RADIATION ABSORBED BY A TOMATO CROP IN A GREENHOUSE

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ABSTRACT

Radiation absorbed by a tall, sparse crop (like tomato) in a greenhouse cannot, in practice, be related straightforwardly to solarimeter and/or net radiometer measurements, due to the large variations from place to place of the measured flux and to the anisotropy of longwave radiation emitted by the heating system. In this paper it is shown how the parameters of the theoretical functions for extinction and reflection of radiation in a dense stand can be derived from simple solarimeter measurements. It is further discussed how downward and upward radiation fluxes at any depth in the stand can be calculated by means of these functions from net radiation measured at its top, when radiation emitted from the heating system is introduced. The relationship obtained in this way is then corrected for radiation exchanges taking place for an incomplete cover (row crop). The resulting estimate of net radiation absorbed (or emitted) by the crop is shown to fit well in a energy balance equation where measured energy fluxes for a greenhouse tomato crop are used.

CONTENTS

LIST OF SYMBOLS

A	= ground area fraction corresponding to a row	-
C	= total thermal capacity per unit ground area	$J.m^{-2}.K^{-1}$
E	= evapotranspiration rate (vapour mass flux)	$kg.m^{-2}s^{-1}$
G	= rate of change of stored heat per unit area	$W.m^{-2}$
H	= sensible heat flux	$W.m^{-2}$
L	= longwave radiation flux (2800 - 40000 nm)	$W.m^{-2}$
LAI	= leaf area index	$m^2.m^{-2}$
R	= total radiation flux	$W.m^{-2}$
S	= shortwave radiation flux (350 - 2800 nm)	$W.m^{-2}$
T	= temperature	K
k	= extinction coefficient in a stand	-
r	= reflectance of a leaf	-
s	= scattering coefficient of a leaf ($r + t$)	-
t	= transmittance of a leaf	-
x	= depth in the stand, positive downwards, with x (z) = 0	m
z	= height of the stand	m
α	= angle between a leaf and a horizontal plane	deg
β	= elevation of the sun	deg
λ	= latent heat of vaporization of water	$J.kg^{-1}$
ρ	= reflectance of a stand	-
τ	= transmittance of a stand	-

Subscripts

a = absorbed

b = beam (direct)

c = diffuse

d = downward

f = fluid (air)

l = leaves

n = net (downward - upward)

p = heating pipes

r = row

s = soil

t = transmitted through at least one leaf

u = upward

x = at a given depth in the stand

0 = non-transmitting and non-reflecting (black)

∞ = dense stand (LAI $\rightarrow \infty$)

1. INTRODUCTION

The rate at which water evaporates from a wet surface can be determined if the total energy available for sensible and latent heat transfer is assumed to be equal to the difference between the net amount of radiative energy absorbed at the wet surface and the rate at which heat is stored in the system.
However, defining the net amount of energy available from radiation for a given plant stand, is a fairly difficult task. Only for a short field crop, completely covering the ground, it may be fairly intuitively stated that the net available energy from radiation is equal to the net radiation (i.e. the difference between incoming and outgoing short- and longwave fluxes) measured above the crop, minus the heat flux into the soil below it.
It is in this way acknowledged that the large-scale radiative properties of the canopy are scarcely influenced by micro-features such as leaf size, shape or orientation, so that net radiation is uniform on a horizontal plane above the crop. Another way of stating this is that the sensor must be 'far enough' for the variability of the properties on a small scale (a few leaves or a single plant) to be averaged out so that the canopy can easily be represented as a uniform horizontal plane, as far as its radiative exchanges are concerned.
Unfortunately, most crops are not as 'amenable', and a non-uniform distribution of the radiation within, above and below the foliage must be accounted for, so that the net absorbed, thus available radiative energy is not obviously related to measured net radiation. This applies to most greenhouse crops: radiation sensors cannot be 'far enough'. The wild scattering of measured radiation fluxes at different places is in fact a common problem with greenhouse experiments.
Moreover, soil cover is mostly incomplete, the paths being a relevant but varying fraction of the greenhouse area, so that a suitable method to estimate the amount of radiation actually used by a greenhouse crop for sensible and latent heat exchanges deserves further investigation.

2. THEORY

Radiation incident on the upper surface of a horizontal plane at a given depth in a horizontally homogeneous stand, has three components: unmodified transmitted solar radiation, solar radiation transmitted through the overlying foliage and the longwave radiation emitted downwards by it. Conversely, radiation incident on the lower surface of the same plane is the sum of solar radiation reflected and radiation emitted by the ground and the underlying foliage. Since radiative properties of the foliage change considerably with wavelength, it is convenient

to split the discussion for short and longwave radiation.
In this context shortwave radiation means the radiation perceived by a conventional solarimeter, i.e. radiation in the spectral range 350 to 2800 nm, that is visible plus near infrared (NIR). By longwave radiation is meant the radiation in the spectral range 2800 to 40000 nm, which is generally called thermal infrared (TIR), because the maximum intensity of radiation emitted by bodies at 'terrestrial' temperatures falls in this range.
Reflection and transmission of single leaves are significant for shortwave radiation and negligible for longwave radiation; on the other hand, longwave radiation emitted by the foliage is important. Accordingly, the following two equations can be written for the net short and longwave radiation on a horizontal plane at some depth x in the canopy, so that the leaf area index reckoned from the top to x is LAI_x

$$S_n = \tau(LAI_x)S - \rho(LAI_x)S \qquad (W.m^{-2}) \qquad (1)$$

$$L_n = L_d(LAI_x) - L_u(LAI_x) \qquad (W.m^{-2}) \qquad (2)$$

where:

S_n = net shortwave radiation

$\tau(LAI_x)S$ = shortwave radiation transmitted by the overlying foliage

$\rho(LAI_x)S$ = shortwave radiation reflected by the underlying surfaces, i.e. soil and foliage

L_n = net longwave radiation

L_d = longwave radiation emitted and transmitted downwards by the overlying foliage

L_u = longwave radiation emitted and transmitted upwards by the underlying surfaces

2.1. Radiation transmitted below a stand of black leaves

It can be shown (MONTEITH, 1975; ROSS, 1975) that an exponential function describes the extinction of radiation transmitted through an ideal canopy of 'black' leaves (non-transmitting and non-reflecting leaves), namely, transmitted radiation $R_0(LAI)$ below a stand of given LAI (leaf area index, i.e. leaf area - one side only - above a unit ground area), can be expressed:

$$\tau_0 = \frac{R_0(LAI)}{R(0)} = e^{-k_0 . LAI} \qquad (-) \qquad (3)$$

Table I. Values of the extinction coefficient (k_o of eq. 3) as deduced from the literature, for idealized leaf angle distributions, black leaves and diffuse radiation from a uniform sky.
α is the angle between the leaves and a horizontal plane. Monteith gave values for extinction of only direct radiation, as depending on solar elevation β.
1) This value is given for all β.
2) 0.50 is given for $\beta = 90^\circ$ and $\beta = 60^\circ$; 0.58 for $\beta = 30^\circ$.
3) Values strongly dependent on β are not mentioned here.

Leaf angle distribution		Monteith	Ross	Goudriaan
Horizontal			1.000	1.050
Conical	$\alpha = 30^\circ$	0.87 1)		
	$\alpha = 45^\circ$			0.829
	$\alpha = 60^\circ$	0.50, 0.58 2)		
Vertical		- 3)	0.436	
Spherical		- 3)	0.684	0.685

where R(0) is the radiation incoming at the top of the stand and k_o is a coefficient related to the geometrical distribution of the leaves and the elevation β of the sun, when direct radiation from the sun is considered. It can be analytically calculated for some idealized leaf angle distribution, as all leaves being at a fixed angle α in respect to a horizontal plane, or all angles having the same probability (the so-called spherical distribution). Values of k_o deduced from the literature (MONTEITH, 1969; ROSS, 1975; GOUDRIAAN, 1977) for diffuse radiation are given in Table I.
The determination of the amount of radiation penetrating a stand of 'black' leaves is thus a purely geometrical problem, whose solution requires only a knowledge of the angle distribution of the leaves.
Note that by means of (3) not only transmitted longwave radiation can be described, but also the amount of shortwave radiation penetrating a plant stand unmodified (i.e. radiation emitted by the portions of sky seen through the foliage). Therefore τ_0 can be interpreted as the fractional area occupied by sun flecks on the soil surface, and $(1 - \tau_0)$ represents soil cover.

2.2. Radiation transmitted below a stand of 'real' leaves

Transmitted shortwave radiation below a canopy of transmitting and reflecting leaves is the sum of unmodified transmitted radiation obtained from eq (3), and of radiation either transmitted or reflected (or both) by some leaves. Radiation transmitted through the leaves R_t, is strongly influenced by their optical properties and is therefore dependent on the wavelength involved.
The vertical profile $R_{t,x}(LAI)$ is not monotonical, increasing from zero at the top of the stand to a maximum value at a certain depth, depending on the wavelength and the stand structure, and then decreasing towards the ground surface. A detailed calculation of transmitted radiation through the leaves is complicated and not needed for many purposes (for any open stand radiation transmitted through the leaves is much smaller than radiation transmitted unmodified), and many empirical formulae have been worked out.
KASANAGA and MONSI (1954), proposed an exponential equation for the total downward radiation below a plant stand of leaves with transmission coefficeint t:

$$\tau = \frac{R_t(LAI) + R_0(LAI)}{R(0)} = e^{-k \cdot LAI} \qquad (-) \qquad (4)$$

$$\text{with: } k = (1 - t) k_o \qquad (-) \qquad (5)$$

Eq. (4) was used also by GOUDRIAAN (1977) with k depending as well on the reflectivity of leaves r:

$$k = \left[(1 - t)^2 - r^2\right]^{0.5} \cdot k_o \qquad (-) \qquad (6)$$

Transmittance t for 'mean' green leaves was given by ROSS (1975) to be 0.20 in the whole shortwave band, being 0.06 in the visible and 0.34 in the NIR. Corresponding values of r are 0.30, 0.09 and 0.51 respectively. Eqs (5) and (6) are only slightly different for the above values.

MONTEITH (1975) produced a review of empirical values of k for real canopies, ranging from k = 1.10 for species with mainly horizontal leaves like clover (*Trifolium repens*) to 0.20 for species with mainly vertical leaves (*Gladiolus*).

2.3. Reflected radiation

In most cases the reflectance of a plant stand is smaller than that of the leaves composing it. In fact the mutual shading of leaves and the multiple scattering within the stand lead to a sort of 'cavity' effect, which produces an additional absorption of radiation. The reflectance of a stand is also influenced by the reflectance of the underlying ground, insofar soil cover is not complete.

Analytical formulae to calculate the reflectance as a function of depth in the stand are very complicated. ROSS (1975) suggested an approximation for the reflectance of a stand for direct radiation ρ_b:

$$\rho_b = \frac{S_u}{S_{b,d}} = \rho_{b,\infty} + (\rho_s - \rho_{b,\infty}) \cdot e^{-(1 + k_o) \cdot LAI_x} \qquad (-) \qquad (7)$$

where:

$\rho_{b,\infty}$ = reflectance of a dense stand for beam radiation

ρ_s = reflectance of the soil.

He did not discuss, however, whether a similar formula could be applied to reflection of diffuse radiation. In the same paper, approximations for the reflectance of a dense stand for both direct and diffuse radiation $\rho_{b,\infty}$ and $\rho_{c,\infty}$ are suggested, as functions of the scattering coefficient of the leaves,

$$s = r + t \qquad (-) \qquad (8)$$

namely

$$\rho_{b,\infty} = \left(\frac{s}{1 + \sqrt{1 - s}}\right) \left(\frac{1}{1 + k_o \cdot \sqrt{1 - s}}\right) \qquad (-) \qquad (9)$$

$$\rho_{c,\infty} = \frac{1 - \sqrt{1 - s}}{1 - s} \left(\sqrt{1 - s} - \tfrac{1}{2} \ln(1 + 2\sqrt{1 - s})\right) \qquad (-) \qquad (10)$$

It will be noted that in this way $\rho_{b,\infty}$ also depends on the canopy architecture (it is a function of k_o) while $\rho_{c,\infty}$ depends only on the optical properties of the leaves. This enables the reflectance for diffuse radiation of a dense stand of 'mean' green leaves (Section 2) in the shortwave band to be calculated.

$$\rho_{c,\infty} = 0.156 \qquad (-) \tag{11}$$

while

$$\rho_{b,\infty} = \frac{0.293}{1 + 0.707\, k_o} \qquad (-) \tag{12}$$

2.4. Transfer of radiation in a stand and its relationship to measured net radiation

It is commonly stated that radiation absorbed by a dense stand enclosed by two horizontal planes at a height 0 and z respectively, is the difference between measured net radiation at the two levels, z and 0. It should be noted, however, that this is true only if:

- longwave radiation fluxes from above and below the stand are both isotropic;
- leaf temperature does not change with depth in the stand and in the horizontal layers (as it may, for example, with a deficient water supply).

Under these assumptions, downward and upward longwave radiation fluxes through a horizontal plane at a depth x in the canopy can be expressed, respectively:

$$L_d(LAI_x) = \left[1 - \tau_0(LAI_x)\right] \cdot L_l + \tau_0(LAI_x) \cdot L_d(0) \qquad (W.m^{-2}) \tag{13}$$

$$L_u(LAI_x) = \left[1 - \tau_0(LAI-LAI_x)\right] \cdot L_l + \tau_0(LAI-LAI_x) \cdot L_s \qquad (W.m^{-2}) \tag{14}$$

where L_l is the longwave radiation emitted by the leaves, according to the Stefan-Boltzmann formula; $L_d(0)$ is the longwave flux from the atmosphere and L_s is the longwave flux from the soil surface.
After substitution of eqs. (13) and (14) the sum of eqs. (1) and (2) can be written for the top and bottom of the canopy. The difference $R_{top} - R_{bottom}$ is, therefore, the radiation absorbed in the stand:

$$R_a = (1 - \tau - \rho) \cdot S + (1 - \tau_0) \cdot L_d(0) - 2 \cdot (1 - \tau_0) \cdot L_l + (1 - \tau_0) \cdot L_s \qquad (W.m^{-2}) \tag{15}$$

According to the assumptions made, net radiation exchanged at height z must be what a net radiometer, placed anywhere on a horizontal plane at that height, would measure:

$$R_n = (1 - \rho)\cdot S + L_d(0) - (1 - \tau_0)\cdot L_l - \tau_0 \cdot L_s \qquad (W.m^{-2}) \qquad (16)$$

Resolving for $L_d(0)$, which is generally unknown and substituting in (15), we get:

$$R_a = (1 - \tau_0)\cdot R_n + \{(1 - \rho)\cdot\tau_0 - \tau\}\cdot S + (1 - \tau_0^2)\cdot(L_s - L_l) \qquad (W.m^{-2}) \qquad (17)$$

Thus, if the radiative properties τ_0, τ and ρ of the stand are known and the fluxes L_s and L_l can be measured or estimated, radiation absorbed by a stand can be easily related to shortwave and net radiation measured above it.

2.5. Application to a row crop

In a row crop only a fraction of the incoming radiation is intercepted by the foliage while the rest can travel unmodified the whole dept of the stand. If it is assumed that no net horizontal exchange of radiation between the crop rows takes place, the transfer of radiation can be described by splitting the problem into two parts. Transfer of radiation within a crop row will be treated as transfer of radiation in a dense stand, and transfer of radiation above the paths will be neglected as not affecting the canopy. Thus radiation absorbed by the canopy is simply

$$R_{a,r} = A \cdot R_a \qquad (18)$$

where A is the fraction of ground area occupied by a row, i.e. the width of a row divided by the total width of a row plus a path. R_a is given by eq. (17) on the understanding that the net radiometer is above a row, i.e. measuring vertical radiative exchanges only between a crop row and the upper hemisphere. It must be stressed that this is a rough assumption since, as GOUDRIAAN (1977) showed, radiation intercepted by the side parts of a row is not negligible. A possible improvement would be to make A an effective area fraction, larger than the fraction corresponding to the actual width of a row.

3. MATERIALS AND METHODS

An experiment was set up in one of the greenhouses of IMAG to study the energy balance of a greenhouse crop. The experiment was the result of collaboration between IMAG and the Department of Physics and Meteorology of the Agricultural University in Wageningen.

3.1. Experimental set-up

The greenhouse is a single-glass, Venlo-type, eight span, E-W oriented one. Heating is provided by hot water circulated in pipes (two pipes, a few centimetres above ground, for each crop row, and one at gutter level for each span); natural ventilation takes place through roof ventilators. Measurements were carried out, in two successive years, with tomato crops (cv-Sonatine and cv-Marathon) grown on rockwool mats 0.3 m wide, 1.6 m apart. Plants were trained in a V-shape, i.e. every other plant was tied to a wire stretched at 2 m height, 0.5 m to one side of the rockwool mat, while the other plants were tied on the other side. Both soil and rockwool were covered with white plastic sheets, so that no evaporation could take place. Accordingly, when reference is made to measured values, only transpiration is considered. In the second year a transparent-lamellae screen was set up in the house. A complete description of the experiment is given in STANGHELLINI (1981) and in VAN 'T OOSTER (1983). Here reference will be made only to the instrumental set up relevant for the present subject.

Incoming shortwave radiation was measured above the house, directly below the roof (above the screen), at two points above a crop row and one below it. Reflected shortwave radiation was measured by a solarimeter placed in reverse just above a crop row (below one of the two solarimeters placed there). Net radiation was measured by sensors placed above, below and within another crop row. Temperature and humidity of the air were measured by Assmann aspirated psychrometers, outside, below the roof, above the canopy, at 1 m height and a few centimetre above the ground. Temperature of the foliage was measured by a Heiman infrared thermometer pointing midway up in a crop row. Heat flux into the ground was measured with two heat flux plates at 0.05 m depth below a rockwool mat and in the middle of a path, respectively.

Most of the measuring devices were near the centre of the greenhouse, where transpiration was also measured. For this purpose a weighing lysimeter developed by the Technical University of Twente (NL) was installed. That lysimeter has a maximum acceptable load of 100 kg and can measure weights with an accuracy of $\pm$ 0.1 g in a laboratory environment. In the greenhouse set up actual accuracy did not exceed 0.3 g, due to some influence of air movement (STANGHELLINI, 1983b). It was working on the vent-out principle, in order to avoid temperature-related problems, as encountered in many previous experiments in greenhouses.

The lysimeter was placed in a pit dug in the ground, carrying a portion of a

crop row, that was thus in line and at the same height with the rest of the row. A complete description of the lysimeter and its set up has been given by BOT *et al.* (1983) and DORMANS (1983).
The output provided by all the instruments was scanned by a data-logger at intervals of 1, 3 or 10 min and stored on disc for further processing. Between the lysimeter and the data logger, a micro-computer was installed which apart from high frequency (>0.2 Hz) filtering of the lysimeter's direct output signal, checked for cummulative transpiration in order to replenish automatically the water consumed (REINDERS, 1982).
Energy output from the heating pipes was calculated as a function of their surface temperature, according to the method described in STANGHELLINI (1983a). Leaf area could be estimated from the mean length of leaves with the procedure developed by VAN DER VARST and POSTEL (1972). LAI was calculated relating the estimated leaf area to the corresponding ground area with a plant density of 2 per m^2.

3.2. Evaluation of transmissivity and reflectivity of a crop row

Ratios of transmitted to incoming shortwave radiation above the canopy were calculated for daily totals of bright days, with various LAI.
The best fit of eq. (4) to the data gave:

$$\tau = \frac{S(LAI)}{S(0)} = e^{-0.75 LAI} \quad (19)$$

Eqs (5) or (6) can be used to derive the extinction coefficient for longwave radiation k_o from $k = 0.75$, provided that both the transmittance and the reflectance of a leaf are measured. Unfortunately, this was possible only in the visible range. It was found that $t = 0.06$ and $r = 0.09$ (v.d. KIEBOOM, 1983). Since these values correspond exactly to the values for a 'mean' green leaf (Section 2.2), it was decided to adopt r and t values for the whole shortwave range, as given in Section 2.2. This yields for the extinction coefficient of radiation in a canopy of black leaves $k_o = 0.94$ (eq. 5) or $k_o = 1.01$ (eq. 6). Both values point to a canopy of (almost) horizontal leaves, as Fig. 1 confirms. The former value was chosen, because it seems more realistic (leaves are not exactly horizontal).
The same procedure was followed for estimating the parameters of the reflection function. Since the soil was covered with white plastic, it could be assumed that reflectance of the soil was much greater than that of a dense stand. Under this condition, eq. (7) can be simplified to:

Fig. 1 Some tomato plants in the greenhouse set up described in Section 3.1, showing an almost horizontal leaf angle distribution

$$\rho \approx \rho_s \, e^{-(1 + k_o)LAI} \tag{20}$$

The best fit gave for the parameters:

$$\rho = 0.45 \cdot e^{-0.68LAI} \tag{21}$$

The value of 0.45 for ρ_s is in good agreement with the reflectivity of the plastic foil (0.55), measured after some use (v.d. KIEBOOM, 1983). The slight underestimate can be explained easily, since not all the ground was white: portions of the rockwool mats were uncovered and the heating pipes were, of course, above the foil. On the other hands the value of 0.68 for the extinction coefficient does not agree well with the value predicted by eq. (20). It should be born in mind, however, that eq. (20) is a rather rough simplification of (7), which was originally derived for direct radiation. According to this reasoning, the value derived with the best-fit procedure in the present study, was adopted without further investigation.

3.3. Estimate of the effective width of a crop row

It follows from the way the crop was trained that the width of crop row was increasing with crop growth, until the top of the plants had reached the training wire. It was observed that with a LAI of 0.5 most of the crop was contained in a strip about 0.5 m wide, while when LAI was 1.6, the top of the plants had reached the training wire, with a row width of 1 m. If these values are divided by 1.6 m, the total width of a crop row and a path, a regression analysis gives:

$$A = 0.83 \cdot (1 - e^{-0.87LAI}) \tag{22}$$

Thus, the area fraction corresponding to a row of fully developed crop (LAI ≃ 2.3) is A = 0.72.

3.4. Inclusion of radiation from the heating pipes

In a greenhouse environment, there is the additional peculiarity that there is a radiation source, namely the heating elements, somewhere within the canopy. In the present set up, there were two pipes in the middle of each path, just above the ground. It is clear that in such a case the requirement of isotropy of the upward radiation flux for the validity of eq. (14) is not fulfilled.

However, since only part of the pipe radiation is intercepted directly by the foliage, the rest (major part) being either transmitted by it or absorbed and re-radiated by the ground, it was decided *as a first approximation* to introduce pipe radiation, calculated from pipe temperature according to the Stephan Boltzmann law, in the formulation as a uniform vertical flux entering a horizontal plane below the foliage. Accordingly, radiation exchanged between the pipes and the foliage was multiplied by the ratio of pipe area to ground area (0.225) and inserted in eq. (17) in lieu of the difference of longwave fluxes from the soil surface and the leaves. It would be more correct to substract from it the heat flux into the ground, since the latter is a fraction of pipe radiation which is not re-radiated, but since the measured ground flux was always small compared to the other fluxes, it was thought that its inclusion in the procedure would not improve its accuracy, given the many - sometimes rough - approximations that had been necessary.

Following the above reasoning, absorbed radiation can be written as a function of the net radiation measured above a crop row (eqs. 17 and 18):

$$R_a = A\left[(1-\tau_0)\cdot R_n + \{(1-\rho)\cdot\tau_0 - \tau\}\cdot S + 0.225(1-\tau_0^2)\cdot(L_p - L_l)\right] \quad (W.m^{-2}) \quad (23)$$

where L_p is the longwave radiation emitted by the heating pipes (Stefan Boltzmann law). A is given by (22), τ by (19), τ_0 by (19) after substitution of 0.94 for 0.75 and ρ by (21).

4. RESULTS

In principle, the only way to check such an equation would be to see whether it would verify the energy balance of the foliage.

As stated in the introduction:

$$R_a = \lambda E + H + G \quad (24)$$

i.e. the energy available for evapotranspiration (λE), sensible heat exchange with the air (H, positive when released by the plant) and storage of heat in the system (G), must be equal to the energy gained (or lost) from radiative exchanges.

Now, R_a is by no means the only term in (24) not known exactly, so that any estimate of it by use of the energy balance depends on the extent to which each term of the right hand side of (24) is known.

Even if it is assumed that evapotranspiration was known with sufficient

Table II. Values of the radiation absorbed by the canopy R_a as predicted by eq. (23) and as obtained from the energy balance eq. (24) for various growth stages of the crop.

Values given refer to time averages over 3 - 10 min values for experimental runs, each 24 h long, beginning at some time during the day mentioned in the first column.

The values for the relevant energy fluxes are also given for reference. For the approximations involved in calculating the flux for the 1981 runs see the text

Date	LAI	R_n	S	LE	R_a (eq. 23)	R_a (eq. 24)
31 Jan. '81	0.61	-28.2	9.4	3.2	0.6	-
5 Mar. '81	0.79	- 5.0	34.6	18.1	4.6	-
20 Feb. '81	0.97	- 0.3	80.9	15.4	6.8	-
14 Mar. '81	1.09	15.1	49.6	19.0	8.9	-
8 Mar. '82	1.32	35.5	43.0	25.5	22.7	24.2
18 Mar. '82	1.85	45.7	56.6	43.9	35.7	40.7
28 May '82	1.95	143.4	167.1	77.1	77.2	78.4
23 Mar. '82	2.04	41.4	48.8	32.0	37.3	29.9
25 Mar. '82	2.16	90.9	102.7	64.1	60.5	63.7
13 May '82	2.26	212.8	224.9	125.4	128.5	127.0

accuracy in the present experiment, and measurements of the temperature of the foliage were representative, sensible heat gained (or lost) from the surrounding air is known insofar as the transfer coefficients are known, i.e. within broad limits. This point clearly needs further investigation but, given the generally small difference in measured leaf and air temperatures, it was decided that, for the present purpose, the value proposed by MONTEITH (1975) for the heat transfer coefficient of flat plates, could be used. Once the fact that heat transfer takes place on a surface 2·LAI times the ground area has been observed, and the appropriate values for the constants inserted, we get:

$$H = 2\cdot LAI \cdot 11.57\left(\frac{|T_l - T_f|}{T_f}\right)^{1/3} \cdot (T_l - T_f) \qquad (W\cdot m^{-2}) \qquad (25)$$

where T_l and T_f are the temperatures of the leaves and the air, respectively, in K.

On the other hand, the amount of energy stored as heat in the system depends on the variations in temperature of its various parts, and on the latter's thermal capacity. An example will clarify this point: the total weight of a plant during the growing season, could range from 0.5 tot 6 kg: if all plants are assumed to have the thermal capacity of water, the estimated thermal capacity corresponding to 1 m^2 of greenhouse area (2 plants per m^2) is $0.4\cdot 10^4$ to $5.0\cdot 10^4$ $J\cdot K^{-1}\cdot m^{-2}$. A variation of plant temperature as small as $1^oC\cdot h^{-1}$ would result in a storage term of 1.1 to 14.0 $W\cdot m^{-2}$. It can be inferred that fluctuations of temperature of the fruits and stems were smaller than the ones observed in foliage temperature, resulting in a storage term proportionally smaller. Thus, not only variations in temperature of the various parts of the canopy (including stems and fruits), but also the thermal capacity corresponding to each should be known for an accurate estimate of the storage term.

According to this interpretation (23) could be tested only using the means of measured values over long time intervals, for which the storage term could be neglected.

Thus, eq. (24) was calculated with H given by (25) and G = 0, using means of measured values for 24 h intervals. The results are shown, for various LAI and climatic conditions in Table 11, where R_a as calculated by (23) is compared with the value resulting from (24), with the simplification explained above. For completeness some values for small LAI's, coming from the 1981 experiment, are also shown, for which measurements of plant temperature were not available. In such circumstances, eq. (24) could not be calculated. while

in eq. (23) pipe radiation was referred to air temperature, assuming that the difference of the latter with plant temperature was small.
Accordingly, values in Table II referring to the 1981 experiment have been given just as an indication of the magnitude of the relevant energy fluxes. On the other hands, values as given in Table II for the 1982 experiment show that eq. (23) is a good estimate of the radiation absorbed by a tomato crop grown as explained.

5. DISCUSSION

The importance of storage on a short-term balance is shown by Fig. 2, where values of R_a according to eqs (23) and (24), when G = 0, are plotted for a spring day with scattered cloudiness. While the pattern and amplitude of variations in both functions are the same, the phase shift between them should be noted. It should be interpreted as a delay between supply of energy [R_a eq. (23)] and its dissipation [R_a eq. (24)] due to the storage of energy in the system, as discussed by STANGHELLINI (1983b). In Fig. 2 the difference between the two functions, i.e. the storage, is also shown. It appears quite clearly that the latter is roughly positive in the morning hours, when the canopy is warming up, and negative in the afternoon, when the energy needed for transpiration has to be supplied, at least partially, by the cooling of the canopy. The flux of energy stored (or released) in such a system is related to variations in its temperature as follows:

$$G = C \cdot \frac{dT_l}{dt} \qquad (W \cdot m^{-2}) \qquad (26)$$

where C is the thermal capacity corresponding to 1 m^2 ground area (Section 4) and $\frac{dT_l}{dt}$ is the time derivative of the temperature of the canopy. It was realized here that the phase shift, as observed in Fig. 2, together with the amplitude of fluctuations in the storage, increased for increasing LAI, thus suggesting an increase in C. Then, the parameters a and b of the linear equation

$$G = a \frac{dT_l}{dt} + b \qquad (W \cdot m^{-2}) \qquad (27)$$

were derived by best-fit of the storage determined as the difference between eq. (23) and (24), against the time derivative of measured plant temperature, for daytime runs with three different LAI's. Results are shown in Table III. Two features deserve attention in Table III: the almost zero intercept b

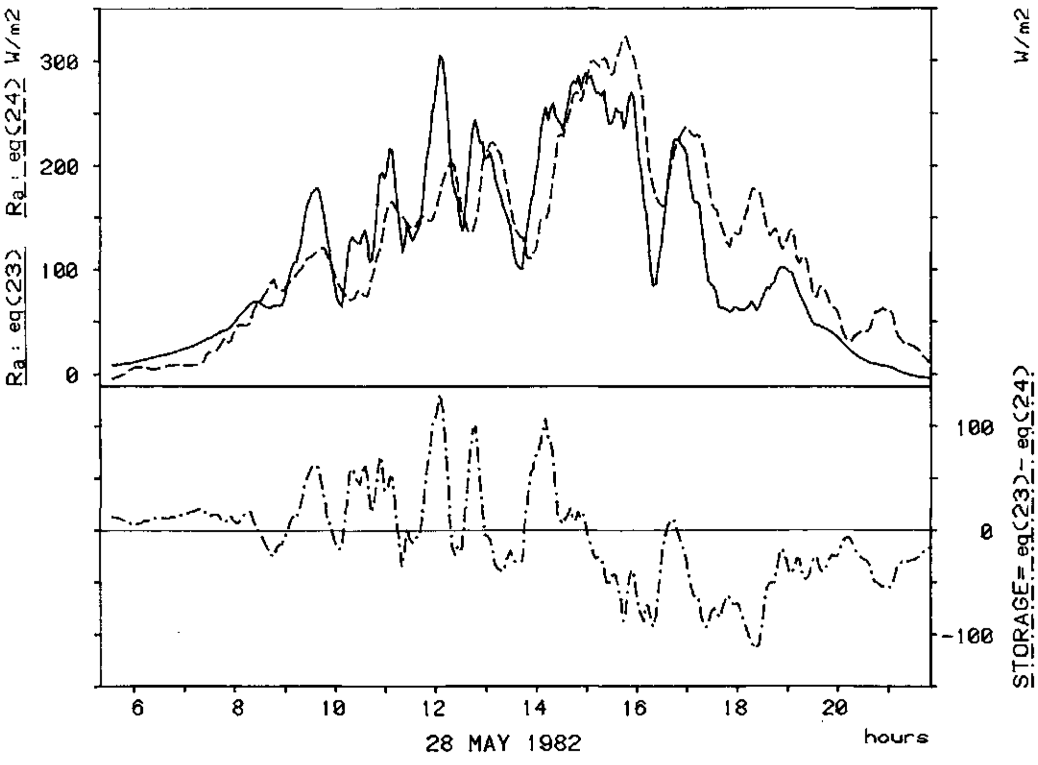

Fig. 2 Radiation absorbed by the canopy during a spring day, with scattered cloudiness, as calculated by eqs (23) and (24) with G = 0, respectively The difference between the two estimates (interpreted as the storage of heat, see text) is shown at the bottom. Line types used are shown below the corresponding names which appear alongside the scale to which they have to be referred

The zeropoint of the right scale has been shifted to improve readibility, but note that the amplitude is the same. Data shown are 9-values progressive means of measured and computed data at 3-min intervals

Table III. Parameters a and b of eq. (27) as obtained by best-fit of the difference of eq. (23) minus eq. (24) against the time derivative of measured foliage temperature
In col. 5 the weight of water corresponding to the thermal capacity given in col. 3 is given, on the understanding that there were two plants per m^2. In col. 6 is an estimate of the average weight of a plant plus substrate derived, for the same day, from the total weight needed to keep the lysimeter balanced. Note that the saturated rockwool substrate for one plant weighed about 6 kg, but no check of the actual water content of the substrate was made for a given experimental run

Day	LAI	a ($J \cdot m^{-2} \cdot K^{-1}$)	b ($W \cdot m^{-2}$)	Kg per plant	Total weight
9 Mar. '82	1.32	$0.605 \cdot 10^4$	+ 1.501	0.7	6.8
28 May '82	1.95	$2.267 \cdot 10^4$	- 5.124	2.7	8.0
13 May '82	2.26	$3.030 \cdot 10^4$	- 4.885	3.6	9.2

(col. 4), is a reassuring feature, when compared with the magnitude of the fluxes (Table II and Fig. 2). On the other hand, the estimated weight of a plant as given in col. 5 appears to be in fairly good agreement with the weight given in col. 6, when the inaccuracy in the weight of the substrate is kept in mind.

To be sure, apart from the many inaccuracies of the theory already pointed out, some inaccuracy is inherent to all the measurements.

An optimistic estimate of the accuracy of an infrared thermometer would be $\pm$ 0.1°C, which would double when the temperature derivative is considered. Moreover, a normal value for the accuracy of a radiation meter is 5%.

Eq. (23), therefore, cannot achieve an accuracy better then 5%. The same reasoning applies to eq. (24) for transpiration measurements as well as for estimates of sensible heat transfer, as discussed above.

A rough assessment of the accuracy eq. (23) can be made by comparing in Table II the results obtained by means of this equation with the values given in the last column. Accordingly, it is found that the relative deviation is 7%.

6. CONCLUSION

It has been discussed how radiative exchanges of a tomato crop in a greenhouse can be estimated introducing some corrections in the theoretical formulations for a dense field crop. It has been shown that the parameters of the theoretical extinction and reflection functions can be easily calculated from simple solarimeter measurements at various growth stages of the crop. In this way radiation absorbed by such a greenhouse crop can be successfully related to net radiation and shortwave radiation measured at the top of the crop, when radiation produced by the heating system is accounted for. The common shortcomiming of the unpresentativeness of radiation measurements below the crop (due to the strong anisotropy of both the transmitted flux and the longwave flux emitted by the heating system) is thus avoided. It is further described how to estimate a simple correction for a 'row area' to which radiative exchanges have to be related.

The radiation calculated in this way as absorbed by the canopy has been shown to verify the energy balance over time intervals long enough for the heat storage in the system to be neglected. The importance of the latter in the short term energy balance of the canopy has been shown and discussed. It can be concluded that the method here described gives satisfactory results, when its accuracy is compared with that with which all the other relevant energy fluxes are known.

ACKNOWLEDGEMENTS

I wish to acknowledge gratefully the financial grant from the Dutch Ministry of Agriculture and Fisheries that allowed me to take part in this project. The study was conducted in collaboration with the Department of Physics and Meteorology of the Agricultural University and I am deeply indebted to Ir. G.P.A. Bot of that Department for his help. I am thankful to Ir. W.P. Mulder, Head of the Climate Control Department of IMAG, for his stimulating support. Much of the experimental work was done by F. Dormans, A. van 't Ooster and J. Reinders, students of the Agricultural University, to whom I am grateful for the pleasant collaboration. Ing. A.M.G. v.d. Kieboom kindly measured the radiative properties of all the samples submitted by me. My husband Dr. M. Menenti offered his help and advice in many circumstances throughout the whole study and devoted some evenings to revising the present paper. Discussion with many collegues was always fruitful for me, and I would like to thank here explicitly Ir. D. Bokhorst and Dipl.Phys. J.A. Stoffers for the time devoted to me. F.J.M. Corver and the horticultural staff of IMAG kept the crop alive and healthy, notwithstanding the experiment.

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