theta$ must be taken in the integration. Thus

$$O(\beta,\lambda) = \sin\beta \cos\lambda \qquad \lambda \leqslant \beta \tag{2.3a}$$

$$O(\beta,\lambda) = \frac{2}{\pi}\left\{\sin\beta \cos\lambda \arcsin\left(\frac{\mathrm{tg}\beta}{\mathrm{tg}\lambda}\right) + (\sin^2\lambda - \sin^2\beta)^{0.5}\right\} \qquad \lambda > \beta \tag{2.3b}$$

The average projection of all the leaves together is given by

$$\bar{O}(\beta) = \sum_{\lambda=1}^{9} F(\lambda)\, O(\beta,\lambda) \tag{2.4}$$

where $F(\lambda)$ describes the leaf inclination distribution, so that

$$\sum_{\lambda=1}^{9} F(\lambda) = 1.$$

Some special leaf angle distributions are

- horizontal
  Here $O(\beta,\lambda)$ is given by $O(\beta,\lambda) = \sin\beta$ (2.5)
- vertical
  Here $O(\beta,\lambda)$ is given by $O(\beta,\lambda) = 2/\pi \cos\beta$ (2.6)
- spherical or isotropic

The distribution function of the leaf inclinations is the same as for the surface elements of a sphere. Then $F(1 - 9)$ is given by
$F(1 - 9) = 0.015;0.045;0.074;0.099;0.124;0.143;0.158;0.168;0.174$
calculated from cos 0 – cos 10, cos 10 – cos 20, etc.
The word isotropic is also used because the projection $\bar{O}(\beta)$ is the same in all directions and equal to 0.5. This value is the ratio between the area of the base of a hemisphere and that of the hemisphere itself.

Section 2.3.4 gives an important simplification for the calculation of $\bar{O}(\beta)$, which was developed by Ross (1975).
The radiation at each level in the canopy is divided in upward and downward radiant fluxes. Both are subdivided into 9 classes of 10 degrees each, thus covering the upper and the lower hemisphere. An azimuthal classification of the radiation is not needed because the leaves have no azimuthal preference. The direct solar flux is treated separately. Its extinction can be calculated with the same equations as used for extinction of radiation in a canopy with black leaves.

2.2.2 Incoming radiation

The incoming radiation may be divided into four spectral regions. For each of these regions the geometric composition should be known which has to be classified only in terms of an inclination distribution, as the leaves do not have an azimuthal preference. Still, with four main spectral regions and nine inclination classes, there are 36 classes of incoming radiation. Fortunately a great simplification is possible.

Spectral regions
The first division of the incoming radiation concerns the distinction between thermal radiation (wavelength larger than 3000 nm) and short-wave radiation (wavelength less than 3000 nm). Compared with the thermal radiation of the sky and that of other spectral regions in the solar radiation the direct solar contribution to the thermal radiation can be neglected. In principle the treatment of the thermal or long-wave radiation is more complex than that of the short-wave radiation, because the leaves themselves radiate in the thermal region. Therefore the modelling of thermal radiation is given after that of the short-wave radiation (Section 2.3.6). There is no practicable correlation between the net thermal radiant flux and the incoming solar radiation, so that they must be measured separately. The thermal radiant flux can best be characterized by an apparent sky temperature. The solar or global radiation can be roughly divided in to three regions: the ultraviolet, the visible and the near-infrared region. At sea level the ultraviolet region (wavelength less than 400 nm) contains only about 3 percent of the total solar radiant energy so that it is neglected further. Thus the spectral composition of the solar radiation is characterized by the ratio of the incoming visible and near-

infrared radiation. Under a clear sky each of them contains about half of the incoming flux, and under an overcast sky the ratio shifts to about 0.6 : 0.4 in favour of the visible region.
More detailed figures can be found in Smithsonian Meteorological Tables (List, 1949) and in Šul'gin (1973).

Geometric distribution
The measured incoming radiation must be distributed over direct and diffuse radiation. The direct radiation has a known inclination, that of the sun. For the distribution of the diffuse light over the nine inclination classes there are two alternative assumptions. According to the first assumption the sky has a uniform radiance, resulting in an isotropic downward radiation. When the radiance is N, the contribution to the irradiance of a horizontal surface from a infinitesimal solid angle $\mathrm{d}\omega$, at inclination β and azimuth α amounts to

$$\mathrm{d}S = N \sin\beta \, \mathrm{d}\omega \qquad (2.7)$$

The solid angle $\mathrm{d}\omega$ is given by

$$\mathrm{d}\omega = \cos\beta \, \mathrm{d}\beta \, \mathrm{d}\alpha \qquad (2.8)$$

so that $\mathrm{d}S$ can also be written as

$$\mathrm{d}S = N \sin\beta \cos\beta \, \mathrm{d}\beta \, \mathrm{d}\alpha \qquad (2.9)$$

Integration of the azimuth α from 0 to 2π results in the contribution from an infinitesimal zone $\mathrm{d}\beta$ at inclination β given by

$$\mathrm{d}S = 2\pi N \sin\beta \cos\beta \, \mathrm{d}\beta \qquad (2.10)$$

Integration of β from zero to $\pi/2$ gives $S = \pi N$ for a constant N. When the diffuse downward flux is denoted by S_d, $\mathrm{d}S$ equals:

$$\mathrm{d}S = 2S_d \sin\beta \cos\beta \, \mathrm{d}\beta \qquad (2.11)$$

Integration of $\mathrm{d}S/S$ between the zone boundaries at ten-degree intervals gives a distribution table, denoted by B_u:

$$B_u(1-9) = 0.030; 0.087; 0.133; 0.163; 0.174; 0.163; 0.133; 0.087; 0.030.$$

This is the uniform overcast sky distribution (UOC). It will be used for the diffuse radiation from an overcast sky, a clear sky and for radiation reflected by the soil surface.

Some investigations will be made with the other assumption, the standard overcast sky (SOC). According to an empirical relation, proposed by Moon & Spenser (1942) and later verified by Grace (1971), the radiance of the standard overcast sky is given by

$$N = N_z (1 + 2\sin\beta)/3 \tag{2.12}$$

In this formula the radiance rises gradually by a factor 3 from the radiance at the horizon to the radiance in the zenith N_z. In Section 2.4.1 this empirical relation will be given a theoretical foundation. Integration of Eqn (2.12) gives

$$S_d = 7\pi N_z/9 \tag{2.13}$$

so that

$$dS = \frac{6}{7} S_d (1 + 2\sin\beta) \sin\beta \cos\beta \, d\beta \tag{2.14}$$

Integration of dS/S between the zone boundaries at ten-degree intervals gives the distribution table for the SOC, denoted by B_s

$$B_s(1 - 9) = 0.015;0.057;0.106;0.150;0.180;0.184;0.160;0.110;0.038$$

The numerical investigations, presented in Section 2.3.2, Table 5 and 6, show that the light extinction and reflection hardly differ under a uniform and a standard overcast sky. Therefore the calculations are done with the simpler UOC distribution, unless stated otherwise.

Table 1. The proportion of diffuse radiation for a very clear sky and some solar heights, for the visible region.

Inclination of the sun	Diffuse/total
5	1.00
15	0.32
25	0.22
35	0.18
45	0.16
90	0.13

Fig. 1 *Scheme of the classification of the incoming radiation in diffuse and direct radiation and in the four main spectral regions.*

	short-wave radiation			long-wave or thermal radiation
	ultraviolet	visible	near-infrared	
total	negligible	clear: 580 $\sin\beta$ overcast: 116 $\sin\beta$	clear (S_c): same as visible overcast: 70% of the visible	see diffuse
diffuse	negligible	clear ($S_{d,c}$): proportion diffuse/total, see Table 1 overcast ($S_{d,o}$): 116 $\sin\beta$	clear: same as visible overcast: 70% of the visible	both clear and overcast, from apparent radiant sky temperature (Section 2.3.6)
direct	negligible	clear (S_b): proportion direct/total is complement of Table 1 overcast: none	clear: same as visible overcast: none	clear: negligible overcast: none

The proportion of diffuse radiation for a very clear sky is given in Table 1, according to de Wit (1965), for some solar inclinations. For intermediate inclinations a linear interpolation is used. The total visible radiant flux under a very clear sky is given by 580 sinβ in J m^{-2} s^{-1}, and one fifth of this value (116 sinβ) under an overcast sky. In the near-infrared region, the radiant flux is taken equal to the visible flux for a clear sky and to 0.7 of the visible flux for an overcast sky. The classification given in this section is summarized in Fig. 1.

2.2.3 Optical properties

The distinction between visible and near-infrared radiation is justified by the shape of the spectral dependence of leaf reflectance and transmittance (Fig. 2). At about 700 nm there is a sharp increase of both. Moreover the reflection and transmission coefficients are almost equal to each other in both regions. In the visible region an average value of 0.1 can be used and of 0.4 in the near-infrared region. These figures hold for many plant species (Brandt & Tageeva, 1967; Gates et al., 1965; Woolley, 1971). Sometimes reflection contains a specular component, but this effect will be neglected in this study. It is assumed

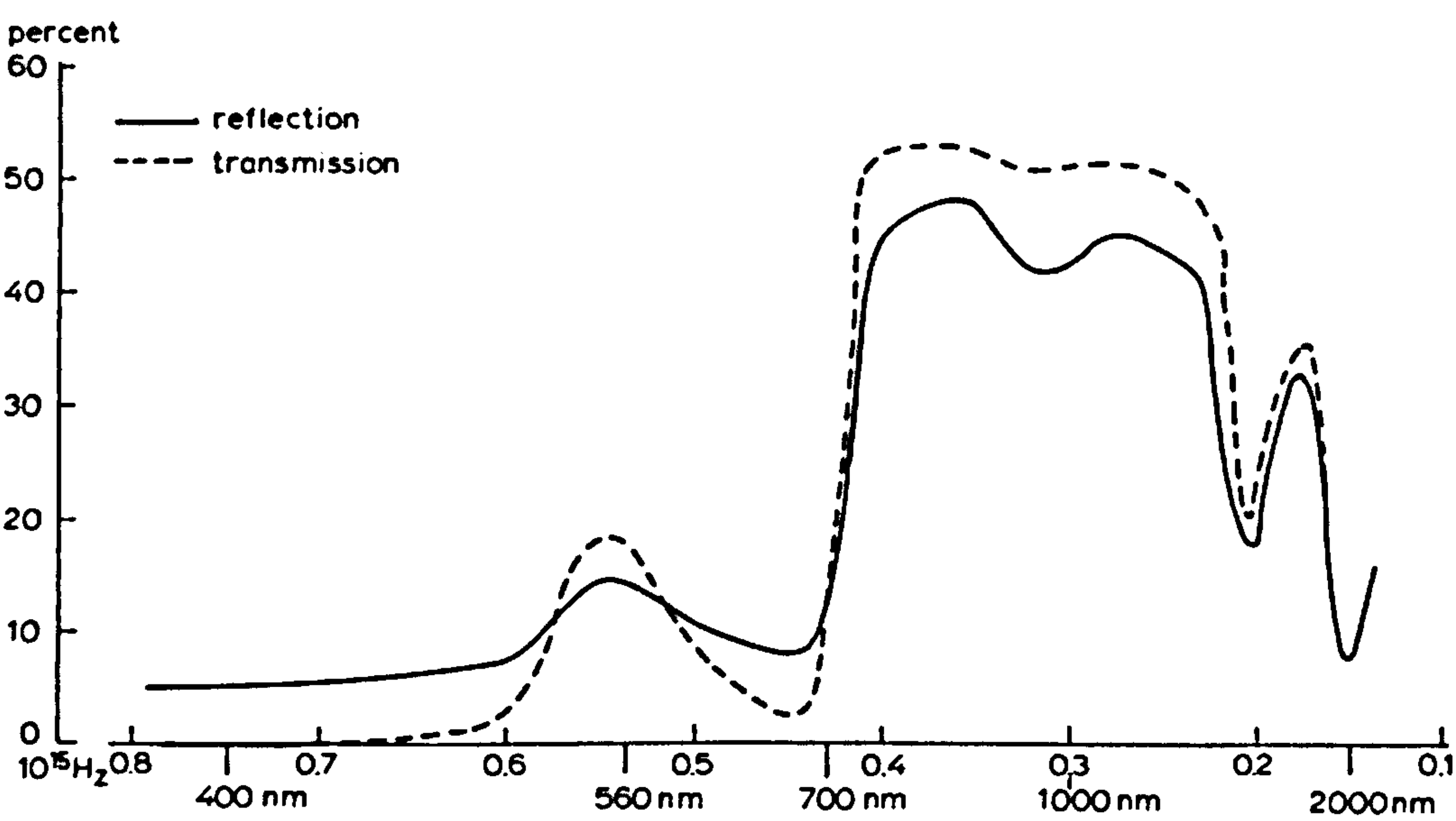

Fig. 2 | Spectral dependence of the leaf reflection and transmission coefficient of a healthy maize leaf.

that leaves reflect and transmit radiation isotropically. It will be shown that this assumption results in isotropically scattered radiation only for horizontal leaves.
Radiation reflected by the soil surface is assumed to be always isotropic. The reflection coefficient of soil does not exhibit a sharp increase at 700 nm, but rises gradually from about 0.1 at 400 nm via 0.2 at 700 nm to 0.35 at 1600 nm for a dry soil and from about 0.04 at 400 nm via 0.1 at 700 nm to 0.25 at 1600 nm for a moist soil (Verhoef & Bunnik, 1975). Thus an average value of 0.1 in the visible region and of 0.25 in the near-infrared region can be used as a first approximation for soil reflectance.

2.3 Elementary models

2.3.1 Horizontal leaves

For horizontal leaves the fraction of radiation intercepted per layer is always equal to the leaf area per layer L_s, independent of the light inclination. Let us denote the downward and upward radiant fluxes between layer j and j–1 by $\varphi_d(j)$ and $\varphi_u(j)$, the leaf reflection coefficient by ρ and the leaf transmission coefficient by τ. The equations for the downward and upward radiation leaving the jth layer then read

$$\varphi_d(j+1) = (1 - L_s)\varphi_d(j) + L_s\{\tau\varphi_d(j) + \rho\varphi_u(j+1)\} \quad (2.15a)$$

$$\varphi_u(j) = (1 - L_s)\varphi_u(j+1) + L_s\{\rho\varphi_d(j) + \tau\varphi_u(j+1)\} \quad (2.15b)$$

To find a solution for this set of equations, it is assumed that for each subsequent layer both downward and upward fluxes are reduced by the same constant reduction factor M. Such an assumption is justified if a solution exists. We therefore try

$$\varphi_d(j+1) = M\varphi_d(j) \quad (2.16a)$$

$$\varphi_u(j-1) = M\varphi_u(j) \quad (2.16b)$$

The whole procedure is considerably simplified by assuming that $\tau = \rho$. From a physical point of view this is a good approximation (Section 2.2.3). The sum of reflection and transmission coefficient is called the scattering coefficient and denoted by σ. After combination of Eqns (2.15) and (2.16) it is found that

$$\frac{\varphi_u(j)}{\varphi_d(j)} = \frac{(M - 1 + L_s)}{\{1 - M(1 - L_s)\}} \quad (2.17)$$

The assumption of a constant M is equivalent to the assumption of exponential extinction. The extinction coefficient K is related to M as

$$M = \exp(- KL_s) \quad (2.18)$$

For small values of L_s this expression approaches

$$M = 1 - KL_s \quad (2.19)$$

When this equation is combined with Eqns (2.17), (2.16) and (2.15), and the simplification is used that $\tau = \rho = 0.5\sigma$, we obtain

$$K_h = (1 - \sigma)^{0.5} \quad (2.20)$$

as was also found by Cowan (1968). The subscript h is used for reference to horizontal leaves. The expression for K can now be substituted into Eqn (2.19) for M, and M is used in Eqn (2.17) to find the ratio of the upward and downward flux. This ratio is independent of j, so that it also represents the reflection coefficient of the stand. We thus find:

$$\rho_h = \frac{\{1 - (1 - \sigma)^{0.5}\}}{\{1 + (1 - \sigma)^{0.5}\}} \quad (2.21)$$

A similar, but more complicated procedure is followed when τ does not equal ρ. For small values of L_s the extinction and reflection coefficient are then given by

$$K_h = \{(1 - \tau)^2 - \rho^2\}^{0.5} \quad (2.22)$$

$$\rho_h = (1 - \tau - K_h)/\rho \quad (2.23)$$

For low values of the leaf area index the reflection of the soil surface considerably disturbs the profiles found above, since in general the reflection coefficient of the soil surface ρ_s is not equal to the reflection of a closed leaf canopy ρ_h. Because of this boundary effect at the bottom, a second exponential profile in the opposite direction appears in the following equation:

$$\varphi_d(LAI) = \varphi_{1d}(0)\exp(K.LAI) + \varphi_{2d}(0)\exp(- K.LAI) \quad (2.24a)$$

$$\varphi_u(LAI) = \frac{\varphi_{1d}(0)}{\rho_h}\exp(K.LAI) + \varphi_{2d}(0)\rho_h \exp(- K.LAI) \quad (2.24b)$$

where ρ_h is given by Eqn (2.21) and $\varphi_{1d}(0)$ and $\varphi_{2d}(0)$ by

$$\varphi_{1d}(0) = \frac{(\rho_h - \rho_s)\exp(-K.LAI)\varphi_d(0)}{\left(\rho_s - \frac{1}{\rho_h}\right)\exp(K.LAI) + (\rho_h - \rho_s)\exp(-K.LAI)} \quad (2.25a)$$

$$\varphi_{2d}(0) = \frac{\left(\rho_s - \frac{1}{\rho_h}\right)\exp(K.LAI)\varphi_d(0)}{\left(\rho_s - \frac{1}{\rho_h}\right)\exp(K.LAI) + (\rho_h - \rho_s)\exp(-K.LAI)} \quad (2.25b)$$

Here ρ_s is the reflection coefficient of the soil surface and $\varphi_d(0)$ the downward flux at the top of the canopy.
Now the effective reflection coefficient of the canopy-soil system is given by

$$\rho_{eff} = \frac{(\rho_s\,\rho_h - 1)\exp(K.LAI) + (1 - \rho_s/\rho_h)\exp(-K.LAI)}{\left(\rho_s - \frac{1}{\rho_h}\right)\exp(K.LAI) + (\rho_h - \rho_s)\exp(-K.LAI)} \quad (2.26)$$

The transmitted fraction below the canopy is

$$\tau_{eff} = \frac{\rho_s - \frac{1}{\rho_h}}{\left(\rho_s - \frac{1}{\rho_h}\right)\exp(K.LAI) + (\rho_h - \rho_s)\exp(-K.LAI)} \quad (2.27)$$

The apparent reflection coefficient is given in Fig. 3 as a function of the leaf area index for visible and near-infrared radiation. For the visible radiation (solid lines) ρ_s was taken as 0 and 0.1 and for the near-infrared radiation (broken lines) ρ_s was taken as 0 and 0.25. The scattering coefficients of the leaves are 0.2 and 0.8, respectively. Above a *LAI* of 2 the influence of the soil surface can be practically neglected.

2.3.2 Canopies with a non-horizontal leaf angle distribution

The fraction intercepted by a layer with leaf area L_s is proportional to the average projection $\bar{O}(\beta)$ (Eqn (2.4)) and inversely proportional to the sine of the inclination of the incident light $\sin\beta$. Therefore the intercepted fraction is given by

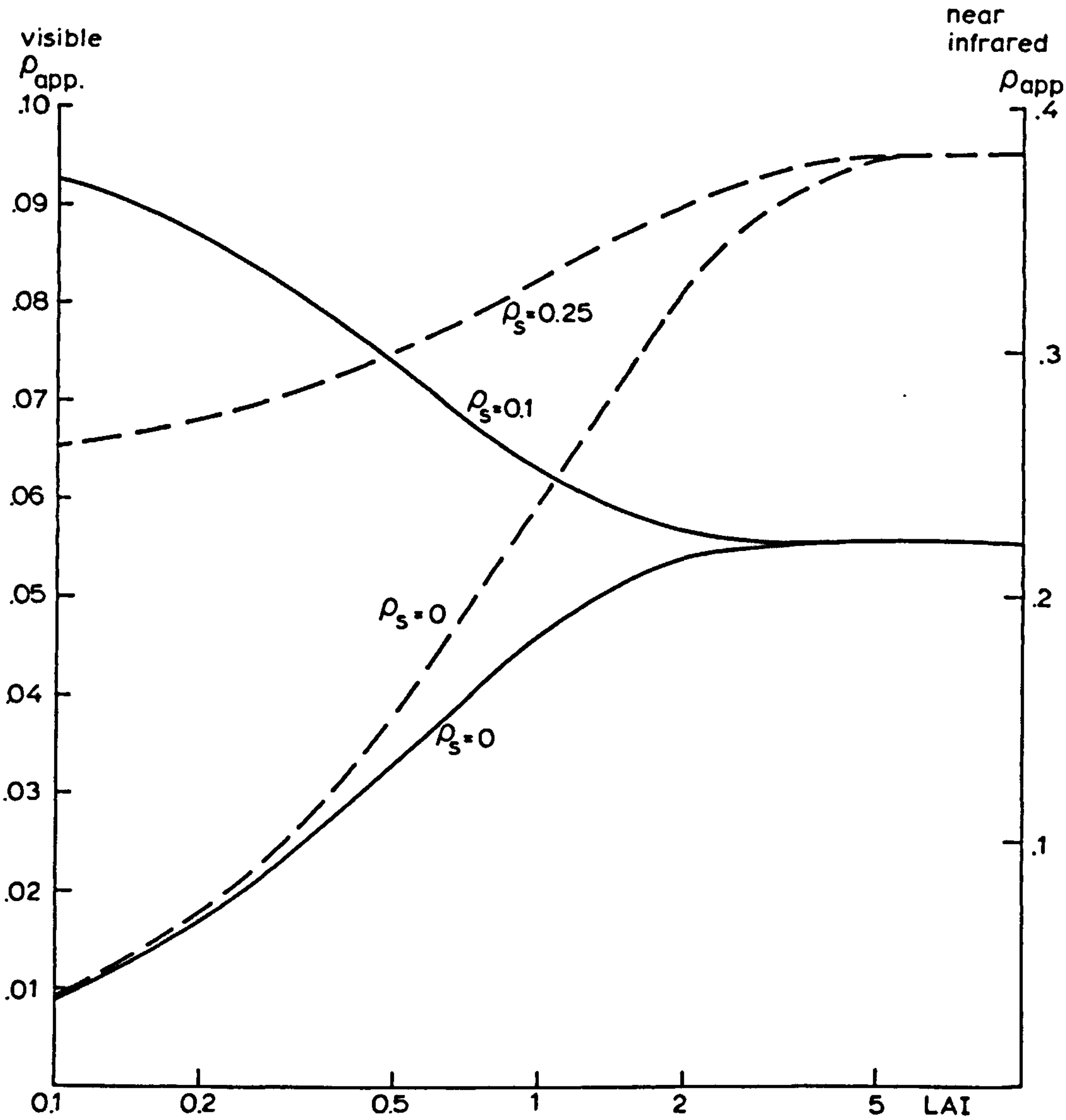

Fig. 3 | Apparent reflection coefficient of the canopy-soil system as function of the leaf area index for two values of the soil reflectance ρ_s. For the visible region (solid lines) the values are indicated on the left ordinate and for the near-infrared region (broken lines) on the right ordinate.

$$M_i(\beta) = L_s\overline{O}(\beta)/\sin\beta \tag{2.28}$$

The fraction of light transmitted through a layer is

$$M_t(\beta) = 1 - M_i(\beta) \tag{2.29}$$

In each subsequent layer the same fraction is transmitted and intercepted. This follows from the assumptions that the leaf angle distribution is not a function of height, that the positions of the leaves in