Effects of cover properties, ventilation rate, and crop leaf area on tropical greenhouse climate

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Experimental results and validation of a simple greenhouse climate model are analysed according to data sets from six prototype greenhouses with three different plastics (reference N0, and two levels of near-infrared reflecting pigments N1 and N2); two ratios of ventilation openings to greenhouse covering area (0.223 and 0.427); a wide range of tomato leaf area index (0.01–4.97); and for three crop-growing periods that represent year-long tropical lowland climatic conditions in Purwakarta (107°30′E, 6°30′S, altitude 25 m), Indonesia. The model with a calibration factor for indirect absorbed solar radiation (indicating the part of the radiation absorbed by the greenhouse cover, structural elements, and soil surface released into the air) Λ of 0.1 satisfactorily calculated greenhouse air temperature T_{Air} with less than 2% error and greenhouse air water vapour pressure deficits D_{Air} with less than 10% error. The errors were higher at low values for the leaf area index. The model performance slightly improved by including the effect of leaf area index on Λ as an exponential term. Measurements and calculations demonstrated that T_{Air} was affected more by variations of ventilation and leaf area index than by the applied cover properties. The leaf area index had the highest impact on greenhouse air temperature, implying that a large proportion of the cooling is achieved by the crop itself. The results enable the model to be used in the design of optimum greenhouse systems for tropical lowland Indonesia.

Nomenclature

C
: coefficient

D
: water vapour pressure deficit, Pa

E
: transpiration, kg m^{-2} s^{-1}

e
actual air water vapour pressure, Pa

G
heat conductance, W m^{-2} Pa^{-1} (for the latent) or W m^{-2} K^{-1} (for others)

I
transmitted radiation, W m^{-2}

k
conductance of heat or mass, m s^{-1}

L
leaf area index, m^2 m^{-2}

P
absorbed solar radiation, W m^{-2}

r
resistance for heat transfer, s m^{-1}

S
outdoor global radiation, W m^{-2}

T
temperature, K

U
external wind speed, m s^{-1}

Λ
calibration factor for indirect absorbed solar radiation

α
absorption coefficient

λ
latent heat of water vaporisation, J kg^{-1}

τ
transmission coefficient

Υ
reflection coefficient

Subscripts

Air
greenhouse air

Can
canopy

CON
convection

Cov
greenhouse cover

d
discharge

e

boundary layer (external)

G
global

i
big leaf (internal)

LAT
latent

Out
outdoor

PAR
photosynthetically active radiation

Soi
soil surface

Sky
sky

Str
greenhouse structural elements

LWR
long-wave radiation

VEN
ventilation

w
wind pressure

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1. Introduction

Tropical lowland climates are characterised by high global radiation, air temperature, air humidity, and sometimes high wind speed and high rainfall. In these regions, open field cultivation has to be adapted to the short crop-growing season that has a suitable climate. High pressure of pests and diseases and unmanageable harsh outdoor climate lead to large production losses.

A greenhouse protects crops against wind, precipitation, weeds, pests, diseases, and animals and enables the grower to control the crop environment. The covering material creates distinct micro-climatic conditions within the greenhouse compared to outside: a decrease of radiation and air velocity, an increase of air temperature and air water vapour pressure, and a greater fluctuation of carbon dioxide concentration (Bakker & Challa, 1995).

The increase of air temperature inside the greenhouse above the prevailing high outdoor air temperature in the tropical lowlands will stress the greenhouse crop. Lowering the air temperature is a major concern for tropical greenhouse climate management. This can be realised by: (1) reducing radiative heat load; (2) removing excess heat through air exchange; and (3) increasing the fraction of energy partitioned into latent heat (Luo et al., 2005).

The first can be achieved by the application of cladding materials containing near-infrared radiation (NIR) reflecting pigments (Hoffmann & Waaijenberg, 2002; [Hemming et al., 2006a] and [Hemming et al., 2006b]), which reduce the solar heat load but admit sufficient photosynthetically active radiation (PAR) (Hare et al., 1984). An ideal covering material for tropical lowland regions would prevent all NIR coming into the greenhouse, which would correspond with a reduction of solar radiation heat load by nearly 50% (Sonneveld et al., 2006). Simulation studies revealed that under average summer conditions in the Netherlands, the application of NIR reflecting greenhouse cover was able to reduce the mean temperature of the greenhouse air by 1 °C, while greater differences occurred at the maximum temperature of the greenhouse air (Hemming et al., 2006a). Conventionally, whitewashing is used to reduce irradiation but this also reduces PAR significantly (Kittas et al., 1999; Baille et al., 2001).

The second can be achieved passively by promoting high natural ventilation in a tropical greenhouse. Maximal rate is achieved with combined sidewall and roof openings (Montero et al., 2001). The ratio of the opening area to greenhouse floor area is suggested to be at a minimum of 60% for a 10 m by 20 m tropical greenhouse in Bangkok (Harmanto et al., 2006).

The third relates to cooling by crop transpiration. This is illustrated by measurements in Bangkok where the outdoor air temperature often exceeds 30 °C. With young tomato (low leaf area index), the maximum temperature difference between greenhouse air and outdoor air reached 5 °C but with a high leaf area index this temperature difference was decreased by 2 °C (Ajwang & Tantau, 2005).

Important parameters for designing the tropical lowland greenhouse are solar radiation, natural ventilation, and crop transpiration. As a first approach to the design of the basic geometry including ventilation openings, computational fluid dynamics (CFD) was applied with reference to the local static climate conditions (Campen, 2005).

For the study of the response to the dynamic outdoor climate, a simple greenhouse climate model was developed and validated under extensive outdoor tropical lowland climate conditions of Indonesia (Impron et al., 2007). This validation was limited to the standard greenhouse with a reference plastic cover and one ventilation opening during a single crop-growing season in the rainy season of 2003/2004. As the model is intended to evaluate the dynamic greenhouse climate in connection to crop production, validation under a wider range of conditions is necessary. In this regard, it is important to establish the accuracy and reliability of the model under varying cover properties, ventilation openings, and seasonal climate conditions to justify model applicability.

The data collected represent greenhouse climate under three cover properties, two levels of ventilation openings, three crop-growing seasons, and a year-long climate. The objective of this study is to analyse the dynamic response of greenhouse climate to these varying conditions. The study also includes validation of the simple greenhouse climate model (Impron et al., 2007) with these extensive data sets. This justifies the application of the model for evaluation of greenhouse climate and crop production in optimal designed greenhouse systems for the tropical lowland of Indonesia.

2. The model

The greenhouse climate model (Impron et al., 2007) was developed on the basis of energy and water vapour balances incorporating five assumptions: (i) only greenhouse air and crop are considered, both being well-mixed compartments (Roy et al., 2002); (ii) boundary conditions and energy inputs are given by the outdoor climate measurements; (iii) solar radiation confers fluxes to the greenhouse cover, the greenhouse structural elements, and the soil surface; (iv) absorbed solar radiation fluxes are released as sensible heat (with some delay) to the greenhouse air; and (v) crop transpiration is calculated according to the Penman–Monteith model. The modelled greenhouse cover is a thin plastic layer with known optical properties defined in the relevant spectral regions.

The model employed three underlying sub-models for radiation distribution, ventilation and transpiration, and enabled calculation of three state variables: average greenhouse air temperature T_{Air} in K, average greenhouse air water vapour pressure (expressed as air water vapour pressure deficit D_{Air} in Pa), and average canopy temperature T_{Can} in K, according to the following equations (Impron et al., 2007):

(1a)

$$0=P_{Can}-G_{Can\text{-}Sky,LWR}(T_{Can}-T_{Sky})-G_{Can\text{-}Air,CON}\times(T_{Can}-T_{Air})-\lambda E_{Can\text{-}Air},$$

(1b)

$$0=P_{Air}+G_{Can\text{-}Air,CON}(T_{Can}-T_{Air})-G_{Air\text{-}Out,CON}\times(T_{Air}-T_{Out})-GA_{ir\text{-}Out,VEN}(T_{Air}-T_{Out}),$$

(1c)

$$0=G_{Air\text{-}Out,LAT}(e_{Air}-e_{Out})-\lambda E_{Can\text{-}Air},$$

where P_{Can} is the solar radiation absorbed by the canopy in W m^{-2} (expressed per unit ground area of the house, as are all terms in these equations); P_{Air} is the imposed indirect solar radiation flux to the greenhouse air (solar radiation absorbed by greenhouse opaque elements and released into the greenhouse air) in W m^{-2}; $G_{Can\text{-}Sky,LWR}$ is the heat conductance (transfer coefficient) between the canopy and sky by long-wave radiation in W m^{-2} K^{-1}; $G_{Can\text{-}Air,CON}$ is the heat conductance between crop and greenhouse air by convection in W m^{-2} K^{-1}; $G_{Air\text{-}Out,CON}$ is the overall sensible heat conductance between the greenhouse and outdoor air via the plastic cover by convection in W m^{-2} K^{-1}; $G_{Air\text{-}Out,VEN}$ is the sensible heat conductance between greenhouse and outdoor air by ventilation in W m^{-2} K^{-1}; $G_{Air\text{-}Out,LAT}$ is the latent heat conductance by ventilation in W m^{-2} Pa^{-1}; $\lambda E_{Can\text{-}Air}$ is the latent heat flux by canopy transpiration in W m^{-2}; T_{Sky} is the temperature of the sky (Aubinet, 1994) in K; T_{Out} is the temperature of the outdoor air in K; and e_{Air} and e_{Out} are the actual greenhouse air and outdoor water vapour pressure, both in Pa.

The value of P_{Can} was calculated according to Goudriaan and Van Laar (1994). The value of P_{Air} was derived according to Impron et al. (2007) as

(2)

$$P_{Air}=\Lambda(P_{Cov}+P_{Str}+P_{Soi}),$$

where Λ is the calibration factor for indirect absorbed solar radiation indicating the part of the radiation absorbed by the greenhouse cover (P_{Cov}), structural elements (P_{Str}), and soil surface (P_{Soi}) released into the air. All radiation terms are in W m^{-2}.

Previous validation of the model for the reference greenhouse showed that a value of 0.1 for Λ fitted best for the data set with a leaf area index from 0.02 to 4.1, resulting in a satisfactory agreement between measurements and calculations of T_{Air} and D_{Air} with less than 5% errors (Impron et al., 2007). Other model parameters were established from the literature in the earlier study: $G_{Can\text{-}Sky,LWR}$ and $G_{Can\text{-}Air,CON}$ (De Zwart, 1996); $G_{Air\text{-}Out,VEN}$ and $G_{Air\text{-}Out,LAT}$ (Impron et al., 2007); and G_{AirOut_CON} (Boulard & Baille, 1993; Boulard & Wang, 2000). The $\lambda E_{Can\text{-}Air}$ was calculated according to the Penman–Monteith model with the boundary layer (external) conductance k_e (Stanghellini, 1987) and the big leaf (internal) conductance k_i (Nederhoff, 1994), both in m s^{-1}.

A complete description of the model, including the estimation of all model parameters is given in Impron et al. (2007).

3. Experimental details

3.1. Greenhouses

Six greenhouses having similar dimensions (Fig. 1) were built in Purwakarta (107°30′E, 6°30′S, altitude 25 m), West Java, Indonesia. The east–west-oriented greenhouses were arranged in two rows of three greenhouses with separation distances within the rows of 9.6 m and 10 m between the rows. Gutter height was 4 m, average height 5.72 m, and the arch-shaped roof had an average roof angle of 27.5°. Each greenhouse volume was 823 m^3 and the covering (sidewalls and roof top) surface area was 386 m^2.

 Full-size image (26K)

Fig. 1. Photograph of the six greenhouses in the field.

3.2. Cover optical properties

Each greenhouse was covered with a 200 μm thick, low-density, ultraviolet-absorbing and -diffusing poly-ethylene film. Three plastic film types were used differing in their NIR reflection properties: the control plastic film without NIR reflection (N0) and two newly developed plastic films with different concentrations of NIR-reflecting pigments (N1 and N2, respectively). The radiometric properties of the films are summarised in Table 1. Indeed, the addition of pigments to the plastics reduced radiation transmission especially in the NIR spectrum. Calculated perpendicular transmission over the whole spectrum according to the Global Spectral Irradiance ASTM G173-03 (2003) for N0 is 12% and 17% higher than that for N1 and N2, respectively.

Table 1.

Transmission τ absorption α, and reflection ϒcoefficients ASTM G173–03 weighted; and thermal transmission coefficient $\tau_{cov,LWR}$, Max Plank weighted for the control plastic film without near-infrared radiation-reflecting pigment (N0) and two newly developed plastic films with different concentrations of near-infrared radiation-reflecting pigments (N1 and N2, respectively)

Film type	**Diffuse**				**Direct ⊥**		
	UVR	**PAR**	**NIR**		**UVR**	**PAR**	**NIR**
N0	0.136	**0.765**	0.758		**0.159**	**0.896**	**0.888**

Film type	Diffuse				Direct ⊥		
	UVR	**PAR**	**NIR**		**UVR**	**PAR**	**NIR**
τ							
α	0.681	**0.052**	0.052		0.658	0.052	0.052
ϒ	0.183	**0.183**	0.190		0.183	0.052	0.060
$\tau_{cov,LWR}$				**0.3845**			
N1							
τ	0.110	**0.733**	0.628		**0.129**	**0.805**	**0.736**
α	0.678	**0.055**	0.055		0.659	0.055	0.055
ϒ	0.212	**0.212**	0.317		0.212	0.140	0.209
$\tau_{cov,LWR}$				**0.4077**			
N2							
τ	0.100	**0.680**	0.572		**0.117**	**0.772**	**0.670**
α	0.646	**0.066**	0.066		0.629	0.066	0.066
ϒ	0.254	**0.254**	0.362		0.254	0.162	0.264
$\tau_{cov,LWR}$				**0.3332**			

Bold values were measured, and the others were estimated.

UVR, ultra violet radiation; PAR, photosynthetically active radiation; NIR, near-infrared radiation.

3.3. Vent characteristics

Ventilation openings were available in all sidewalls. In the roof, the width of the horizontal ventilation opening below the lifted cover was 2 m over the full length of the greenhouse. All ventilation openings were covered with insect nets (Mononet 600; Rovero Systems B.V., the Netherlands). In Experiment 1, the ventilation opening in the sidewalls had a width of 2.75 m. In Experiments 2 and 3 the width of the ventilation opening in the left and right walls was reduced to 0.75 and 1.75 m in the front and rear walls in order to amplify the radiation effect compared to the ventilation effect.

3.4. Periods of measurements

Climatologically, the site is characterised by two distinct seasons: dry from June to October and wet from November to May. Experimental data were collected for three successive field experiments. Experiment 1 was started (transplanting) on 23/10/2003 at the beginning of the wet season and ended (last harvest) on 27/1/2004 in the middle of the wet season. Experiment 2 was from 22/03/2004 in the middle of the wet season till 6/7/2004 at the end of the wet season. Experiment 3 was between 23/7/2004 at the beginning of the dry season and 26/10/2004 at the end of the dry season. Therefore, the three successive experiments represented a year-long variation of outdoor climatic conditions.

3.5. Leaf area index

In each experimental period, tomato variety 'Lentana' was grown in the greenhouses with burned rice husks in a black poly-ethylene bag as the growing medium. Plants were arranged in a double-row high-wire system with a density of 2.94 plants m^{-2} on five beddings covered with plastic mulch (silver colour side up, black side down). Destructive samplings were made regularly at 2-weekly intervals. Specific leaf area was determined from measurements of leaf area and its corresponding dry weight, and thus the leaf area index deduced.

3.6. Climate measurements

Global radiation and PAR were measured at a height of 4 m inside three greenhouses with different covering materials and outdoor using 4 pyranomters (CM11, Kipp and Zonen, Delft, the Netherlands) and 4 PAR sensors (TFDL, Wageningen, The Netherlands). Indoor sensors were mounted at a representative position, which was not constantly shaded by the insect nets in the roof opening. Air temperature and air relative humidity were measured by dry and wet bulb ventilated hygrometers (Priva Hortimation, De Lier, the Netherlands) inside all greenhouses, at a height of 1.5 m at the start of the experiment and later at 25 cm above the growing crop, and outdoors at a height of 1.5 m. Outdoor wind speed was measured at a height of 10 and 2 m by cup anemometers.

All sensors were connected to two data loggers (Datataker 500, Data Electronics, Rowville, Australia). These data loggers scanned all signals every 1 s and computed 15-min averages for logging. Daily rainfall was measured manually using a rainfall gauge.

3.7. Model set-up

The whole experiment consisted of three successive experiments (Experiments 1, 2, and 3), each with two replicates of the three greenhouse plastic cover types (greenhouses N0, N1, and N2). The model, previously evaluated to be satisfactory for the standard plastic greenhouse N0 during Experiment 1 (Impron et al., 2007), is applied to the other data sets and the greenhouse modifications. Greenhouse transmission for different cover properties was calculated using ray-tracing (Swinkels et al., 2000). The variation in openings was used to quantify the ventilation effects. In Experiment 1, the ratio of the total ventilation opening to greenhouse covering surface area was 0.427 with a discharge coefficient C_d of 0.662 (Bot, 1983). In Experiments 2 and 3, the ratio was 0.223 and C_d was 0.672. The wind pressure coefficient C_w was validated by CFD calculations (Campen, 2005) to be 0.04. The ventilation sub-model was described according to Bot (1983), Boulard and Baille (1995), and Roy et al. (2002).

3.8. Selection of data sets for model validation

Nine data sets were collected according to three experiments (growing seasons) and three types of greenhouse covers from October 2003 to October 2004. The outdoor climatic conditions during Experiments 1, 2, and 3 are summarised in Table 2. In general, the measured climatic conditions in Purwakarta, Indonesia, are typical of tropical lowlands. Although the daily outdoor global radiation S ranged from 5.1 to 25.0 MJ m^{-2} d^{-1} with seasonal average of 17.0–19.8 MJ m^{-2} d^{-1}, which is considered not too high, the radiation levels are coupled with average air temperatures of around 27.5 °C and sometimes with maxima above 35 °C; these represent high levels of boundary conditions for tropical lowland greenhouses.

Table 2.

Summary of climatic conditions during the three successive experiments and the data used for model validation

	Experiment 1			**Experiment 2**			**Experiment 3**			**Model validation**		
	Max	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**	**Ave**
Daily S, MJ m^{-2} d^{-1}	24.6	5.1	17.0	23.9	5.8	18.1	25.0	13.1	19.8	24.6	11.3	19.1
Instantaneous S, W m^{-2}	1188	0	197	1063	0	209	1055	0	230	1188	0	220
Daily PAR, MJ m^{-2} d^{-1}	10.8	2.2	7.3	10.7	2.6	7.9	10.6	5.9	8.4	10.8	5.3	8.2
Instantaneous PAR, W m^{-2}	494	0	87	464	0	91	451	0	97	494	0	95
Daily PAR to S ratios	0.49	0.40	0.44	0.50	0.40	0.44	0.46	0.40	0.42	0.47	0.40	0.43
Daily atmospheric τ	0.63	0.13	0.44	0.64	0.18	0.51	0.65	0.35	0.54	0.64	0.30	0.52

	Experiment 1			Experiment 2			Experiment 3			Model validation		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
T_{Out}, °C	38.1	22.0	27.2	36.5	20.0	27.2	37.5	20.3	27.5	37.5	20.2	27.4
RH, %	100	37	82	100	37	82	98	24	73	98	33	78
D_{Out}, kPa	3.8	0.0	0.8	3.1	0.0	0.8	4.6	0.1	1.2	4.3	0.1	0.9
U, m s^{-1}	8.3	0.0	1.5	6.8	0.0	1.3	6.7	0.0	1.8	6.8	0.0	1.7

S, outdoor global radiation; PAR, outdoor photosynthetically active radiation; *τ*, transmission coefficient; T_{Out}, outdoor air temperature; RH, outdoor air relative humidity; D_{Out}, outdoor air water vapour pressure deficit; *U*, wind speed at a 10 m height; Max, maximum value; Min, minimum value; Ave, average value.

In each data set, 14 non-successive days were selected for model validation (Table 2), while 7 out of these 14 days were taken at the days of destructive crop samplings with a leaf area index of 0.01–4.97.

4. Results and discussion

4.1. Greenhouse climate

4.1.1. Radiation

Three types of greenhouse cladding were characterised mainly by the differences in their radiation transmission coefficients. The orders of magnitudes of global and PAR transmission by the greenhouses, I_G and I_{PAR}, always follow N0>N1>N2 (Fig. 2 and Fig. 3). On average, across the three experimental periods, I_G and I_{PAR} were 12.0, 11.0, 10.2 MJ m^{-2} d^{-1} and 5.4, 5.0, 4.8 MJ m^{-2} d^{-1}, for N0, N1, and N2, respectively. The overall transmission coefficients by the greenhouse for global radiation were 0.66, 0.60, 0.56, and 0.69, 0.64, 0.61 for PAR for N0, N1, and N2, respectively. These differences were due to the NIR reflection pigments inside the films N1 and N2 (Table 1). In all greenhouse types over the three successive experiments, there tended to be smaller daily averages of radiation transmission coefficient on clear sunny days. The calculated daily I_{PAR} to I_G ratios for overall averages were 0.45, 0.46, and 0.47 for N0, N1, and N2, respectively; these were close to the calculated theoretical values of 0.45, 0.47, and 0.48.

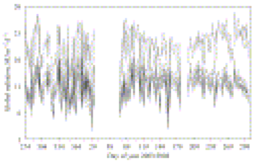 Full-size image (43K)

Fig. 2. Daily global radiation *S*; lines from top to bottom represent *S* outdoor and inside greenhouses with three different plastic films (reference N0, and two levels of near-infrared radiation-reflecting pigments N1 and N2).

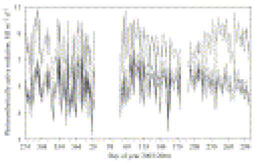 Full-size image (43K)

Fig. 3. Daily photosynthetically active radiation PAR; lines from top to bottom represent PAR outdoor and inside greenhouses with three different plastic films (reference N0, and two levels of near-infrared radiation-reflecting pigments N1 and N2).

The calculated global radiation transmission coefficient by the greenhouses varied through the day. In the early morning, greenhouse transmission coefficients were higher and lower in the late afternoon; during the day when the sun elevation angle was high (from 09:00 to 15:00) the greenhouse transmission coefficients were between these two values. This time-dependent variability can be attributed to the radiation sensor location. During periods with clouds, the transmission coefficients of the greenhouses were less variable due to the high diffuse radiation component. The diurnal variation of the greenhouse transmission coefficient has been reported by Cooman (2002) and Heuvelink (1996). The daily average value of the transmission coefficient is practically more applicable because the variability is smoothed.

4.1.2. Air temperature and air water vapour pressure deficit

Air inside the greenhouses is enclosed by the plastic films and by the insect nets. The plastic film is partly transparent for thermal radiation, but prevents water vapour transmission. Water vapour is exchanged via the ventilation openings with nets. Diurnal variations in T_{Air} and D_{Air} are mainly affected by outdoor weather, leaf area index, and ventilation openings.

The daily courses of T_{Air} and D_{Air} and *L* are given in Fig. 4 and Fig. 5. T_{Air} and D_{Air} were higher inside an empty greenhouse compared to outdoor (start of Experiment 1). Additional closing of the ventilation opening amplified these differences (start of Experiments 2 and 3). For example, the differences of the average values of the maximum T_{Air} initially were around 1 °C and then became 3 °C and the maximum D_{Air} of 0.3 kPa became 0.8 kPa.

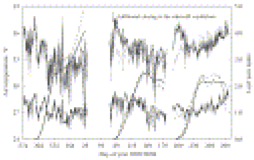 Full-size image (57K)

Fig. 4. Measured maximum (upper lines) and average (lower lines) air temperature and leaf area index for the three greenhouse experiments: ——, film type N0; ——, film type N1; - - - - -, film type N2; ·······, outdoor temperature; the diagram shows that the internal climate is virtually indistinguishable under the three films.

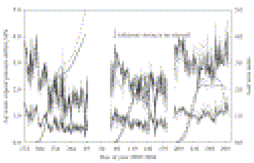 Full-size image (60K)

Fig. 5. Measured maximum (upper lines) and average (lower lines) air water vapour pressure deficit and leaf area index for the three greenhouse experiments: ——, film type N0; ——, film type N1; - - - - -, film type N2; ·······, outdoor; the diagram shows that the internal climate is virtually indistinguishable under the three films.

Growing crops inside the greenhouses increased the energy conversion into latent heat and increased the air water vapour content, while decreasing greenhouse T_{Air} and D_{Air}. This can be seen more clearly in Experiments 2 and 3 (Fig. 4 and Fig. 5). In later stages of crop growth with a high leaf area index, the maximum T_{Air} was often lower than the maximum T_{Out}. The differences between inside and outdoor air water vapour pressure deficit became much higher when the ventilation walls were partly closed, due to reduced water vapour removal.

In each experimental period, temperature differences between greenhouses due to the differences in cladding optical properties were less than 0.1 °C for the mean values of average temperatures and less than 0.3 °C for the mean values of maximum temperatures (Table 4).

In general, greenhouse climate was close to outdoor climate due to the suitable greenhouse design, especially with high ventilation openings. The effects of the different greenhouse-covering materials within the applied range are smaller than the effects of the reduction of greenhouse ventilation openings. The leaf area index has the highest impact on greenhouse air temperature, implying that a high amount of cooling can be contributed by the crop itself.

4.2. Diurnal course of air temperature and air water vapour pressure deficit

The diurnal courses of T_{Air} and D_{Air} from three selected days are given in Fig. 6. These are days with a daily integral outdoor global radiation of about 20 MJ m^{-2} d^{-1}. The first day has a fully open ventilation opening, no crop; the second day, a partly closed ventilation opening, no crop; and the third day, a partly closed ventilation opening, fully developed crop (*L* 1.91). When the greenhouses were empty and the ventilation walls were open, the calculated 24-h, day, and night averages of T_{Out} were lower than T_{Air}. During the daytime the average T_{Out} was about 0.8 °C lower than T_{Air}. The differences increased to around 1.8 °C as the ventilation openings were partly closed. The differences become much lower to only about 0.2 °C when the crops inside the greenhouses had a higher leaf area index of about 1.91, although the ventilation openings were partly closed. On these 3 days, similar responses of D_{Air} prevailed.

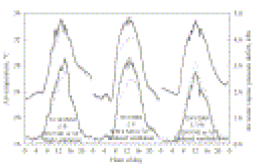 Full-size image (45K)

Fig. 6. Diurnal course of air temperature (upper lines) and air water vapour pressure deficit (lower lines) from three different dates for the three greenhouse experiments: ——, film type N0; ——, film type N1; - - - - -, film type N2; ······, outdoor; *S* outdoor global radiation; *L* leaf area index; the diagram shows that the internal climate is virtually indistinguishable under the three films.

4.3. Evaluation of the model

The original model was tested first with all nine data sets applying the calibration factor for indirect absorbed solar radiation Λ of 0.1 and one of the results is presented for illustration of the state variables T_{Air} and D_{Air} for 3 non-successive days of Experiment 1 greenhouse N2 (Fig. 7). In Experiments 1 and 3 the performance of the model was satisfactory with error of the mean values less than 1% for the T_{Air} and D_{Air}, and less than 6% for the I_G and I_{PAR} (Table 3). In Experiment 2, the errors were higher; around 1.3% for the T_{Air}, 5–10% for the D_{Air}, and of 3–9% for the I_G and I_{PAR} (Table 3). In most cases, the values were underestimated. The error seemed to be higher when the crop leaf area index was low. This might be attributed to the value of Λ.

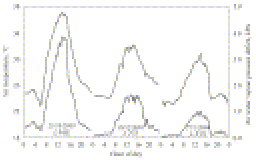 Full-size image (35K)

Fig. 7. Example of model validation for three non-successive days in greenhouse N2 of Experiment 1; variation in the greenhouse air temperature (upper lines) and the greenhouse air water vapour pressure deficit (lower lines): ———, measured; ———, calculated; the model validation was with the calibration factor for indirectly absorbed solar radiation Λ=0.1; *L* leaf area index.

Table 3.

Mean values of the measured (Meas) and calculated (Cal) transmission of global and photosynthetically active radiation by the greenhouse I_G and I_{PAR}, greenhouse air temperature T_{Air}, and greenhouse air water vapour pressure deficit D_{Air} and their corresponding values of the error in % and root-mean-square error (RMSE); calculations were with calibration factor for indirectly absorbed solar radiation Λ=0.1

Film type	**Experiment 1**				**Experiment 2**				**Experiment 3**			
	Meas	**Cal**	**Error**	**RMSE**	**Meas**	**Cal**	**Error**	**RMSE**	**Meas**	**Cal**	**Error**	**RMSE**
N0												
I_G, W m^{-2}	139	134	4	41	149	144	4	44	149	151	−2	61
I_{PAR}, W m^{-2}	62	61	2	17	68	65	4	20	66	69	−4	23
T_{Air}, °C	27.3	27.2	0.3	0.3	27.8	27.5	1.3	0.7	27.4	27.3	0.5	0.5
D_{Air}, kPa	0.72	0.71	2.0	0.11	0.84	0.76	9.7	0.20	1.12	1.11	0.4	0.13
N1												
I_G,	125	117	6	41	138	126	9	49	135	132	2	55

Film type	Experiment 1				Experiment 2				Experiment 3			
	Meas	**Cal**	**Error**	**RMSE**	**Meas**	**Cal**	**Error**	**RMSE**	**Meas**	**Cal**	**Error**	**RMSE**
W m^{-2}												
I_{PAR}, W m^{-2}	58	57	2	16	62	61	3	20	60	64	−7	22
T_{Air}, °C	27.3	27.1	0.7	0.3	27.7	27.4	1.2	0.6	27.4	27.2	0.8	0.5
D_{Air}, kPa	0.71	0.70	0.9	0.07	0.80	0.76	5.2	0.19	1.09	1.10	−0.6	0.15
N2												
I_G, W m^{-2}	116	108	6	33	128	116	9	40	126	123	3	43
I_{PAR}, W m^{-2}	54	53	1	14	61	57	6	18	58	60	−3	19
T_{Air}, °C	27.3	27.1	0.5	0.3	27.8	27.4	1.4	0.7	27.5	27.2	1.0	0.5
D_{Air}, kPa	0.69	0.70	−0.3	0.08	0.82	0.75	8.0	0.20	1.14	1.10	3.5	0.13

A scatter plot of Λ vs. L (Fig. 8) for the data sets of Experiments 1 and 3 clearly shows that Λ of 0.1 was suitable in most cases at high L. More scattered Λ values were observed in Experiment 2, but some also satisfying Λ of 0.1. At a leaf area index less than 1, Λ values were often higher than 0.1, resulting in underestimation of the radiation effect when applying Λ of 0.1 in the original model. This condition can partly be explained by the fact that when the leaf area index is low, soil surface is less covered and thus it receives more solar radiation and thereby releases more heat into the greenhouse air. A simple approach to account for this effect is by establishing Λ as a variable of L. At a very low leaf area index, the Λ values were between 0.1 and 0.4 with a mean value of 0.25. The values of Λ tend to decrease as L increases. Accordingly, the following equation is proposed:

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6WXV-4RSHR61-1&_user=6763742&_coverDate=04%2F30%2F2008&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1369959775&_rerunOrigin=scholar.google&_acct=C000070526&_version=1&_urlVersion=0&_userid=6763742&md5=c5651a947765cb0f4b2d857056c0ad5e

(3)

$$\Lambda = 0.10 + 0.15 \exp(-L).$$

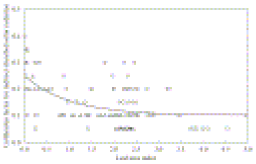 Full-size image (25K)

Fig. 8. Scatter plot of calibration factor for indirect absorbed solar radiation Λ as a function of leaf area index L: □, Experiment 1; ○, Experiment 2; △, Experiment 3; the line is according to Λ=0.10+0.15 exp(−L).

Modification of the values according to Eq. (3) was applied in all data sets. In the original model, the average absolute errors were 0.5%, 1.3%, 0.8% for T_{Air} and 1.1%, 7.6%, 1.5% for D_{Air}; in the modified model, the errors were 0.3%, 1.1%, 0.6% for the T_{Air} and 1.5%, 5.2%, 1.4% for D_{Air}, respectively, for Experiments 1, 2, and 3. Hence, adaptation of Λ slightly improves model performance.

4.4. Effects of variations of cover properties, ventilation openings, and leaf area index

As a result of cover property variations, the calculated I_G in greenhouse N0 was 12% and 19% higher than that in greenhouse N1 and N2, respectively. However, the measured T_{Air} and D_{Air} data did not show variation coupled to cover properties in the greenhouses.

Greenhouse and outdoor air temperatures were strongly coupled by ventilation. Therefore, in Experiments 2 and 3, the ratio of the total ventilation opening to greenhouse covering surface area was reduced to 0.223 compared to 0.427 in Experiment 1. Under a high ventilation flux, the difference of T_{Air} and T_{Out} was small. Under reduced ventilation airflow in Experiments 2 and 3, T_{Air} increased considerably especially at a low leaf area index (Fig. 4). At a high leaf area index, transpiration has a more dominant effect on lowering the greenhouse air temperature.

The mean values of measured daily average T_{Air}, maximum T_{Air}, and average D_{Air} between greenhouses differed by less than 0.1, 0.3 °C, and 0.03 kPa, respectively (Table 3 and Table 4). With the variation of cover properties, ventilation openings, and leaf area index implemented in the model, the mean values of calculated daily average T_{Air}, maximum T_{Air}, and average D_{Air} between greenhouses also differed by less than 0.1, 0.2 °C, and 0.01 kPa, respectively (Table 3 and Table 4).

Table 4.

Mean values of the measured and calculated maximum and minimum greenhouse air temperature T_{Air} and their corresponding values for the difference between the measured and calculated and the % error; calculations were with calibration factor for indirectly absorbed solar radiation Λ=0.1; N0, N1, N2, film type

	Experiment 1			**Experiment 2**			**Experiment 3**		
	N0	**N1**	**N2**	**N0**	**N1**	**N2**	**N0**	**N1**	**N2**
Maximum									
Measured T_{Air}, °C	32.86	32.97	32.58	34.32	34.36	34.62	34.90	34.80	34.94
Calculated T_{Air}, °C	32.84	32.75	32.71	34.20	33.99	33.90	34.92	34.77	34.75
Difference T_{Air}, °C	0.02	0.22	−0.13	0.12	0.37	0.72	−0.02	0.03	0.19
Error, %	0.06	0.66	−0.39	0.36	1.09	2.09	−0.04	0.06	0.54
Minimum									
Measured T_{Air}, °C	23.75	23.77	23.74	23.48	23.50	23.58	22.14	22.12	22.11
Calculated T_{Air}, °C	23.49	23.47	23.49	22.99	22.83	22.94	21.69	21.66	21.72
Difference T_{Air}, °C	0.26	0.30	0.25	0.49	0.67	0.64	0.45	0.46	0.39
Error, %	1.09	1.26	1.05	2.07	2.85	2.70	2.02	2.11	1.75

In the model, the radiation calibration factor Λ was determined by fitting calculated to measured T_{Air} during the daytime. No compensation was made for the rate of released heat by the soil surface to the air that might increase T_{Air} during the night time. This simplification was of little consequence as indicated in the results. In general, the model was able to follow the diurnal course of T_{Air} and D_{Air} satisfactorily (Fig. 7) with the mean values of the calculated state variables T_{Air} and D_{Air} close to the measured ones (Table 3). On a diurnal basis, the calculation error for the maximum temperature during the daytime was smaller than the error for the minimum temperature during the night time (Table 4).

5. Conclusions

The climate inside the experimental greenhouses was close to the outdoor climate due to high ventilation openings. The effect of the different greenhouse covering materials within the range on greenhouse climates that were realised was smaller than the effect of the reduction of greenhouse ventilation openings. The leaf area index had the highest impact on greenhouse air temperature, implying that the crop itself can provide a large amount of cooling.

The model performed well for the extensive full-year data sets with a calibration factor for indirect absorbed solar radiation Λ of 0.1, but with a higher error at a low leaf area index. The model performance was slightly improved on including the effect of leaf area index on the Λ as an exponential term. This can be understood from the decrease of absorbed and released solar energy by the soil surface thus reducing the indirect effect of solar radiation on air temperature at a higher leaf area index.

Under current validation conditions, where greenhouse air temperature proved to be closely coupled with the outdoor one, the model demonstrated a more profound effect of ventilation and leaf area index than of cover properties. The variation in cover properties of the experimental greenhouses was too small to show effects. This means that a proper greenhouse design with a high ventilation capacity is necessary for tropical lowland conditions. The use of near-infrared radiation (NIR)-reflecting greenhouse coverings obviously makes sense when a higher amount of NIR is reflected without losing too much photosynthetically active radiation (PAR). More research is required in this area.

The present results establish confidence in use of the model for scenario studies on optimum greenhouse systems for a tropical lowland in Indonesia.

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