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Interception and absorption of radiation by wheat canopies

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RESUMO

Analisaram-se medições da transmissão da radiação total e da radiação fotossinteticamente activa (PAR) no coberto de uma cultura de trigo. A transmissão média diária, antes do alongamento do caule, é adequadamente descrita pelo modelo exponencial com um coeficiente de extinção (K) constante. Quando se utilizou o índice de área cultural os valores de K foram 0.422 ± 0.009 e 0.602 ± 0.010 para a radiação total e a PAR, respectivamente. Os valores de K variaram rapidamente após o alongamento do caule. Construiu-se um modelo que contabiliza as contribuições de todos os elementos do coberto, de acordo com as suas distribuições angulares e propriedades ópticas. Neste processo os parâmetros x do modelo elipsoidal para as distribuições angulares de folhas verdes e amarelas foram calculados (x foi de 1.03 para as folhas verdes e > 100 para as folhas amarelas). Os valores simulados da média diária e horária dos coeficientes de transmissão foram muito próximos dos valores medidos. Este modelo de intercepção da radiação pode ser utilizado com vantagem para simular a assimilação após o alongamento do caule, e o ambiente radiante de infestantes de emergência tardia. Apresentou-se também um modelo para o coeficiente de reflexão diário do coberto. Uma equação de regressão, obtida a partir de medições horárias deste coeficiente, pode ser utilizada para calcular os valores instantâneos a partir dos coeficientes diários.

SYNOPSIS

Measurements of transmission and reflection of total radiation and photosynthetically active radiation (PAR) by a wheat crop canopy were analysed.

Daily average transmission, before the end of stem elongation, is adequately described by the exponential model with a constant extinction coefficient (K). When crop area index (CAI) was used K values were 0.422 ± 0.009 and 0.602 ± 0.010 for total radiation and PAR, respectively. After stem elongation, daily values of K changed rapidly. A model that accounts for the contributions of all elements of the canopy, according to their angle distributions and optical properties was constructed. The x parameter of the ellipsoidal model for

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the angle distribution of green (GL) and yellow leaves (YL) was computed (x was 1.03 for GL and >100 for YL). Simulated values of daily average and hourly transmission coefficients were very close to the measured. This model of interception and absorption of radiation may be used with advantage to simulate canopy assimilation after stem elongation and the radiation environment of late emerging weeds.

A model was also presented for the daily reflection coefficient. A regression equation, obtained from hourly measurements of this coefficient, can be used for calculation of instantaneous values from the daily coefficients.

1. Introduction

Plant canopy photosynthesis and transpiration are governed by the amount and distribution of the radiation absorbed by the relevant plant parts. The fraction of radiation absorbed by the canopy (α_c), considered as a whole, is:

$$\alpha_c = 1 - \tau_c - \rho_c + \rho_s \tau_c \ , \tag{1}$$

where τ_c and ρ_c are the transmission and reflection coefficients of the canopy, and ρ_s is the reflection coefficient of the soil (Monteith & Unsworth, 1990). In more detailed approaches, the canopy is divided into thin layers of leaf area, where an average absorbed flux density is computed for the calculation of layer photosynthesis and/or transpiration (e.g., De Wit, 1965; Goudriaan & Van Laar, 1978; Stockle, 1992). Since Goudriaan (1986), the number of layers necessary for integration to the canopy level was reduced to three, without appreciable loss of accuracy.

The transmission of beam radiation ($\tau_{c,b}$) through a plant canopy, with random distribution of its elements, is described by Bouguer's law:

$$\tau_{c,b} = \exp[-K(\theta)\, L] \ , \tag{2}$$

where $K(\theta)$ is the extinction coefficient, which is a function of the azimuth angle, θ; and L is the leaf area index (area of leaves per unit area of ground). An equivalent form of this equation is used for the individual layers to integrate interception by the whole canopy, and for the attenuation of diffuse radiation (De Wit, 1965; Goudriaan, 1977; Goudriaan & Van Laar, 1978; Stockle, 1992). Several models have been used to obtain values for K (De Wit, 1965; Cowan, 1968; Monteith, 1973; Goudriaan, 1977; Ross, 1981; Goel & Strebel, 1984; Campbell, 1986; Goudriaan, 1988) for virtually any leaf-angle distribution.

All the models referred to above, that describe interception of radiation, use simplifications and idealizations that may bring some inaccuracy to calculations in some real situations. Plant growth models inherit these assumptions. Common assumptions of the interception submodels are the following:

1) leaf area index (L) is the relevant variable to be used in the equations of the form of (2) (e.g., Groot, 1987; Kvifte, 1987; Van Keulen & Seligman, 1987; Penning de Vries *et al.*, 1989);
2) usually L includes both green and yellow leaf areas, but often, especially when dealing with the transmission of PAR, only green leaves are considered;
3) the extinction coefficient is constant throughout the crop cycle. Similar assumptions have been made in the context of the reflection of total radiation and PAR.

This paper reports measurements of transmission and reflection coefficients of total radiation and PAR of a spring wheat canopy analysed in relation to plant area indices. The contribution to interception of elements of the stand, other than the leaves, is included. Common assumptions, such as the constancy of the extinction coefficient throughout the crop cycle, will be validated. A model of transmission that accounts for the contributions of all elements of the canopy to interception of radiation is presented, validated and compared with other models. A model for the description of reflection is also presented.

2. Materials and methods

Spring wheat (*Triticum aestivum* L., cv. Pesudo) was grown in the fields of Quinta da Amoreira, near Cartaxo, Portugal (39° 10′ N; 8° 43′ W; 7 m above M.S.L.) in 1992, as part of a three year experiment. The soil is a deep loamy sand: Eutric Fluviosols (FAO, 1988). Measured organic matter contents in the soil profile were very low ($\leq 1.2\%$), extractable P and K were very high, and pH(KCl) was around 7.5. The electrical conductivity of the saturation extract in a composite sample between 0–50 cm was low (0.177 $\mathrm{dS.m^{-1}}$).

The soil was disked twice before sowing, when 36 $\mathrm{kg.ha^{-1}}$ of N and 92 $\mathrm{kg.ha^{-1}}$ of P were incorporated. One 600 $\mathrm{m^2}$ plot was sown at a 200 $\mathrm{kg.ha^{-1}}$ seeding rate. Additional nitrogen was applied as split dressing, 70 $\mathrm{kg.ha^{-1}}$ of N at tillering and 70 $\mathrm{kg.ha^{-1}}$ at stem elongation. Soil water was monitored with a neutron moisture meter, in 0.10 m increments to 1.20 m, in two access tubes.

Sowing was done on 22 January. Plants emerged on 11 February; anthesis and dead-ripe maturity occurred on 27 April and 4 June. Rows were 12 cm apart and were oriented in the northeast-southwest direction.

Meteorological data were collected above the crop. These included global radiation (S_t), reflected solar radiation (S_r), and total downward and upward radiation fluxes (Q_d and Qu), photosynthetically active radiation (PAR) and reflected PAR. Pyranometers were of the Moll-Gorczinsky type (from Kipp and Zonen); pyrradiometers were from Philipp Schenk (Mod. 8111), and quantum sensors were from Skye Instruments. The transmission coefficient of total radiation was measured with three tube solarimeters placed horizontally. One radiometer (Delta-T devices, Mod. TSL) was positioned over the crop at 1.2 m height and oriented perpendicular to the plant rows. Two other radiometers (built to the design of Green & Deuchar, 1985) were installed in equivalent position, but 5 cm above the ground. Transmitted PAR was measured with a line quantum sensor (Li-Cor) placed horizontally 5 cm above the ground and perpendicular to the rows. Measurements started 29 days after emergence (DAE) and ended after the occurrence of maturity (156 DAE).

Ten consecutive days of transmitted PAR were discarded because the line quantum sensor was in an incorrect position. Reflected total-radiation data suffered extensive losses due to poor electrical contacts.

One meter of row in four random locations was harvested weekly. From each sample 20 plants were randomly selected, divided in four groups of five plants, and partitioned into green leaves (GL), yellow leaves (YL), stems (ST) (sheaths were included), and ears (ER). The area of each sample was measured with an optical planimeter with a conveyor (Li-Cor, Model 3100). The area of stems and ears was taken as their projected area, not their cylindrical surface area. Plant parts were oven dried (70 °C) and weighed. Green leaf area index (GAI), yellow leaf area index (YAI), stem area index (SAI), and ear area index (EAI) were computed as the product of the estimated weight of the plant part in unit area and the respective specific area (i.e., area of the plant part in the sample per unit dry weight). Leaf area index (LAI) is GAI + YAI, and crop area index (CAI) is LAI + SAI + EAI. Daily values of these area indices were obtained from estimates of dry weight given by a logistic fit to the data multiplied by the estimates of the specific indices given by interpolation using weekly values. Phenological growth stage was assessed weekly, using a modified Haun scale (Klepper *et al.*, 1982) before anthesis, and Zadoks decimal codes (Zadoks *et al.*, 1974) hereafter.

3. Results and discussion

3.1. Canopy transmission

Figures 1 and 2 show that the transmission coefficients (also known as fractional transmission) of total radiation and PAR depict a different course when plotted against CAI or GAI. In both cases there were two values of transmission for the same value of area index. There are two phases.

Figure 1

Transmission of daily total radiation in relation to area indices: (A) crop area index (CAI), (B) green leaf area index (GAI)

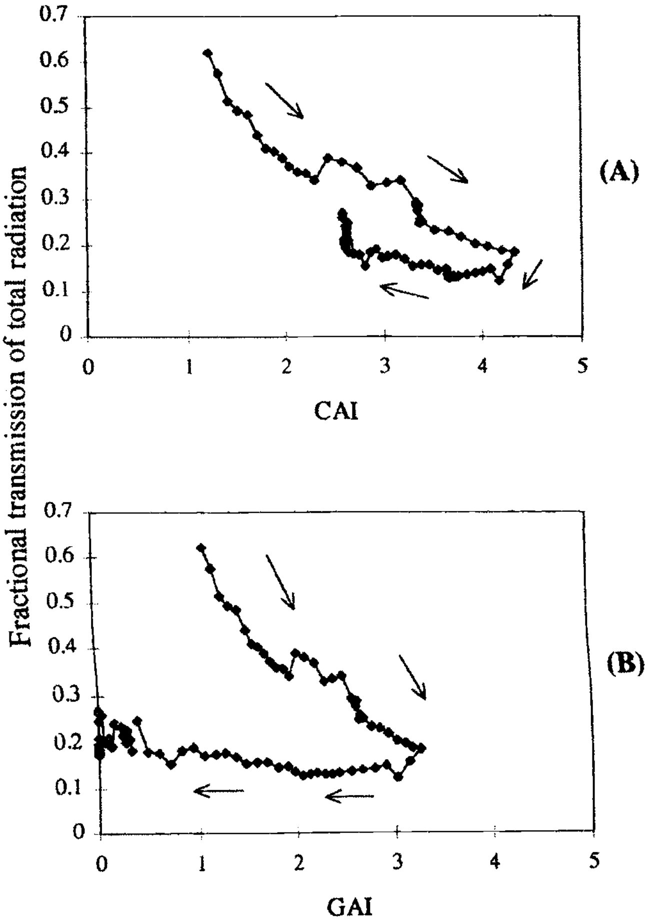
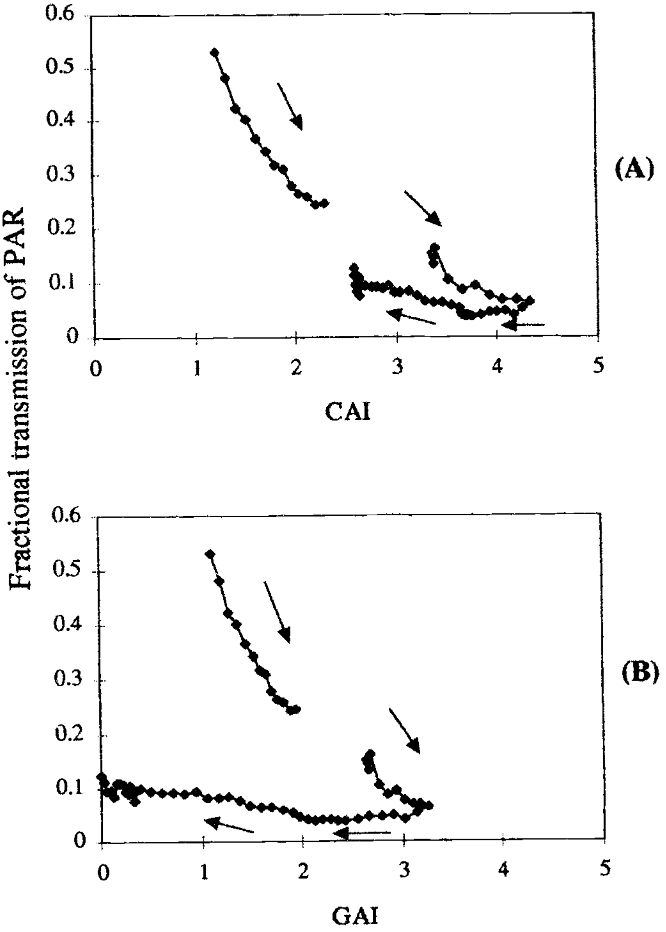


Figure 2

Transmission of daily PAR in relation to area indices:
(A) crop area index (CAI), (B) green leaf area index (GAI)



Before peak area index is attained, an increase of intercepting surface corresponds to a clear decrease in transmission. A small increase in transmission was noticed later, when area index is decreasing. The difference between Fig. 1 A and Fig. 1 B or Fig. 2 A and Fig. 2 B clearly shows the importance of the non-green leaf plant parts in the interception process. Soon after anthesis GAI is less than half of CAI (Fig. 3).

Figure 3

Time-course of above-ground area partition of the canopy.
GL, YL, ST and ER refer to green leaves, yellow leaves, stems, and ears

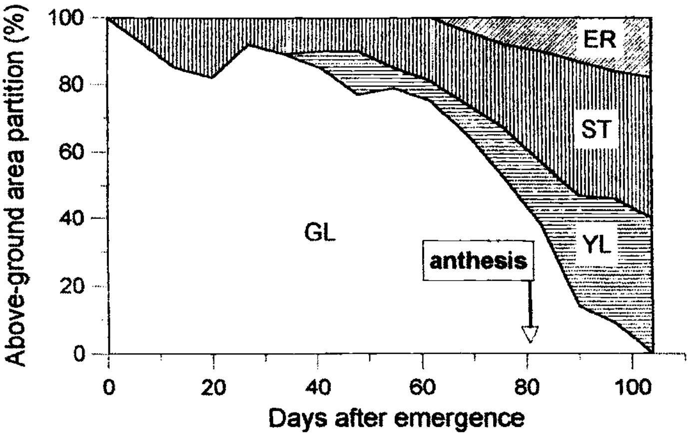


Figure 4 plots the course of the extinction coefficients of total radiation and PAR versus CAI and LAI. These values were obtained by non-linear regression analysis using (2), where CAI was the area index used. After flag leaf appearance, there was a steady increase in the computed daily values of these coefficients.

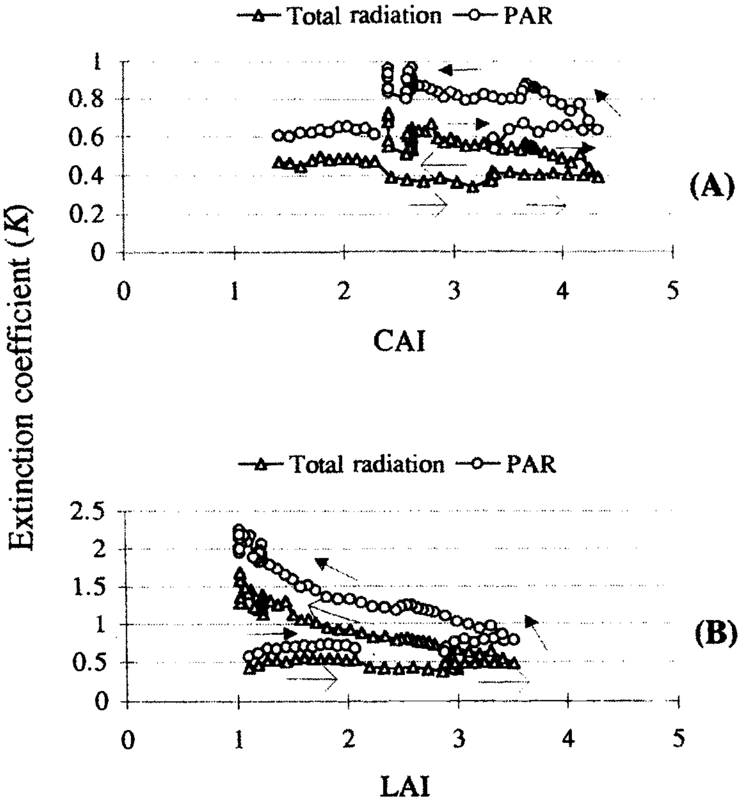
These snake-like plots (Fig. 1, 2, 4) show that, in parallel with stage development, considerable structural change occurs in the canopy. Ear emergence and senescence are among the causes for variation in extinction coefficient throughout the period of crop development. It should be stressed that the exponential model of interception (2) is very sensitive to changes in the extinction coefficient. Before the end of stem elongation (DOY 104) extinction coefficients changes very little. The average values of the extinction coefficient, using CAI as area index, were 0.422 ± 0.009 and 0.602 ± 0.010 for total radiation and PAR (Fig. 4).

Green (1987) found a K of PAR that averaged 0.67, before anthesis, using LAI as the area index. Thorne *et al.* (1988) reported a mean value of K for PAR of 0.46 between unfolding of the first leaf and appearance of the flag leaf and a value of about 0.61 around anthesis. In this paper, transmitted PAR was obtained either from instantaneous measurements made near midday, 24 h integrals of PAR or percentage ground cover measured photographically;

the area index used was CAI-EAI. Before full canopy cover, Aslyng & Hansen (1985), found $K = 0.44$, with continuous measurement of transmitted PAR and considering CAI. These authors consider that the exponential model is only valid in this period. Gallagher & Biscoe (1978) found, in the rapid growth phase, an average value of K of 0.33, when LAI and total radiation were considered. Our results for total radiation and PAR are in good agreement with most of the values mentioned above. Notice that the ratio between the K values for PAR and for total radiation is 1.34 (Green, 1987).

Figure 4

Daily coefficients of extinction for total radiation and PAR in relation to area indices: (A) crop area index (CAI), (B) leaf area index (LAI)

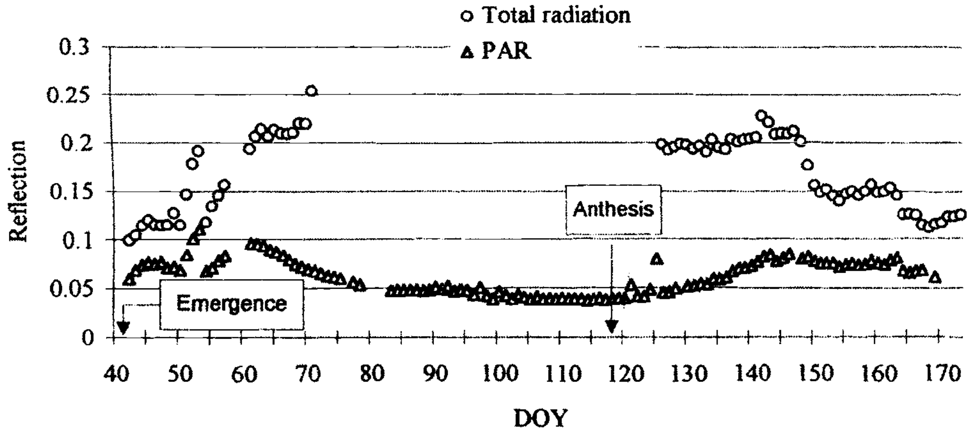


3.2. Canopy reflection

The time-course of the reflection coefficients of total radiation and PAR are shown in Fig. 5. In the first two weeks after emergence rain was frequent, and the reflection coefficients were low. High values depicted in this period correspond to a dry period. The reflection coefficient of total radiation soon reached values between 0.20 and 0.26, which are commonly reported as being characteristic of wheat crop at full cover (Monteith, 1959; Piggin & Schwerdtfeger, 1973). The reflection coefficient of PAR is minimum (about 0.04) shortly before anthesis, when peak CAI is attained (Abreu *et al.*, 1997).

Figure 5

Time-course of the reflection coefficients of total radiation and PAR averaged over the day. Days of the year (DOY) of emergence and anthesis were 41 and 156



4. Description and validation of the models

4.1. Canopy transmission

In the following analysis we will analyse two situations. Before the end of stem elongation (DOY 104), when LAI is low, concentration of area in the rows of plants and the relatively low height of plants attained raises doubts about the validity of the random model. Fortunately, in this section the extinction coefficients change very little, thus facilitating the use of (2) with an empirical value of the extinction coefficient. After this stage we consider that the effect of row structure is lost and the canopy transmits light according to the random canopy equations.

Fuchs & Stanhill (1980) and Campbell & Van Evert (1994) present models for row crops. Since the detailed information needed to use these models is not available, we will not extend our analysis any further before the end of stem elongation. The daily average K for total radiation and PAR were given in Fig. 4 when CAI was used in (2). For the simulation of hourly K values one possibility is to multiply the empirical extinction coefficient of beam radiation when the sun is at the zenith by $\sec\theta$. This is equivalent to the assumption that the relation between θ and K_b that exists in spherical leaf angle distributions, in random canopies, is valid. We integrated the transmission of beam radiation in a model canopy for a twelve-hour day at 39° 10′ N. We assumed that radiation follows a sinusoidal wave (e.g., Monteith & Unsworth, 1990), and that the canopy has a spherical leaf angle distribution. The ratio between the extinction coefficient of beam radiation when the sun is at the zenith and the daily average extinction coefficient was 0.61.

Let us now consider the interception on days after stem elongation. Ideally, a wheat crop canopy can be divided into a number of layers, in which the angular distribution of the leaves (or any other element of the canopy) is constant. If these are considered black (bk), with random distribution in space, and with random azimuth, the exponential model can be used and the usual equations to calculate the extinction coefficients apply. The transmission coefficient of the stand of black elements, $\tau(\theta)_{bk}$, is then given by the product of the transmission coefficients of the layers:

$$\tau(\theta)_{bk} = \prod_{i=1}^{n} \tau(\theta)_{bk(i)} = \exp\left[-\sum_{i=1}^{n}\left(K(\theta)_{bk(i)}\, L_i\right)\right] . \tag{3}$$

Here, the transmission coefficient of the stand, $\tau(\theta)_{bk}$, and the transmission coefficients of the n layers i, $\tau(\theta)_{bk(i)}$, are functions of the zenith angle θ. $K(\theta)_{bk(i)}$ is the extinction coefficient of layer i, and L_i is the area index of the element present in the i^{th} layer of the canopy.

Diffuse radiation comes from all directions. If a uniform distribution of diffuse radiation in the sky hemisphere is assumed, the diffuse transmission is (Ross, 1981):

$$\tau_{d(bk)} = 2\int_{0}^{\pi/2} \tau(\theta)_{bk}\, \sin(\theta)\, \cos(\theta)\; d\theta\ . \tag{4}$$

In real canopies scattering occurs allowing for an enhancement of the transmission of radiation. Goudriaan (1977) demonstrated that the extinction coefficients of such canopies can be derived from the extinction coefficients for canopies of black leaves, provided that solar elevation is larger than the elevation angles of most leaves. The relation between extinction coefficients is then given by

$$K = \sqrt{\alpha}\, K_{bk} \,, \tag{5}$$

where α is the absorptivity of the leaves.

Global radiation (S_t) is both beam (S_b) and diffuse radiation (S_d). These components of global radiation are independently transmitted through the canopy. It follows that total transmission is

$$\begin{aligned} S_t\, \tau(\theta)_t &= S_b\, \tau(\theta) + S_d\, \tau_d \,, \\ \tau(\theta)_t &= (1 - F_d)\, \tau(\theta) + F_d\, \tau_d \,, \end{aligned} \tag{6}$$

where the fractional transmission of global radiation, $\tau(\theta)_t$, is obtained by weighing the fractional transmissions of beam and diffuse radiation ($\tau(\theta)$ and τ_d) with the fraction of global radiation that is beam, $(1 - F_d)$, and diffuse, F_d, respectively.

Substituting (3), (4) and (5) into (6), we get a general model:

$$\begin{aligned} \tau_t = {} & (1 - F_d) \exp\left[-\sum_{i=1}^{n}\left(K_i \sqrt{\alpha_i}\, L_i\right)\right] \\ & + F_d\, 2\int_0^{\pi/2} \exp\left[-\sum_{i=1}^{n}\left(K_i \sqrt{\alpha_i}\, L_i\right)\right] \sin\theta \cos\theta \, d\theta \,, \end{aligned} \tag{7}$$

where the notation was simplified.

The model in (7), when applied to describe interception by the whole wheat canopy, can be specialised. In a wheat stand three layers can, ideally, be distinguished:

1) a layer of ears;

2) a subsequent layer where green leaves and green stems coexist;

3) a layer of yellow leaves and stems.

Accordingly, the exponent of the exponential function in square brackets ((7)), can be replaced as follows:

$$\left[-\sum_{i=1}^{n}\left(K_i\sqrt{\alpha_i}\,L_i\right)\right]=\left[-\sqrt{\alpha}\left(K_g\,\mathrm{GAI}+K_y\,\mathrm{YAI}+\tan\theta\,(\mathrm{EAI}+\mathrm{SAI})\right)\right], \qquad (8)$$

where K_g and K_y are the extinction coefficients for green leaves and yellow leaves. In (8) all stems are assumed to make up one layer. The extinction coefficient for the vertical elements (stems and ears) was deduced by treating them as cylinders ($K = 2\tan\theta/\pi$; Cowan, 1968; Ross, 1981) with area of the ears and stems as the projected area. Absorptivity of green leaves is 0.80–0.90 and 0.40–0.50, for PAR and total radiation, respectively (Goudriaan, 1977; Ross, 1981; Monteith & Unsworth, 1990; Walter-Shea & Norman, 1991). Notice that dry matter and area partitioning may be estimated if the appropriate reference system is used (Abreu *et al.*, 1994).

To use the specialised model described by (7), with the substitution indicated by (8), there is need to calculate the extinction coefficients K_g and K_y. A convenient way to calculate the extinction coefficient of beam radiation in a canopy of black leaves, for a wide range of canopy structures, is given by the model that assumes ellipsoidal leaf angle distribution (Campbell, 1986). Using this model the extinction coefficient, $K(\theta)_E$, is

$$K(\theta)_E=\frac{\sqrt{x^2+\tan^2\theta}}{x+1.774\,(x+1.182)^{-0.733}} \qquad (9)$$

which is a function of a single parameter x and the zenith angle, θ.

The method to determine the parameters x, given by (9), for green and yellow leaves, was:

1) Twenty-six clear days, spread in time from 63 to 117 DAE were selected to yield hourly data. Clear days were chosen to minimise the importance of the diffuse radiation part in (7). Daily and hourly transmission coefficients of total radiation and PAR were calculated, using hourly data of global radiation, PAR, and the transmitted values measured by a line quantum sensor and two line radiometers.

2) The hourly transmission coefficients of diffuse radiation in a day were assumed to be equal to the average transmission coefficient of radiation for that day. This assumption is justified by the fact that the sun in its apparent trajectory integrates (4). An average of 25% diffuse radiation in global and PAR was assumed, based upon data from Lisbon (Abreu & Campbell, 1996).

3) The absorptivities for total radiation and PAR were set to 0.45 and 0.90, respectively.

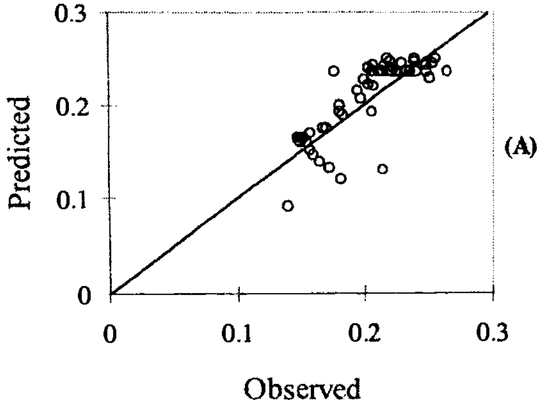
4) Finally, using our data on area partition (Abreu *et al.*, 1997) the specialised model could be inverted to yield the values of the parameters x for the layers of GL and YL, using a non-linear regression algorithm (Marquart, 1963). The program computes hourly estimates for the transmission coefficients of the canopy, using a set of values given to the x-parameters, compares the estimates of the transmission coefficients with the measured values of this variable, and a new set of x-parameters is determined. The process evolves iteratively until a given tolerance is met.

The estimated x parameter for the GL layer is 1.03 ± 0.06 ($\pm$ S.E.). The parameter estimates for YL were very high and converged very slowly to 467.7. This is a consequence of the extremely low sensitivity of the ellipsoidal model to the x parameter when x values are of this magnitude. As the leaves become horizontal $x \to \infty$.

For comparison, a model that uses only LAI = GAI + YAI in (7), but otherwise similar, was tested. The number of data points and the method used to compute x of the ellipsoidal model were the same. Estimates of daily values of the transmission coefficients, using both models, show that the specialised model performs much better than the model where only LAI is considered (Table 1). In Fig. 6 the predicted versus observed plots show that, in general, the specialised model delivers good estimates (for more details see Table 1). Nevertheless, predicted PAR transmission was systematically higher than the observed values. This may have been due to underestimation of above-ground dry matter for the location where the line quantum sensor was positioned. This model of interception and absorption of radiation may be used with advantage to simulate canopy assimilation after stem elongation and the radiation environment of late emerging weeds.

Figure 6

Predicted and observed (A) daily fractional transmissions of total radiation and (B) of PAR. The specialised model presented in this paper was used from the end of stem elongation to maturity



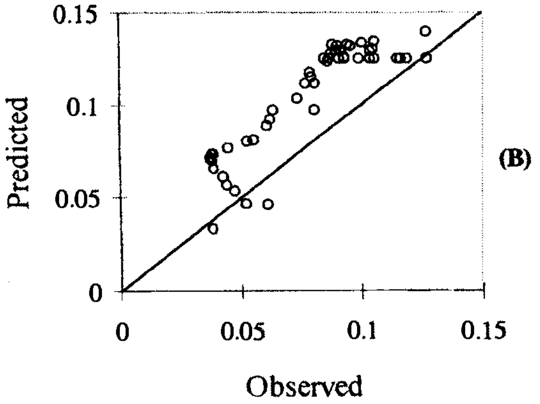


Table 1

Statistics from linear regression analysis of predicted versus observed values. N is the number of observations, $\overline{P}$ and $\overline{O}$ are the average predicted and observed values, s_p and s_o are their standard deviations, a and m are the intercept and slope of the line, and SE is the standard error

Simulation	N	$\overline{P}$	$\overline{O}$	s_p	s_o	a, m	SE (r^2 in %)
Hourly values of fractional transmission of total radiation and PAR in clear days, given by the specialised model (eq. (7) with the substitution indicated by eq. (8))	573	0.10	0.12	0.06	0.07	$a = 0.00$ $m = 0.76$	0.022 (87)
Same as in the row 1, but when only LAI was considered	573	0.19	0.12	0.08	0.07	$a = 0.09$ $m = 0.78$	0.060 (48)
Daily transmission of global radiation using the specialised model	54	0.19	0.18	0.04	0.04	$a = 0.04$ $m = 0.83$	0.024 (66)
Daily transmission of PAR using the specialised model	50	0.10	0.08	0.03	0.03	$a = 0.02$ $m = 1.03$	0.013 (83)
Daily reflection coefficient of PAR using the model in eq. (10). Only days without rain and with a previous dry day were considered	62	0.051	0.051	0.015	0.015	$a = 0.00$ $m = 0.93$	0.003 (98)

4.2. Canopy reflection

We chose a variant of Goudriaan's approach for daily reflection. Reflection coefficient (ρ_c) is

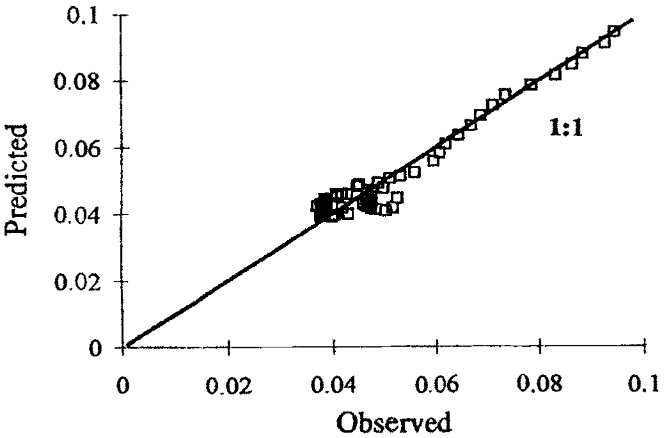
$$\rho_c = \rho_c^* - (\rho_c^* - \rho_s) \exp(-P\,\mathrm{CAI}) \;, \tag{10}$$

where ρ_c^* is the reflection coefficient of a very deep canopy, ρ_s is the soil reflection coefficient, and P is an empirical parameter.

Regression analysis was done using the values of the reflection coefficient of PAR and the corresponding values of CAI. The parameters in (10), except for ρ_c^* that was estimated from the data (0.036), were found by non-linear regression (Marquart, 1963). Only days without rain and with a previous dry day were considered to avoid changes in soil reflection. The fitted values were: $\rho_s = 0.19 \pm 0.01$ and $P = 0.87 \pm 0.04$. Fig. 7 shows the fitted equation and data and more statistics of the regression are presented in Table 1.

Figure 7

Predicted versus observed daily reflection coefficients of PAR, using the model in (10)



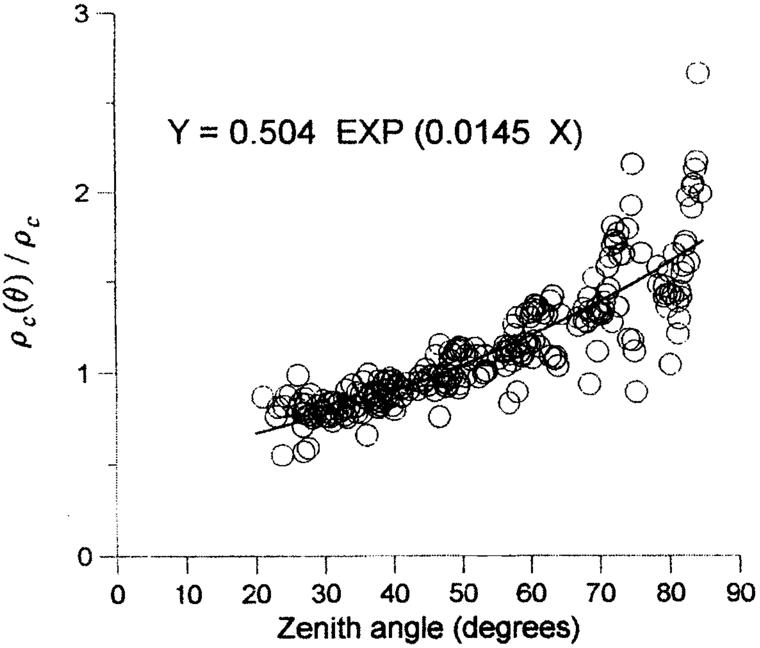
Instantaneous values of reflection can be computed using an empirical model derived from 251 hourly values of the reflection coefficient of PAR, $\rho(\theta)_c$, from 23 clear days. We used (6), assuming that F_d in clear days is 0.25 and that reflection coefficient of diffuse radiation is the same as the coefficient of daily reflection, $\rho(\theta)_c$, to estimate hourly reflection of beam radiation, $\rho(\theta)_{c,b}$. The equation is

$$\frac{\rho(\theta)_{c,b}}{\rho_c} = A \exp(B\,\theta) \ , \tag{11}$$

where the ratio between the instantaneous and daily reflected PAR is given as a function of the zenith angle (θ) in degrees (Fig. 8). The parameter A and B are 0.504 ± 0.017 and 0.145 ± 0.001, with r^2 equal to 77%.

Figure 8

Ratio between the hourly and daily reflection coefficients of PAR in relation to zenith angle. Data are 251 hourly values from all clear days (23)



5. Conclusions

Fractional transmission of total radiation and PAR of a wheat canopy were described differently before the end of stem elongation and after. In the first period of crop growth the exponential model was apparently valid, with almost constant values of the extinction coefficients of total radiation and PAR. Nevertheless, the values in this study are lower than expected from the equations derived for canopies with random distribution of the foliage in space and with random azimuth. In this first period the obvious solution is empirical. The second period is characterised by rapid changes of the extinction coefficients, no matter what area index is considered. This is the time when the fractional interception is higher, although the green area is not always abundant.

A model of light transmission performed well when the contribution of all the plant, for their characteristic geometrical and optical properties, was included.

Daily reflection coefficient was described by a single equation. Hourly reflection was well fit by an empirical function.

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