A Greenhouse Crop Production System for Tropical Lowland Conditions

I M P R O N

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Impron

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Abstract

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The goal of this research was to improve greenhouse crop production under tropical lowland conditions. The dynamics of greenhouse climate were analyzed using a simple greenhouse climate model (GCM), while the growth and development of a determinate tomato crop were quantified using the INTKAM greenhouse crop simulation model. By combining the GCM and INTKAM models, ways to improve tomato production under tropical lowland greenhouse were investigated. Model calculations were calibrated and validated with experiments in six prototype greenhouses with three different near infrared (NIR) transmissivities during three periods with different tropical lowland climate characteristics.

The greenhouses having high natural ventilation capacity showed a climate closely coupled to the outdoor climate. Greenhouse air temperature T_{Air} was affected more by variation in ventilation and leaf area index than by the applied NIR transmission. Simulation shows that lowering T_{Air} can be achieved by: (i) reducing near infrared radiation (NIR) transmission especially for bigger greenhouses and humid conditions, (ii) increasing ventilation openings and (iii) transpiration cooling, especially under hot and dry conditions. GCM study indicated that naturally ventilated model greenhouses of up to size of 14400 m^2 were capable to create T_{Air} close to or lower than outdoor air temperature T_{out} when the greenhouse crops had leaf area index of higher than 0.5.

Crops with low number of trusses produced substantially lower fruit weight than crops with high number of trusses. Determinate tomato clearly exhibit high fruit abortion, with the number of fruits per truss decreasing as truss number increases. This partly can be explained by low source – sink strength ratio during the productive period. Effort to increase tomato production might require adequate crop management aimed at finding the appropriate source – sink balance. Scenario studies revealed that fruit production by a determinate tomato crop can be increased slightly by using zero NIR transmittance plastic film and by planting three crops per year (which is current practice). However, when the number of fruits can be maintained constant through appropriate crop management measures, the production would increase with increasing fruit load and the lengthening production period through fewer plantings per year.

Key words: tropical lowland climate, tropical lowland greenhouse, plastic greenhouse, near infrared radiation (NIR) reflecting plastic, greenhouse climate model, determinate tomato, crop growth, development, truss appearance rate, crop simulation model, INTKAM.

With love to my wife,
EMILIA BASSAR
my son,
MUHAMMAD LAUDA
and my daughter,
ETHEREAL LAUDIA

Contents

Nomenclature

A	area, m^2
c	concentration, kg m^{-3}
C	ambient carbon dioxide concentration, ppm (in Chapter 5)
	coefficient (in other chapters)
c_p	specific heat of air, J kg^{-1} K^{-1}
d	diagonal length of greenhouse floor, m
D	water vapour pressure deficit, Pa
DAP	day after planting, day
DD	degree-days, ^{o}C d
DM	cumulative dry matter production. g m^{-2}
e	actual air water vapour pressure, Pa
E	transpiration, kg m^{-2} s^{-1}
e^*	saturation air water vapour pressure, Pa
F	aspect ratio
$FRND$	decreasing number of fruits per truss
$FRNC$	seasonal constant number of fruits per truss
G	heat conductance, W m^{-2} Pa^{-1} (for the latent) or W m^{-2} K^{-1} (for others)
g	gravitational acceleration, m s^{-2}
h	average greenhouse height, m
H	heat exchange, W m^{-2}
I	transmitted radiation, W m^{-2}
K	sky clearness index
k	transfer rate for heat or mass, m s^{-1}
l	length, m
L	leaf area index, m^2 m^{-2}
M	molar weight, kg $kmol^{-1}$
O	light obstruction factor
P	absorbed solar radiation, W m^{-2}
$PARi$	simulated values of PAR interception, W m^{-2}
R	universal gas constant, J $kmol^{-1}$ K^{-1}
r	resistance for heat transfer, s m^{-1}
S	outdoor global radiation, W m^{-2}
SLA	specific leaf area, cm^2 kg^{-1} or m^2 kg^{-1}
T	temperature, K
t	time, day
TAR	truss appearance rate, number of trusses per day
TRN	truss number
u	average air speed inside greenhouse, m s^{-1}

U	external wind speed, m s^{-1}
w	width, m
κ	extinction coefficient
φ	volumetric airflow per unit ground area, m^3 s^{-1} m^{-2}
Φ	volumetric airflow, m^3 s^{-1}
Λ	calibration factor for indirect absorbed solar radiation
ς	ventilation reduction of the insect-proof screen
α	absorption coefficient
χ	characteristic width dimension of a leaf, m
δ	slope of the saturation air water vapour pressure function, Pa K^{-1}
ε	radiation use efficiency, g MJ^{-1} (in Chapter 5)
	emission coefficient (in other chapters)
γ	thermodynamic psychometric constant, Pa K^{-1}
λ	latent heat of water, J kg^{-1}
ρ	density of air, kg m^{-3}
σ	Stefan–Boltzmann constant, W m^{-2} K^{-4}
τ	transmission coefficient
Υ	reflection coefficient

Subscripts

Air	greenhouse air
Ave	average
b	base
Can	canopy
CO_2	CO_2
CON	convection
Cov	greenhouse cover
d	discharge
dif	diffuse
dir	direct
e	boundary layer (external)
E	extraterrestrial
F	experiment-dependent parameter for the specific leaf area
G	global
g	greenhouse ground
i	big leaf (internal)
LAT	latent
LWR	long-wave radiation

Max	maximum
Min	minimum
n	net
NIR	near-infrared radiation
o	ventilation opening
Out	outdoor
PAR	photo synthetically active radiation
r	roof opening
s	side opening
Scr	insect screen
Sky	sky
Soi	soil surface
Str	greenhouse structural elements
UVR	ultra-violet radiation
VEN	ventilation
w	wind pressure

1

General introduction

1.1. Need and challenges for protected cultivation in tropical lowland of Indonesia

Protected cultivation of crops inside a greenhouse covered with transparent plastic film or glass is one of the most recently developed specialisations of horticulture (Bakker & Challa, 1995). In this integrated production and protection system cleaner crops are produced at better quality with less pesticide, less water, less land and more carefully directed fertilization compared to open field production (Baudoin & Von Zabeltitz, 2002). It also allows year round production in regions where this is not possible in the open field. In the Netherlands, greenhouse crop production has become a highly industrialised process with full control of growing conditions. Fresh weight production of about 5 to 10 times than in open field is realised but this is linked to high energy costs (Van Henten, 1994). Great efforts are made to improve the efficiency of production inputs to meet the demands from society to reduce pollutant emissions to groundwater and atmosphere. This is realised by applying substrate growing, avoiding completely the application of dangerous chemicals for soil sterilisation, by the large scale application of biological control, reducing strongly the application of crop protecting chemicals, by applying closed watering systems, reducing the leakage of nutrients to the environment, and by lowering the energy consumption of the greenhouse by improved insulation by thermal screens and by climate control strategies more carefully aimed at crop requirements (Bot, 2004; Van Ooteghem, 2007). So for moderate climate regions, advanced greenhouses with a large scale production and product handling are able to provide fresh horticultural fruits and vegetables throughout the year. The same holds for flowers and ornamentals.

Greenhouses have also been introduced in regions with very different climatic conditions such as in the tropical lowland (Baudoin & Von Zabeltitz, 2002; Den Belder *et al.*, 2002; Harmanto *et al.*, 2006; Kleinhenz *et al.*, 2006, Impron *et al.*, 2007, 2008). The tropical lowland climate is characterised by prevailing high levels of irradiation, high air temperature and high air humidity (Von Zabeltitz, 1999). In this region, conventionally crops are grown in the open field year round with up to three successive growing seasons. On the first sight these conditions do not demand the application of greenhouses. However, harsh outdoor climate-related events (such as seasonally high wind speed and heavy rainfall in the wet season or water shortage in the dry season) together with high level of infestation of pests and diseases often damage the open field grown crops, strongly reducing crop production and crop quality. Protection of high value crops in a greenhouse may offer an alternative to cope with these problems. Then greenhouse crop cultivation is expected to produce high quality vegetables in peri-urban areas to secure the supply of safe and environmentally friendly produced food for the urban population. Moreover it may save water and may avoid water pollution. The cropping system and integrated pest management aimed at reduction of plant protection chemicals are also important aspects in such greenhouse crop cultivation system which requires special attention.

Protected cultivation may solve the above described problems, however as mentioned, outdoor climatic conditions in tropical lowland strongly differ from those in moderate climate greenhouse production areas, such as in The Netherlands. Simply applying a greenhouse design aimed at moderate outdoor climate conditions will introduce a great risk. The challenge for the introduction of protected cultivation in the tropical lowland like in Indonesia is on the one hand to design a greenhouse crop production system adapted to the local outdoor climate, characterised by high levels of irradiation, outdoor temperature and humidity, in which a manageable microclimate inside the greenhouse can be created within a range suitable for crop production and with low risk for infestation of pest and diseases and on the other hand to adapt the cropping system.

1.2. Scope, objective and questions of the research

Scope of research

Development of an adaptive greenhouse production system starts with the static design phase in the selection of the geometry, sizes, and materials for construction and coverings. The starting point for our study was the result of computational fluid dynamics (CFD) modelling for the design of the main geometrical dimensions of the greenhouse and its ventilation openings by taking extreme local climate parameters as static reference boundary conditions (Campen, 2005) in order to prevent heating up of the greenhouse during high irradiation and high outside temperatures. Insect nets were mounted in the ventilation openings to reduce plagues. In this way the greenhouse geometry of the research prototypes was defined as the most optimal to meet the high ventilation requirements. Calculations with different types of insect nets were conducted. Then in our study the climate dynamics inside the greenhouse during varying outdoor climatological conditions were analysed. Greenhouse climate and crop growth can be quantified in relation to dynamic outdoor conditions and the physical properties of the greenhouse and its equipment (Bot, 1983; Bot & Van de Braak, 1995).

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 prevailing high outdoor air temperature in the tropical lowland will stress the greenhouse crop. Lowering the air temperature is the 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).

Great potential to face high irradiation in combination with high outdoor temperature is in the application of near infrared radiation (NIR) reflecting cover material. These plastic films may have cooling effects during high irradiation (Hoffman & Waaijenberg, 2002, Hemming *et al.*, 2006a) by filtering (reflection or absorption) NIR without considerable loss of photosynthetically active radiation (PAR) needed for plant growth. Taking into account that NIR contains about 50% of the energy content of the global radiation, the heat load could theoretically be reduced by 50% for ideal NIR reflecting materials. Reduction of the heat load can also be realised by the application of shading materials. However, then also PAR level is reduced. This can be applied for crops demanding low light levels like ornamentals. We are aiming for growing vegetable crops demanding high PAR levels. Therefore the application of NIR reflecting materials is a central item in our study. Removing excess heat from greenhouse compartments can be achieved passively by promoting high natural ventilation. If crops are grown inside the greenhouse, transpiration serves as important means to increase the fraction of energy partitioned into latent heat. In summary, radiation distribution, natural ventilation, and crop transpiration are the key processes determining the climate in the tropical lowland greenhouse and these processes will be studied in interaction with crop production.

Objective and questions of the research

To increase the income of local farmers in the tropical lowland crop production systems have to be developed to increase crop production compared to open field production. The objective of this research is to develop an adapted type of greenhouse cultivation system for tropical lowland. Developing such a system requires realization of suitable greenhouse climate. So, an important general question to judge applicability of greenhouses in tropical outdoor climate is: *does the outdoor climate in tropical lowland allow the realisation of optimum conditions for many greenhouse horticultural crops and does this require a special approach in the design of an adapted greenhouse?*

The expected climate conditions inside the tropical lowland greenhouse is driven by the outdoor climate conditions and affected by the optical properties of the covering material, the ventilation rate through the openings covered with insect nets and crop transpiration. These effects need to be quantified, and therefore more specific research questions are formulated as follow: "W*hat are the effects of (a) NIR reflecting films, (b) ventilation rate (c) insect nets in the openings (d) greenhouse size (e) crop transpiration on diurnal and seasonal dynamics of climate in the greenhouse in relation to the outdoor climate conditions in tropical lowland?"*

In tropical lowland, we expect to observe some detrimental effects of high air temperature on crop growth and development. These detrimental effects should be minimal in the optimal greenhouse conditions. Therefore, with respect to crop responses to greenhouse climate, the following research question is formulated: *"What responses are exhibited by a tomato crop (as model crop) cultivated inside the greenhouse in terms of its growth, development and production?"*

1.3. Outline of the thesis

Since the chapters in this thesis are self-contained and based on published and submitted articles, some repetition among chapter sections are inevitable but this makes independent reading of the chapters easier.

To study the effect of cover properties, ventilation rate and crop transpiration a simple greenhouse climate model was developed and presented in **Chapter 2**. The physical basis of the model being solar radiation spectral distribution, cover optical properties, ventilation process, crop transpiration and model parameterisation are reviewed. Calibration and validation by field experiments, and application of the model are discussed. In **Chapter 3** effects of cover properties, ventilation rate, and crop leaf area on tropical greenhouse climate are analysed according to extensive experimental results. A comprehensive validation of the greenhouse climate model is presented. In **Chapter 4** a scenario study regarding tropical lowland greenhouse design is presented in order to optimise the cooling capacity. In this chapter, variations of near infrared radiation transmission coefficients affecting solar radiation input, variations of greenhouse dimension aspects affecting ventilation, and variations of leaf area indexes affecting transpiration are evaluated. **Chapter 5** presents experimental results and simulation of growth and development of a determinate tomato crop under tropical lowland greenhouse conditions. In this chapter, various ways to improve tomato production are also studied. **Chapter 6** gives an overall discussion of the study. Emphasis is given on ways to creating operational greenhouse crop production system for tropical lowland conditions based on experimental data and simulation studies. Applicability of the simple greenhouse climate model for the design of greenhouse in tropical lowland are briefly discussed. Major aspect of determinate tomato growth characteristics, ways to improve tomato production, and some possible constraints in improving tomato production in tropical lowland greenhouse are highlighted. Finally, recommendation for the future practical application and for research needed, not only on the physical greenhouse but also on the crop aspects, are given.

2

Simple greenhouse climate model as a design tool for greenhouses in tropical lowland

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Abstract
Six prototypes plastic greenhouses were built in the tropical lowlands of Indonesia. The geometrical dimensions were designed using computational fluid dynamics (CFD) by taking local climate parameters as static reference boundary conditions. It is necessary to evaluate the climate dynamics inside the greenhouse during varying climatological conditions. A greenhouse climate model was developed to optimise cover properties and ventilation rate as main parameters, calculating only three state variables: average greenhouse air temperature T_{Air}, average greenhouse air water vapour pressure (expressed as air water vapour pressure deficit D_{Air}), and average canopy temperature T_{Can}. Solar radiation distribution, air exchange by ventilation, and crop transpiration constituted the backbones of the model. The climate outdoor and inside the test greenhouses with crops having leaf area index from 0.02 to 4.10 were measured for one growing season. Measurements and calculations of T_{Air} and D_{Air} agreed satisfactorily, with less than 5% errors. It is concluded that the model is robust and could be used as a design tool for the tropical lowland greenhouse.

2.1. Introduction
Crop cultivation in tropical lowlands is subject to various stresses: heavy rainfall during the rainy season; water shortage during the dry season (Von Zabeltitz, 1999); and insect infestations. Cultivation in a greenhouse protects crops from these extremes. Protection against insect infestation requires the application of screens in the ventilating openings; however, these screens restrict natural ventilation needed to prevent high indoor air temperatures at the prevailing high levels of solar irradiation. Recently, with the adaptation of the optical properties of covering materials, it has become possible to reduce the thermal load of the greenhouse (Hoffmann & Waaijenberg, 2002; Hemming *et al.*, 2006a). The problem is to find the optimal combination of restricted natural ventilation and adapted optical cover properties.

The objectives of this study are: (i) to evaluate the adaptation of the covering optical properties to lower heat load in the greenhouse; (ii) to evaluate the effectiveness of natural ventilation, restricted by insect screens to remove excess heat from the greenhouse compartment; (iii) to evaluate the dynamic behaviours of the climate in the greenhouse during varying climatologic conditions; and (iv) to evaluate the growth of crop grown in the greenhouse with this dynamic behaviour.

This paper focuses on the development of a simple dynamic model for the greenhouse climate enabling the optimisation of the cover properties and ventilation rate. The model is required to quantify the effects of cover properties and ventilation on the greenhouse climate. The effect of crop transpiration is also considered because this is crucial in the cooling process.

The model was calibrated and validated in a field experiment in six prototype greenhouses in the tropical lowland of Indonesia applying reference cover. Effect of cover properties and ventilation will be presented in another paper. The geometry for optimal natural ventilation for the prototype greenhouses was previously designed applying computational fluid dynamics (CFD) with reference to local static climate conditions (Campen, 2005).

2.2. Model development

2.2.1. Basis of the model

Extensive greenhouse climate models with many state variables including heating and energy storage have been reported previously (Bot, 1983; De Zwart, 1996). The current model proposed is aimed at quantifying the effects of cover properties and ventilation on greenhouse air temperature, including the cooling effect of crop transpiration in unheated greenhouses. Therefore, the model was restricted to only the three state variables needed to evaluate the system: average greenhouse air temperature; average greenhouse air water vapour pressure; and average canopy temperature. Because the model is aimed at design at static conditions short term dynamics are not crucial so the model can be static, thereby following the dynamics of the outdoor weather.

The following assumptions are made: (i) the greenhouse air and crop are considered as well-mixed compartments (Roy *et al.*, 2002); (ii) boundary conditions are outdoor solar radiation, outdoor air temperature and sky temperature; (iii) solar radiation imposes fluxes to the greenhouse cover, the greenhouse structural elements, the crop canopy, and the soil surface; (iv) the mentioned absorbed solar radiation fluxes are released (with some delay) for a determined part to the greenhouse air; and (v) the greenhouse cover is one thin plastic layer. Its optical properties are defined in the relevant spectral regions.

Then canopy and greenhouse air temperature follow from the steady state energy balances over the canopy and the greenhouse air respectively, as indicated in **Fig. 2.1**:

$$0 = P_{Can} - H_{Can\text{-}Sky,LWR} - H_{Can\text{-}Air,CON} - \lambda E_{Can\text{-}Air} \quad \textbf{(2.1a)}$$

$$0 = P_{Air} + H_{Can\text{-}Air,CON} - H_{Air\text{-}Out,CON} - H_{Air\text{-}Out,VEN} \quad \textbf{(2.1b)}$$

where: P_{Can} is the absorption of solar radiation by the canopy; $H_{Can\text{-}Sky,LWR}$ is the heat exchange between canopy and sky by long-wave radiation; $H_{Can\text{-}Air,CON}$ is the sensible heat exchange between canopy and greenhouse air by convection; $\lambda E_{Can\text{-}Air}$ is the latent heat flux by canopy transpiration; P_{Air} is the imposed indirect solar radiation flux to the greenhouse air (solar radiation absorbed by greenhouse opaque elements and released to the greenhouse air), $H_{Air\text{-}Out,CON}$ is the overall heat exchange between greenhouse and outdoor air through the plastic cover by convection; and $H_{Air\text{-}Out,VEN}$ is the sensible heat exchange between greenhouse and outdoor air by ventilation. All fluxes are in W m^{-2} greenhouse area.

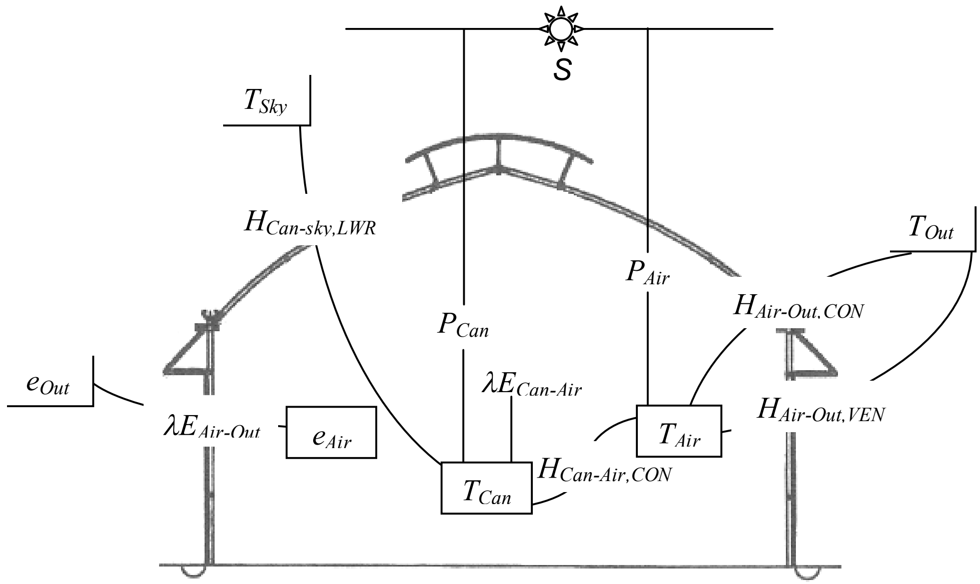

Fig. 2.1 – Representation of the state variables, fluxes, and boundary conditions: e_{Air} and e_{Out}, water vapour pressure of the greenhouse and outdoor air; T_{Can}, T_{Air}, T_{Out} and T_{Sky}, temperatures of the canopy, greenhouse air, outdoor air and sky; S, outdoor global radiation; P_{Can}, absorption of solar radiation by canopy; P_{Air}, imposed indirect solar radiation flux to the greenhouse air; $\lambda E_{Air\text{-}Out}$, latent heat exchange between greenhouse and outdoor air by ventilation; $\lambda E_{Can\text{-}Air}$, latent heat flux by canopy transpiration; $H_{Can\text{-}Sky,LWR}$, long-wave radiation exchange between canopy and sky; $H_{Air\text{-}Out,CON}$, overall heat exchange between greenhouse and outdoor air through the plastic cover; $H_{Can\text{-}Air,CON}$, sensible heat exchange between canopy and greenhouse air by convection; and $H_{Air\text{-}Out,VEN}$, sensible heat exchange between greenhouse and outdoor air by ventilation

The heat transfer terms in the steady state balances are a function of the acting temperature differences, so the basic equation for canopy temperature is derived from **Eq. (2.1a)** as:

$$0 = P_{Can} - G_{Can\text{-}Sky,LWR}\,(T_{Can} - T_{Sky}) - G_{Can\text{-}Air,CON}\,(T_{Can} - T_{Air}) - \lambda E_{Can\text{-}Air} \qquad \textbf{(2.2a)}$$

where: $G_{Can\text{-}Sky,LWR}$ is the heat conductance (transfer coefficient) between 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}; T_{Can}, T_{Sky} and T_{Air} are the temperatures of the crop, the sky and the greenhouse air, respectively, in K.

The basic equation for greenhouse air temperature is derived from **Eq. (2.1b)**:

$$0 = P_{Air} + G_{Can\text{-}Air,CON}\,(T_{Can} - T_{Air}) - G_{Air\text{-}Out,CON}\,(T_{Air} - T_{Out}) - G_{Air\text{-}Out,VEN}\,(T_{Air} - T_{Out}) \qquad \textbf{(2.2b)}$$

where: $G_{Air\text{-}Out,CON}$ 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}; and T_{Out} is the outdoor air temperature in K.

The state variable actual greenhouse air water vapour pressure e_{Air} in Pa, needed for the sub-model on crop transpiration, can be calculated from the latent heat balance over the greenhouse air:

$$0 \quad = \quad G_{Air\text{-}Out,LAT}\,(e_{Air} - e_{Out}) - \lambda E_{Can\text{-}Air}\,(S,\, T_{Air},\, T_{Can},\, e_{Air}) \qquad \mathbf{(2.2c)}$$

where: $G_{Air\text{-}Out,LAT}$ is the latent heat conductance by ventilation in W m^{-2} Pa^{-1}; e_{Out} is the actual outdoor air water vapour pressure in Pa; and S is the outdoor global radiation in W m^{-2}.

Solar radiation distribution

Distribution of solar radiation determines the first terms in the model **Eqs. (2.2a)** and **(2.2b)**. Direct *dir* and diffuse *dif* components of the S distribute differently. According to Spitters *et al.* (1986) they are calculated as a function of the ratio between S and extraterrestrial radiation S_E with S_E being calculated according to Allen *et al.* (1998). All radiation is in W m^{-2}.

Another important item is the spectral distribution. According to the Global Spectral Irradiance ASTM G173-03 (2003), the reference total global energy is partitioned into ultra- violet radiation (UVR) (4.6%), photosynthetically active radiation (PAR) (43.4%), and near- infrared radiation (NIR) (52.0%). The partition would vary slightly with meteorological conditions but a fixed ratio is chosen as given in brackets.

To allow evaluation of the effect of the radiometric properties of the reference cover used in the prototype greenhouse, they are defined in terms of transmission τ, absorption α, and reflection Υ coefficients for the spectral regions of UVR, PAR, and NIR; and for the radiation components of diffuse and direct (**Table 2.1**). The greenhouse transmission coefficient for the direct PAR spectrum $\tau_{PAR,dir}$ is calculated by ray-tracing (Swinkels *et al.*, 2000) as a function of solar position (elevation and azimuth) as given in **Table 2.2**. The factor $\tau_{PAR,dir}$ is used to determine the greenhouse transmission for the whole spectrum of global radiation.

Table 2.1 – Transmission τ, absorption α, and reflection Υ coefficients for the reference plastic cover, ASTM G173–03 weighted

	Diffuse			Direct ⊥		
	UVR	PAR	NIR	UVR	PAR	NIR
τ	0.136	**0.765**	0.758	**0.159**	**0.896**	**0.888**
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

Bold values were measured, the others estimated
UVR, ultra-violet radiation; PAR photosynthetically active radiation; NIR near-infrared radiation

Table 2.2 – Photosynthetically active radiation transmission coefficient of the greenhouse covering structure as a function of azimuth and elevation calculated with MatLight model (Swinkels *et al*., 2000)

Azimuth, degree	Elevation, degree										
	0	5	10	20	30	40	50°	60	70	80°	90
0	0.000	2.542	1.586	1.068	0.844	0.747	0.696	0.648	0.624	0.607	0.601
10	0.000	2.583	1.595	1.060	0.840	0.745	0.693	0.646	0.623	0.606	0.601
20	0.000	2.578	1.585	1.056	0.839	0.747	0.692	0.646	0.623	0.605	0.602
30	0.000	2.521	1.554	1.024	0.825	0.742	0.687	0.646	0.624	0.606	0.602
40	0.000	2.398	1.479	0.982	0.805	0.735	0.679	0.645	0.625	0.604	0.601
50	0.000	2.205	1.373	0.923	0.780	0.716	0.670	0.642	0.622	0.606	0.602
60	0.000	1.967	1.249	0.862	0.750	0.695	0.662	0.639	0.621	0.604	0.602
70	0.000	1.698	1.112	0.808	0.717	0.678	0.652	0.634	0.618	0.605	0.601
80	0.000	1.415	0.993	0.767	0.692	0.659	0.645	0.631	0.617	0.605	0.601
90	0.000	1.277	0.952	0.763	0.688	0.659	0.645	0.632	0.619	0.607	0.602

The absorbed solar radiation by the greenhouse cover P_{Cov} and by the greenhouse structural elements P_{Str} (both in W m^{-2} as all fluxes given below) are defined as:

$$P_{Cov} = \alpha_{Cov,UVR,dif} S_{UVR,dif} + \alpha_{Cov,UVR,dir} S_{UVR,dir} + \alpha_{Cov,PAR,dif} S_{PAR,dif} + \alpha_{Cov,PAR,dir} S_{PAR,dir} + \alpha_{Cov,NIR,dif} S_{NIR,dif} + \alpha_{Cov,NIR,dir} S_{NIR,dir} \quad \textbf{(2.3)}$$

$$P_{Str} = \alpha_{Str} (\tau_{UVR,dif} S_{UVR,dif} + \tau_{UVR,dir} S_{UVR,dir} + \tau_{PAR,dif} S_{PAR,dif} + \tau_{PAR,dir} S_{PAR,dir} + \tau_{NIR,dif} S_{NIR,dif} + \tau_{NIR,dir} S_{NIR,dir})$$

where for example: $\alpha_{Cov,PAR,dir}$ is the absorption coefficient of greenhouse cover in the direct PAR spectrum; $S_{PAR,dir}$ is the direct component of global radiation in the PAR spectrum; α_{Str} is the absorption coefficient of the greenhouse structural elements, not being spectral selective and assumed equal for diffuse and direct solar radiation; and $\tau_{UVR,dif}$ is the greenhouse transmission coefficient for the diffuse UVR spectrum.

The transmitted radiation by the greenhouse is given with an example for the PAR I_{PAR}:

$$I_{PAR,dif} = (1 - \alpha_{Str}) \{(1 - O_{Scr})\, \tau_{PAR,dif} S_{PAR,dif} + O_{Scr}\, S_{PAR,dif}\, \tau_{PAR,dif}\, \tau_{Scr,dif}\} \quad \textbf{(2.4)}$$

$$I_{PAR,dir} = (1 - \alpha_{Str})\, (\tau_{PAR,dir} S_{PAR,dir})$$

$$I_{PAR} = I_{PAR,dif} + I_{PAR,dir}$$

where: $I_{PAR,dif}$ and $I_{PAR,dir}$ are the transmitted radiation by the greenhouse for diffuse and direct PAR, respectively; O_{Scr} is the light obstruction factor of the insect screen; and $\tau_{Scr,dif}$ is the diffuse radiation transmission coefficient of the insect screen.

The greenhouse transmissions for the UVR I_{UVR} and for the NIR I_{NIR} are calculated in similar way as done for the I_{PAR}. The transmission of the global radiation by the greenhouse I_G is then calculated as:

$$I_G = I_{UVR} + I_{PAR} + I_{NIR} \quad \textbf{(2.5)}$$

Absorption of diffuse solar radiation by the canopy is calculated according to Goudriaan and Van Laar (1994):

$$P_{PAR,Can} = (1 - 0.057)\, \{1 - \exp(-0.715\, L)\}\, I_{PAR} \quad \textbf{(2.6a)}$$

$$P_{NIR,Can} = (1 - 0.389)\, \{1 - \exp(-0.358\, L)\}\, I_{NIR} \quad \textbf{(2.6b)}$$

$$P_{Can} = P_{PAR,Can} + P_{NIR,Can} \quad \textbf{(2.6c)}$$

where: $P_{PAR,Can}$ and $P_{NIR,Can}$ are the absorption of PAR and NIR by the canopy, respectively; and L is the leaf area index in $m^2\ m^{-2}$.

Following the notations in the model, P_{Air} is determined as:

$$P_{Air} = \Lambda\, \{P_{Cov} + P_{Str} + (I_G - P_{Can})\} \quad \textbf{(2.7)}$$

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 ($I_G - P_{Can}$) released to the air.

Ventilation process

For the tropical lowland greenhouse, the ventilation process is crucial in realising an acceptable indoor climate. CFD modelling (Campen, 2005) for the design of the test prototype greenhouse indicated that both continuous sidewall and roof top ventilation were needed for sufficient ventilation efficiency with insect screens in the openings. For such greenhouse, the general ventilation principles can be applied (Bot, 1983; De Jong, 1990; Boulard & Baille, 1995), keeping in mind the greenhouse-specific aspects.

The geometry of a single rectangular opening is defined by its length l_o and width w_o, both in m (Bot, 1983). For the total greenhouse half of the openings are for inflow and half for outflow so the effective opening area equals 0.5 A_o with A_o being the total ventilation opening in the greenhouse in m^2 (Bot, 1983; Boulard & Baille, 1995). The flow resistance can be expressed in the aspect ratio F_o (Bot, 1983) or the discharge coefficient C_d (Boulard & Baille, 1995; Roy *et al.*, 2002) with $C_d = F_o^{-0.5}$. Bot (1983) experimentally determined the aspect ratio for a rectangular opening without flaps as:

$$F_o = 1.75 + 0.7 \exp\{-(l_o / w_o) / 32.5\} \quad \textbf{(2.8)}$$

The combined pressure difference over the opening due to the wind and temperature effect drives the airflow through the opening Φ_{VEN} in m^3 s^{-1} as extensively reported in literature (Bot, 1983; De Jong, 1990; Boulard & Baille, 1995; Roy *et al.*, 2002). Therefore, for greenhouses with both side and roof openings and applying C_d for the flow resistance of the opening it was derived that (Roy *et al.*, 2002)

$$\Phi_{VEN} = C_d \{((2\, g\, ((A_s A_r)^2 / (A_s^2 + A_r^2))\, (T_{Air} - T_{Out}) / T_{Out}) + ((A_s + A_r) / 2)^2 (C_w U^2)\}^{0.5} \quad \textbf{(2.9)}$$

where: g is the gravitational acceleration in m s^{-2}; A_s is the area of side opening in m^2; A_r is the area of roof opening in m^2; C_w is the wind pressure coefficient; and U is the external wind speed at 10 m reference height in m s^{-1}.

If greenhouse air temperature is lower than outdoor air temperature, the air is stagnant so the temperature effect can be neglected:

$$\Phi_{VEN} = 0.5\, (A_s + A_r)\, C_d\, C_w^{0.5}\, U \quad \textbf{(2.10)}$$

The coefficient C_w is greenhouse dependent while it relates the reference wind speed to the ventilation driving pressure difference over the opening. Therefore the geometry of the greenhouse, the obstacles near the greenhouse and wind direction play a role. A number of investigations provide a wide range of C_w values (Boulard & Baille, 1995; Fatnassi *et al.*, 2004).

When the ventilation reduction ς of the insect-proof screen is known, the airflow through the opening with screen $\Phi_{Scr,VEN}$ in m^3 s^{-1} is estimated as:

$$\Phi_{Scr,VEN} = \Phi_{VEN}\,(1 - \varsigma) \tag{2.11}$$

The airflow per unit ground area from the greenhouse air to the outdoor air φ_{VEN} in m^3 s^{-1} m^{-2} and the average wind speed inside the greenhouse u in m s^{-1} are defined as:

$$\varphi_{VEN} = \Phi_{Scr,VEN} / A_g \tag{2.12a}$$

$$u = \Phi_{Scr,VEN} / (h\ d) \tag{2.12b}$$

where: A_g is the greenhouse ground area in m^2; h is the average greenhouse height in m; and d is the diagonal length of greenhouse floor in m.

Crop transpiration

Crop transpiration is calculated according to the Penman–Monteith (P–M) evaporation model. The P–M model, sometimes referred to as 'big leaf' model, is based on the overall energy balance over the crop with large leaf area index:

$$\lambda E_{Can\text{-}Air} = (\delta_{Air}\, I_n + \rho\, c_p\, D_{Air}\, k_e) \,/\, \{\delta_{Air} + \gamma\,(1 + k_e / k_i)\} \tag{2.13}$$

where: δ_{Air} is the slope of the saturated air water vapour pressure function at greenhouse air temperature in Pa K^{-1}; I_n is the net radiation at the canopy in W m^{-2}; $\rho\, c_p$ is the volumetric specific heat of air in J m^{-3} K^{-1}; D_{Air} is the water vapour pressure deficit of the greenhouse air in Pa; γ is the thermodynamic psychometric constant in Pa K^{-1}; k_e and k_i are the boundary layer (external) conductance and the big leaf (internal) conductance in m s^{-1}. Note that $I_n = P_{Can} - H_{Can\text{-}Sky,LWR}$.

Value of k_e is approximated according to Stanghellini (1987):

$$k_e = 2\, L / r_e \tag{2.14a}$$

$$r_e = 1174\, \chi^{0.5} / \{(\chi\, [T_{Can} - T_{Air}] + 207\, u^2)^{0.25}\} \tag{2.14b}$$

where: L is the leaf area index in m^2 m^{-2}, r_e is the leaf boundary layer resistance for the heat transfer in s m^{-1}; and χ is the characteristic dimension of a leaf in m. Stanghellini included factor of 2 L to make the k_e suitable for the P–M model.

Value of k_i is approximated according to Nederhoff (1994):

$$k_i = 0.0203\ \{1 - 0.44\ \exp(-2.5\times10^{-3}\, I_{PAR})\}\ \exp(-3.1\times10^{-4}\, c_{CO2}) \tag{2.15}$$

where: c_{CO2} is the ambient CO_2 concentration, expressed here in ppm. Here, I_{PAR} is expressed in µmol s^{-1} m^{-2}. The conversion for PAR is 1 W m^{-2} = 4.5 µmol s^{-1} m^{-2}.

2.2.2. Parameter estimations

Most model parameters can be estimated from literature. The long-wave radiative heat conductance between canopy and sky is calculated as function of crop development according to De Zwart (1996):

$$G_{Can\text{-}Sky,LWR} = 4\ \{(T_{Can} + T_{Sky})\,/\,2\}^3\ \varepsilon_{Can,LWR}\ \sigma\ \{1 - \exp(-\kappa_{Can,LWR}\ L)\}\ \tau_{Cov,LWR} \tag{2.16}$$

where: $\varepsilon_{Can,LWR}$ is the long-wave radiation emission coefficient of the canopy; σ is the Stefan–Boltzmann constant; $\kappa_{Can,LWR}$ is the long-wave radiation extinction coefficient of the canopy; and $\tau_{Cov,LWR}$ is the long-wave radiation transmission coefficient of the cover.

The sensible heat conductance between the canopy and the air is related to the boundary layer conductance for water vapour transport according to (De Zwart, 1996):

$$G_{Can\text{-}Air,CON} = 2\ L\ \rho\ c_p\,/\,r_e \tag{2.17}$$

Leaves exchange sensible heat at both sides of the leaf so the exchange area equals 2 L.

The overall sensible heat conductance between the greenhouse and outdoor air via the cover for a single span plastic greenhouse can be considered as dependent on external wind speed due to the external convection (Boulard & Baille, 1993; Boulard & Wang, 2000) as:

$$G_{Air\text{-}Out,CON} = 6 + 0.5\ U \tag{2.18}$$

The sensible and latent heat conductance between the greenhouse and outdoor air via ventilation openings are given as:

$$G_{Air\text{-}Out,VEN} = \rho\ c_p\ \varphi_{VEN} \tag{2.19}$$

$$G_{Air\text{-}Out,LAT} = \lambda\ M\ \varphi_{VEN}\,/\,R\ T \tag{2.20}$$

where: M is the molar weight of water in kg kmol^{-1}; R is the universal gas constant in J kmol^{-1} K^{-1}; and T is the air temperature in K.

Temperature of the sky for all sky conditions is according to Aubinet (1994):

$$T_{Sky} = 94 + 12.6 \ln(e_{Out}) - 13\,K + 0.341\,T_{Out} \quad \textbf{(2.21)}$$

where: K is the sky clearness index and is the average value of the ratio between S and S_E for the given day.

The saturation air water vapour pressure e^* in Pa as a function of air temperature (NASA, 2005) and slope of the saturation air water vapour pressure function δ in Pa K^{-1} are given as:

$$e^* = 2.229\times10^{11} \exp(-5385 / T) \quad \textbf{(2.22a)}$$

$$\delta = (5385 / T^2)\, 2.229\times10^{11} \exp(-5385 / T) \quad \textbf{(2.22b)}$$

2.3. Experimental details

2.3.1. Experimental site and test greenhouse dimensions

Six greenhouses having the same dimensions (**Fig. 2.2**) according to Campen (2005) were built in Purwakarta (107°30′ E, 6°30′ S, altitude 25 m), West Java, Indonesia for field experimentation. The greenhouses were covered with three types of 200 μm thick low density polyethylenes, UVR absorbing and diffusing, differing in NIR reflection.

Fig. 2.2 – Photograph of the greenhouses in the field

Two rows of three greenhouses were arranged, the distance between the greenhouses within the rows was 9.6 m and the distance between the rows was 10 m.

Ventilation openings were available in the sidewalls with width of 2.75 m. In the roof, the width of the horizontal ventilation opening below the lifted cover was 2 m. The ground area of the greenhouse was 144 m^2, the volume was estimated to be 823 m^3, average height was 5.72 m and average roof angle was 27.5°. All ventilation openings were covered with Mononet 600 insect screens.

2.3.2. Crop, cultural procedures, leaf area index and transpiration measurements

Tomato of a determinant growing type (variety 'Lentana') was grown in the six test greenhouses. Five beddings, all covered with plastic mulch (silver colour upside, black downside), were prepared in each greenhouse allowing excess irrigation water to drip via a 0.076 m gutter made of half poly vinyl chloride (PVC) pipe to the drainage collector placed outdoor each greenhouse. Each tomato plant was grown on a black polybag. The crops were transplanted at a leaf area index of 0.02 and cultivated according to the high-wire system. The crops were arranged in a double-row system with plant density of 2.94 m^{-2}.

Destructive samplings were made regularly with a 2 weeks interval. Specific leaf area was determined from measurement of leaf area and its corresponding dry weight, and thus the leaf area index was deduced. Crop transpiration during daytime (06:30 to 17:15) at a leaf area index of 1.39 was measured for two successive days at day of year (DOY) 322 and 323 by manually weighing and solving the water balance between irrigation and drainage from a total of 18 plants.

2.3.3. Measurement of climate

Global radiation and PAR were measured at a height of 4 m inside three greenhouses and outdoors using 4 pyranomters (CM11, Kipp and Zonen, Delft, The Netherlands) and 4 PAR sensors (TFDL, Wageningen, The Netherlands). Indoor sensors were mounted at a position meant not to be constantly shaded by the insect screens 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 with growing crop at 25 cm above the crop, and outdoors at a height of 1.5 m. Outdoor wind velocity 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.

2.4. Results and discussion

All reported results are based on data collected in the greenhouse with reference cover during one growing season, from 23 October 2003 to 27 January 2004 with outdoor climate as summarized in **Table 2.3**.

Table 2.3 – Summary of climatic condition during the experiment, for months of October, November, December 2003 and January 2004

	Average or instantaneous value			
	October	November	December	January
Rainfall, mm $month^{-1}$	23	117	156	235
Sum S, MJ m^{-2} d^{-1}	18.7	17.5	15.3	16.9
Maximum sum S, MJ m^{-2} d^{-1}	24.6	22.7	22.6	23.3
Maximum S, W m^{-2}	1134	1070	1084	1188
Clearness of sky, %	48	44	40	44
Sum PAR, MJ m^{-2} d^{-1}	8.4	7.6	6.8	7.2
Wind speed, m s^{-1}	1.6	1.4	1.7	1.4
Maximum wind speed, m s^{-1}	8.33	6.45	5.73	5.41
Temperature maximum, ^{o}C	34.2	33.1	32.2	32.1
Temperature minimum, ^{o}C	23.4	24.0	23.7	23.6
RH maximum, %	95.1	97.0	96.3	98.0
RH minimum, %	46.1	40.7	34.5	35.2
D_{Out} maximum, kPA	2.75	2.23	1.86	1.78
D_{Out} minimum, kPA	0.98	0.77	0.69	0.58

S, outdoor global radiation; PAR, photosynthetically active radiation; RH, outdoor air relative humidity; D_{Out}, outdoor air water vapour pressure deficit

Two sets of data were discriminated (**Table 2.4**).

Table 2.4 – List of the data used for model calibration and model validation

	2003					2004	
Model Calibration	1	2	3	4	5	6	7
DOY	296	322	336	350	364	13	27
Measured L	0.02	1.39	2.42	2.60	2.89	3.45	4.10
Model validation	1	2	3	4	5	6	7
DOY	302	316	330	344	358	7	21
Estimated L	0.07	0.81	2.15	2.53	2.75	3.18	3.84

DOY, day of year; L, leaf area index

Each data set represented seven individual days with various conditions of crop growth and weather so that the model was calibrated and validated on independent extensive boundary conditions. In the model, **Eqs. (2.2a)**, **(2.2b)** and **(2.2c)** were iteratively solved to calculate the state variables T_{Air}, e_{Air} and T_{Can}. Moreover, I_G and I_{PAR} were calculated from the radiation data. The variables, except T_{Can}, were also measured. Accuracy of model results was evaluated using percent error of the mean values and root-mean-square error (RMSE).

Table 2.5 – Values of parameters used in the model

Parameter	Value	Description
Plastic cover		
Thermal transmission $\tau_{cov,LWR}$	0.3845	Measured
Insect screens		
Transmission for diffuse $\tau_{Scr,dif}$	0.765	Deduced from comparable screens
Transmission for direct $\tau_{Scr,dir}$	0.882	Deduced from comparable screens
Ventilation reduction ς	0.40	Measured
Greenhouse		
Width, side ventilation $w_{o,s}$, m	2 x 2.75	By design
Length, side ventilation $l_{o,s}$, m	2 x 24.6	By design
Width, roof ventilation $w_{o,r}$, m	2	By design
Length, roof ventilation $l_{o,r}$, m	15	By design
Volume, m^3	823	By design
Floor area, m^2	144	By design
Average height h, m	5.7	By design
Diagonal length d, m	17.8	By design
Structural absorption α_{Str}	0.03	De Zwart (1996), modified
Screen absorption α_{Scr}	0.04	De Zwart (1996)
Screen light obstruction O_{Scr}	0.21	By design
Wind pressure coefficient C_w	0.04	Campen (2005), CFD calibrated
Discharge coefficients		
Side ventilation $C_{d,s}$	0.662	Bot (1983); calculated
Roof ventilation $C_{d,r}$	0.676	Bot (1983); calculated
Crop canopy coefficients		
Thermal extinction $\kappa_{Can,LWR}$	0.64	Stanghellini (1987)
PAR extinction $\kappa_{Can,PAR}$	0.715	Goudriaan & Van Laar (1994)
PAR reflection $\Upsilon_{Can,PAR}$	0.057	Goudriaan & Van Laar (1994)
NIR extinction $\kappa_{Can,NIR}$	0.358	Goudriaan & Van Laar (1994)
NIR reflection $\Upsilon_{Can,NIR}$	0.389	Goudriaan & Van Laar (1994)
Thermal emission $\varepsilon_{Can,LWR}$	0.987	Sugita *et al.* (1996)

PAR, photosynthetically active radiation; NIR, near-infrared radiation; CFD, computational fluid dynamics

The ventilation sub model was parameterised with the CFD results (Campen, 2005) applying Econet SF insect screen. This screen has a ventilation reduction of 0.44 (Ajwang & Tantau, 2005). Meanwhile the ventilation reduction of the Mononet 600 used in the experimental prototype greenhouse was determined to be 0.40. Accordingly, values for C_w of 0.04 and average u of 0.10 m s^{-1} were derived. With values for χ of 0.05 m, and $T_{Can} - T_{Air}$ of 2 K (Stanghellini, 1987), the calculated value for $G_{Can\text{-}Air,CON}$ is 11.2 L W m^{-2} K^{-1} in the crop transpiration model. The other parameters for the model are given in **Table 2.5**.

2.4.1. Calibration of the model

Measured and computed radiation data agreed well (**Fig. 2.3**) however at midday during clear days with high direct radiation level a difference was observed. Interaction between direct radiation and greenhouse construction elements (structure, plastics, and screens) produces unevenness of shadow patterns inside the greenhouse. One stationary radiation instrument placed inside the greenhouse then deviates from the average.

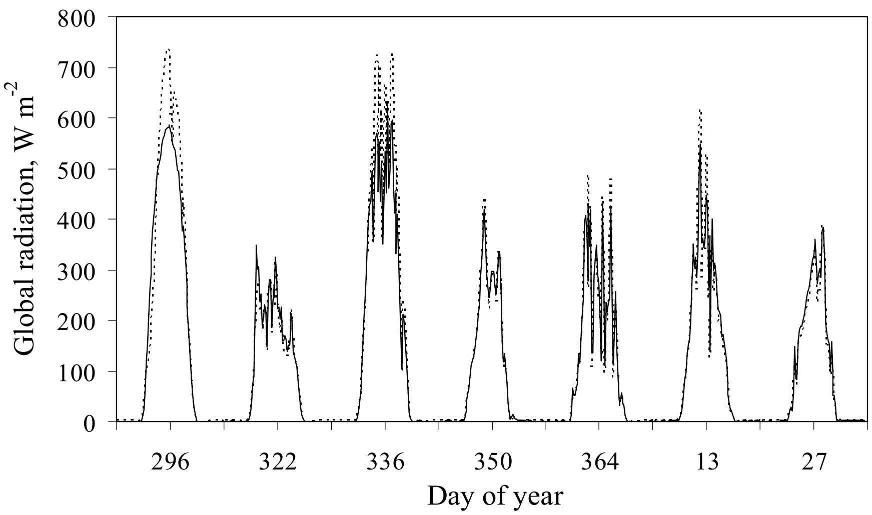

Fig. 2.3 – Model calibration for 7 non-successive days. Time courses of the global radiation transmission through the greenhouse: ——, measured; ------, calculated

Several tests revealed that only a small part of the solar radiation absorbed by the opaque elements of the greenhouse, as expressed in **Eq. (2.2b)**, was released to the greenhouse air. Therefore, a value of 0.1 for the calibration factor Λ, as applied in **Eq. (2.7)**, fitted best for the data set with leaf area index from 0.02 to 4.1. The use of a value for Λ of 0.1 for an extensive range of leaf area index is helpful, because it allows the simple model to be suitable for various climatic conditions independently from growth stages. The value for Λ of 0.1 was related to the naturally ventilated plastic greenhouse with a high coupling between the greenhouse and the outdoor climatic conditions

The agreement between the measured and calculated states variables T_{Air}, and e_{Air} (expressed as vapour pressure deficit D_{Air}) was evident at 5 out of 7 days used for the model calibration (**Fig. 2.4**). The error observed at DOY 350 could be related to an error on the measured T_{Out}, whiltst the errors observed at DOY 364 could be related to an error on the measured e_{Air}. The behaviour of the computed T_{Can} (**Fig. 2.4**) was comparable to the T_{Can} reported by other researchers (Yang *et al.*, 1990; Boulard & Baille, 1993; Papadakis *et al.*, 1994).

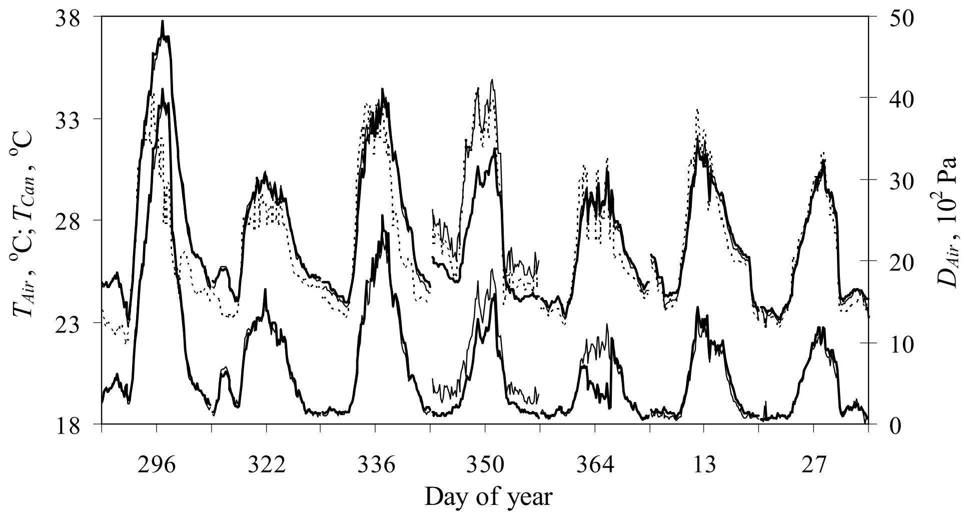

Fig. 2.4 – Model calibration for 7 non-successive days. (Upper graph) Time courses of the greenhouse air temperature T_{Air}: —, measured; ——, calculated; canopy temperature T_{Can}: -----, calculated; (Lower graph) time courses of the greenhouse air water vapour pressure deficit D_{Air}: —, measured; ——, calculated

The measured and calculated cumulative daytime transpiration fluxes on the two successive days they were measured, were comparable (measured 1.57 mm and 1.59 mm; calculated 1.78 mm and 1.58 mm, respectively). This indicates that applying k_e of Stanghellini (1987) and k_i of Nederhoff (1994) in the P–M model was justified.

Table 2.6 – Mean values of the measured and computed transmission of global and photosynthetically active radiation by the greenhouse I_G and I_{PAR}, and the air temperature and water vapour deficit in the greenhouse T_{Air}, and D_{Air} and their corresponding values for the percent error and root mean square error (RMSE).

	Measured	Calculated	Percent error	RMSE
I_G, W m^{-2}	150	142	5	42
I_{PAR}, W m^{-2}	67	64	4	17
T_{Air}, °C	27.28	27.17	0.4	0.36
D_{Air}, kPa	0.73	0.72	2.4	0.10

Number of data 762

2.4.2. Validation of the model

For the validation data set (**Table 2.4**) the model calculated I_G and I_{PAR} and the states variables T_{Air}, D_{Air} (**Fig. 2.5**) satisfactorily. The errors were less then 5% with RMSE of 42 W m^{-2} for I_G, 17 W m^{-2} for I_{PAR}, 0.39°C for T_{Air}, and 0.10 kPa for D_{Air} (**Table 2.6**).

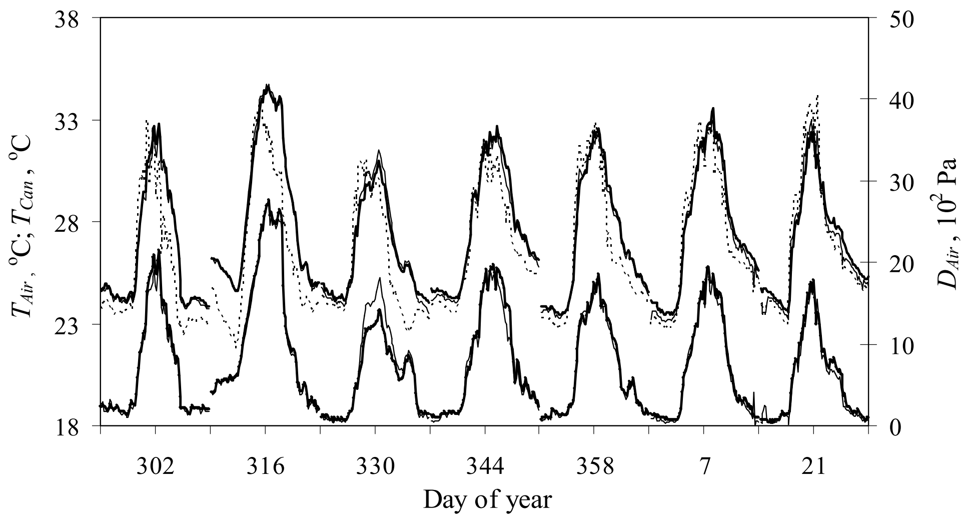

Fig. 2.5 – Model validation for 7 non-successive days. (Upper graph) Time courses of the greenhouse air temperature T_{Air}: —, measured; ——, calculated; canopy temperature T_{Can}: -----, calculated; (Lower graph) time courses of the greenhouse air water vapour pressure deficit D_{Air}: —, measured; ——, calculated

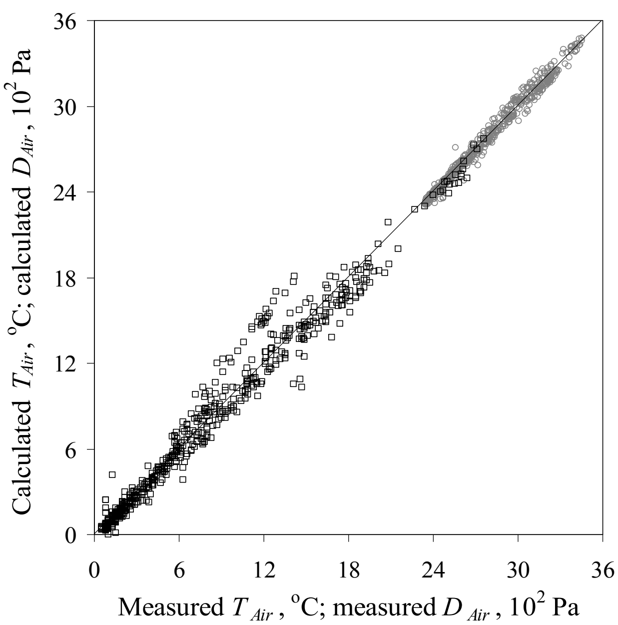

Fig. 2.6 – Model validation for 7 non-successive days. Calculated versus measured: □, greenhouse air water vapour pressure deficit D_{Air}; ○, greenhouse air temperature T_{Air}

Scatter plot of the measured and computed T_{Air} and D_{Air} (**Fig. 2.6**) shows that the calculated and measured data were well represented around the 1:1 line. Therefore we can conclude that the simple model is capable of representing the greenhouse behaviour satisfactorily.

2.4.3. Application of the model

The radiation distribution sub model is capable to calculate radiation transmission by the greenhouse including reduction of NIR transmission through the cover. Variation in greenhouse dimension and ventilation openings closely corresponds to variation in airflow through the openings, which can be quantified in the ventilation submodel. The effect of the crop is evaluated in the transpiration submodel. Each submodel is uniquely simulating effects of variation of their corresponding parameters on the state variables. With these features, the model is applicable for: (i) evaluating the effects of ventilation, cover properties, and crop transpiration on the inside greenhouse climate; and (ii) designing an optimal tropical lowland greenhouse based on the selection of the greenhouse dimensions (floor area, volume, ventilation area) and the covering material properties

2.5. Conclusions

A simple dynamic climate model was developed enabling the calculation of three state variables: average greenhouse air temperature; average greenhouse air water vapour pressure and average canopy temperature. The model was parameterised, calibrated, and validated thoroughly. A consistent performance of the model was observed, both in the calibration and validation stage. All calculation errors were less than 5% of the measured mean values. It is concluded that the model is robust and could be used as design tool for the tropical lowland greenhouse, optimizing especially cover properties and ventilation. However, the size and geometry of the ventilation openings realizing the designed ventilation has to be determined subsequently by, *e.g*. CFD modeling.

3

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

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Abstract

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 satisfactory 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 value for the leaf area index. The model performance slightly improved by including the effect of leaf area index on the 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 high amount of cooling is achieved by the crop itself. The results enable the model to be used in the design of optimum greenhouse system for tropical lowland in Indonesia.

3.1. Introduction

Tropical lowland climates are characterised by high global radiation, air temperature, air humidity, and sometime high wind speed and high rainfall. In these regions, open field cultivation has to be adapted to a 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 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 obove prevailing high outdoor air temperature in the tropical lowland will stress the greenhouse crop. Lowering the air temperature is the 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 (NIR) reflecting pigments (Hoffmann & Waaijenberg, 2002; Hemming *et al.*, 2006a, 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 mean temperature of the greenhouse air by 1^{o}C, while higher differences at maximum temperature of the greenhouse air occurred at the maximum temperature of the greenhouse air (Hemming *et al.*, 2006b). 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 10m by 20m tropical greenhouse in Bangkok (Harmanto *et al.*, 2006).

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

Important parameters for designing the tropical lowland greenhouse are solar radiation, natural ventilation, and crop transpiration. As a first approach in 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.

3.2. 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):

$$0 = P_{Can} - G_{Can\text{-}Sky,LWR}\,(T_{Can} - T_{Sky}) - G_{Can\text{-}Air,CON}\,(T_{Can} - T_{Air}) - \lambda E_{Can\text{-}Air} \quad \textbf{(3.1a)}$$

$$0 = P_{Air} + G_{Can\text{-}Air,CON}\,(T_{Can} - T_{Air}) - G_{Air\text{-}Out,CON}\,(T_{Air} - T_{Out}) - G_{Air\text{-}Out,VEN}\,(T_{Air} - T_{Out}) \quad \textbf{(3.1b)}$$

$$0 = G_{Air\text{-}Out,LAT}\,(e_{Air} - e_{Out}) - \lambda E_{Can\text{-}Air} \quad \textbf{(3.1c)}$$

where: P_{Can} is the absorption of solar radiation 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 to the greenhouse air) in W m^{-2}; $G_{Can\text{-}Sky,LWR}$ is the heat conductance (transfer coefficient) between 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:

$$P_{Air} = \Lambda\,(P_{Cov} + P_{Str} + P_{Soi}) \qquad \textbf{(3.2)}$$

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 under reference greenhouse showed that a value of 0.1 for the Λ fitted best for the data set with leaf area index from 0.02 to 4.1, resulting in a satisfactorily 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 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); 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).

3.3. Experimental details

3.3.1. Greenhouses

Six greenhouses having similar dimensions (**Fig. 3.1**) were built in Purwakarta (107°30′ E, 6°30′ S, altitude 25 m), West Java, Indonesia.

Fig. 3.1. Photograph of the six greenhouses in the field

The east-west oriented greenhouses were arranged in two rows of three greenhouses with separation distance 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 average roof angle of 27.5^{o}. Each greenhouse volume was 823 m^3 and covering (sidewalls and roof top) surface area was 386 m^2.

3.3.2. Cover optical properties

Each greenhouse was covered with 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 3.1**.

Table 3.1 – Transmission τ, absorption α, and reflection Υ coefficients, 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	τ	0.136	**0.765**	0.758	**0.159**	**0.896**	**0.888**
	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, the others estimated.
UVR, ultra-violet radiation; PAR photosynthetically active radiation; NIR near-infrared radiation.

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 for N1 and N2, respectively.

3.3.3. 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 m and to 1.75 m in the front and rear walls in order to amplify the radiation effect compared to the ventilation effect.

3.3.4. 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 experimentations. Experiment 1 was started (transplanting) on 23/10/2003 at the beginning of the wet season and ended (last harvest) on 27/1/2004 at the middle of wet season. Experiment 2 was from 22/03/2004 at 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.

3.3.5. 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 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 upside, black downside). Destructive samplings were made regularly with a 2 weeks interval. Specific leaf area was determined from measurements of leaf area and its corresponding dry weight, and thus the leaf area index deduced.

3.3.6. 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 outdoor at a height of 1.5 m. Outdoor wind velocity 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.

3.3.7. 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 satisfactorily 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 ventilation openings was used to quantify the ventilation aspects. In Experiment 1, the ratio of the total ventilation opening to greenhouse covering surface area was 0.427 with 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 & Baille (1995) and Roy *et al.* (2002).

3.3.8. 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 condition during Experiments 1, 2, and 3 is summarised in **Table 3.2**.

In general, the measured climatic conditions in Purwakarta, Indonesia, are typical of tropical lowland. 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 temperature of 27.5°C and sometimes with maxima above 35°C; these represent high levels of boundary conditions for tropical lowland greenhouses. In each data set, 14 non-successive days were selected for model validation (**Table 3.2**), while 7 out of these 14 days were taken at the days of destructive crop samplings with the leaf area index of 0.01–4.97.

Table 3.2 – Summary of climatic condition 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} day^{-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} day^{-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
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 10 m height, Max maximum value, Min minimum value, Ave average value

3.4. Results and discussion

3.4.1. Greenhouse climate

Radiation

Three types of greenhouse cladding were characterised mainly by the differences in their radiation transmission coefficients. Order of magnitudes of global and PAR transmission by the greenhouses, I_G and I_{PAR}, always follow N0 > N1 > N2 (**Figs. 3.2** and **3.3**). The daily courses of T_{Air} and D_{Air} and L are given in **Figs. 3.4** and **3.5**. 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 3.1**). In all greenhouse types over the three successive experiments, there tended to be smaller daily averages of radiation transmission coefficient on clear sunny day. The calculated daily I_G to I_{PAR} ratios for overall averages were 0.45, 0.46, and 0.47 for N0, N1, and N2 respectively; these were close to calculated theoretical values of 0.45, 0.47 and 0.48.

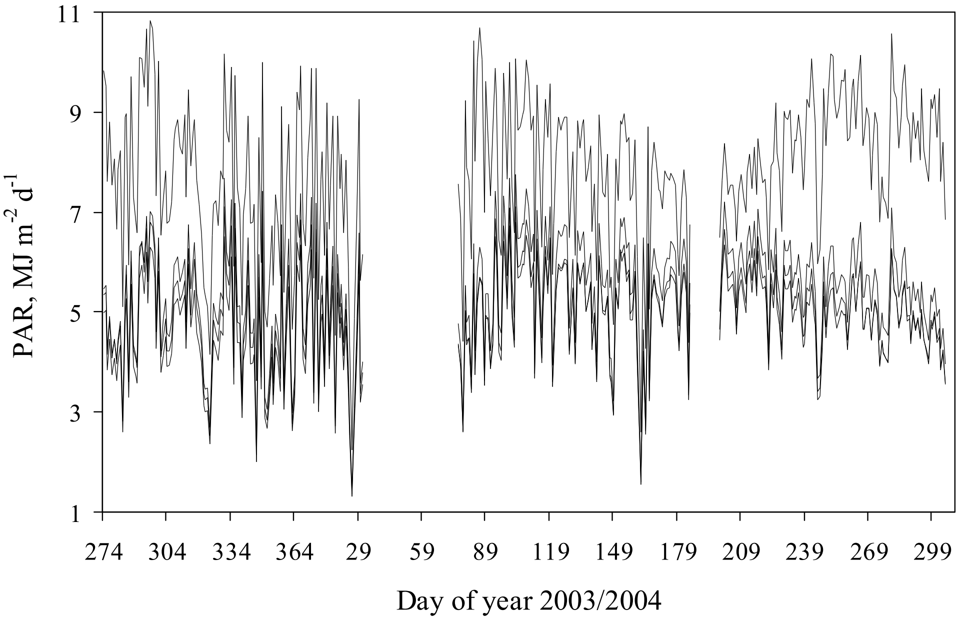

Fig. 3.2 – Daily global radiation *S*; lines from top to bottom represent *S* outdoor and inside greenhouses with three different plastic films (reference N0, and two levels of near-infrared reflecting pigments N1 and N2)

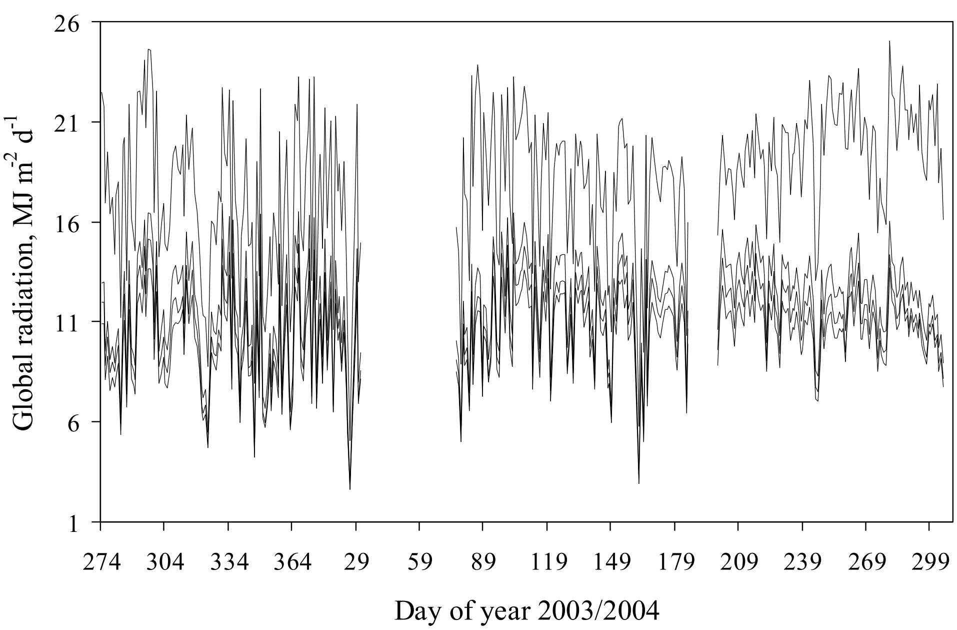

Fig. 3.3 – Daily photosynthetically active radiation PAR; lines from top to bottom represent PAR outdoor and inside greenhouses with three different plastic films (reference N0, and two levels of near-infrared reflecting pigments N1 and N2)

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 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 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.

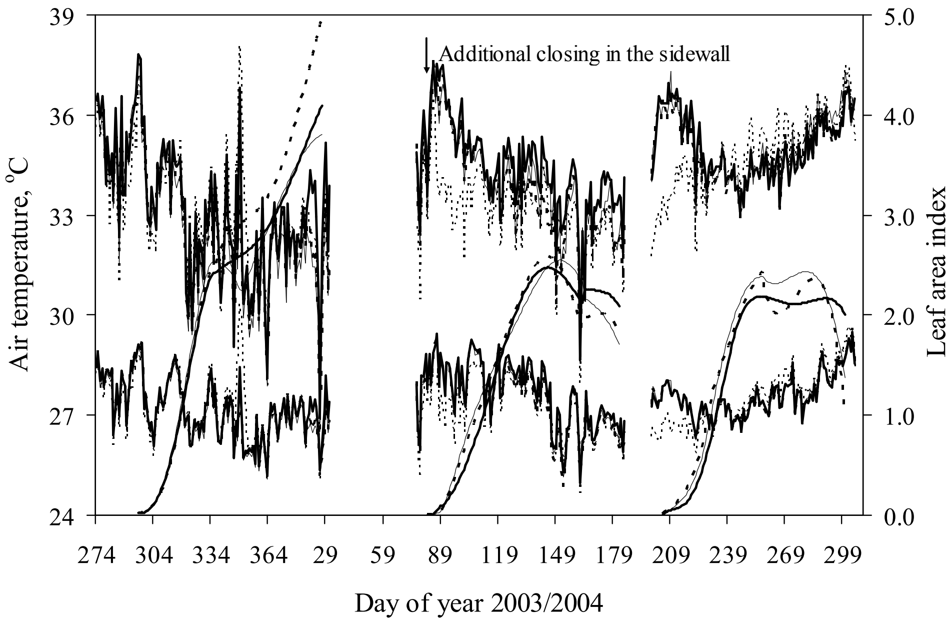

Fig. 3.4 – Measured maximum (upper lines) and average (lower lines) air temperature and leaf area index for the three greenhouse experiments: ▬▬, film type N0; ——, film type N1; - - -, film type N2; ------, outdoor; the diagram shows that the internal climate is virtually indistinguishable under the three films

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 variation in T_{Air} and D_{Air} are mainly affected by outdoor weather, leaf area index, and ventilation openings.

T_{Air} and D_{Air} were higher inside an empty greenhouse compared to outdoor (start of Experiment 1). Additional closing of ventilation opening amplified these differences (start of Experiments 2 and 3). For example, the differences of average values of the maximum T_{Air} initially were around 1°C then became 3°C and the maximum D_{Air} of 0.3 kPa became 0.8 kPa. Growing crops inside the greenhouses increase the energy conversion into latent heat and increases the air water vapour content, while decreasing greenhouse T_{Air} and D_{Air}. This can be seen more clearly in Experiment 2 and 3 (**Figs. 3.4** and **3.5**).

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.

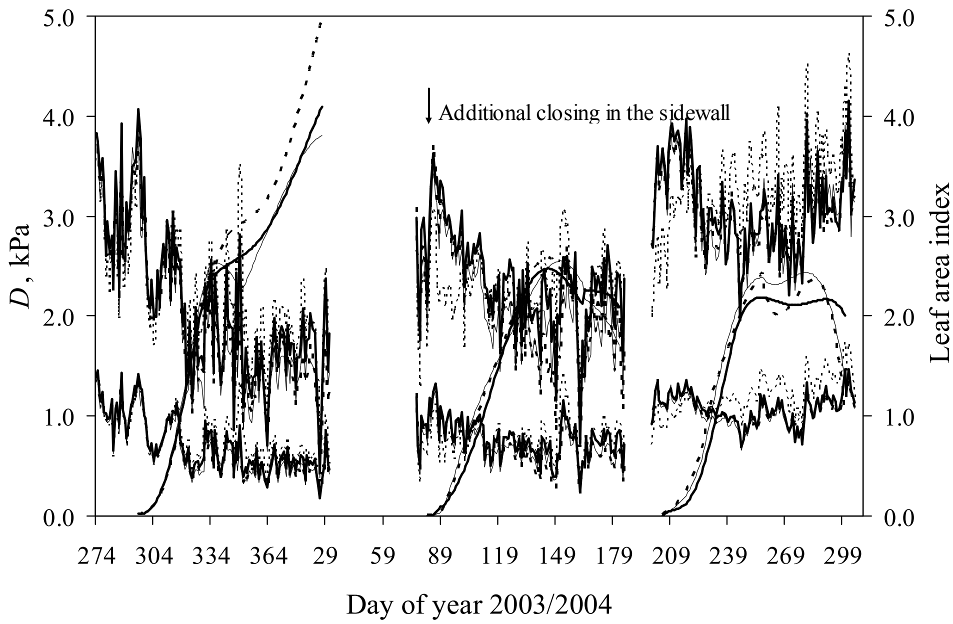

Fig. 3.5 – Measured maximum (upper lines) and average (lower lines) air water vapour pressure deficit D and leaf area index for the three greenhouse experiments: ▬▬, film type N0; ——, film type N1; - - -, film type N2; ------, outdoor; the diagram shows that the internal climate is virtually indistinguishable under the three films

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 3.4**).

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.

3.4.2. 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. 3.6**. These are days with daily integral outdoor global radiation of about 20 MJ m^{-2} d^{-1}. The first day has 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, full developed crop (*L* 1.91). When the greenhouses were empty and the ventilation walls were open; the calculated 24-hour, day, and night averages of T_{Out} were lower than T_{Air}.

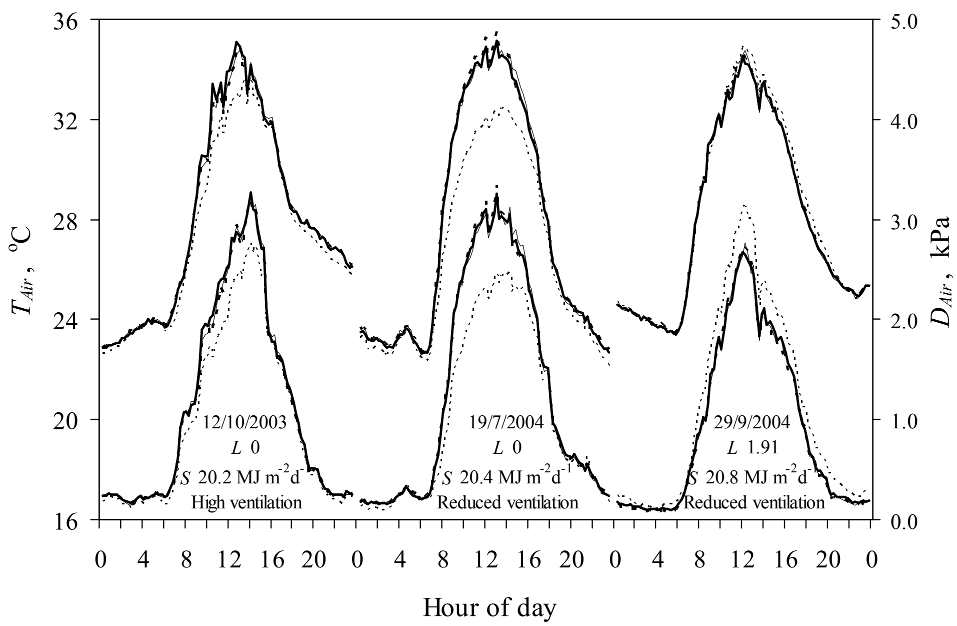

Fig. 3.6 – Diurnal course of air temperature T_{Air} (upper lines) and air water vapour pressure deficit D_{Air} (lower lines) from three different dates for the three greenhouse experiments: ▬▬, film type N0; ——, film type N1; - - -, film type N2; ------, outdoor; S outdoor global radiation; *L* leaf area index; the diagram shows that the internal climate is virtually indistinguishable under the three films

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 opening were partly closed. On these three days, similar responses of D_{Air} prevail.

3.4.3. 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. 3.7**).

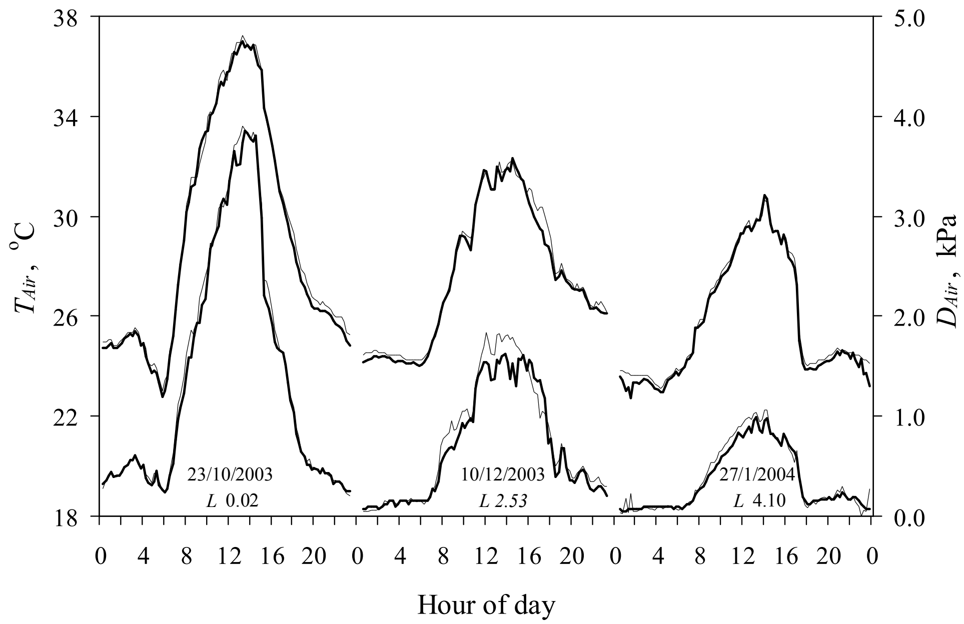

Fig. 3.7 – Example of model validation for 3 non-successive days in greenhouse N2 of Experiment 1; variation in the greenhouse air temperature (upper lines) and the greenhouse air water vapour pressure deficit (lower lines): ▬▬, measured; ——, calculated; the model validation was with the calibration factor for indirect absorbed solar radiation $\Lambda = 0.1$; L leaf area index

In Experiment 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 3.3**). In Experiment 2, the errors were higher; of 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 3.3**). In most cases, the values were underestimated. The error seemed to be higher when crop leaf area index was low. This might be attributed to the value of Λ.

A scatter plot of Λ vs. L (Fig. 3.8) 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 partly can be explained by the fact that when 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:

$$\Lambda = 0.10 + 0.15 \exp(-L) \tag{3.3}$$

Modification of the values according to **Eq. (3.3)** was applied in all data sets. In the original model, 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.

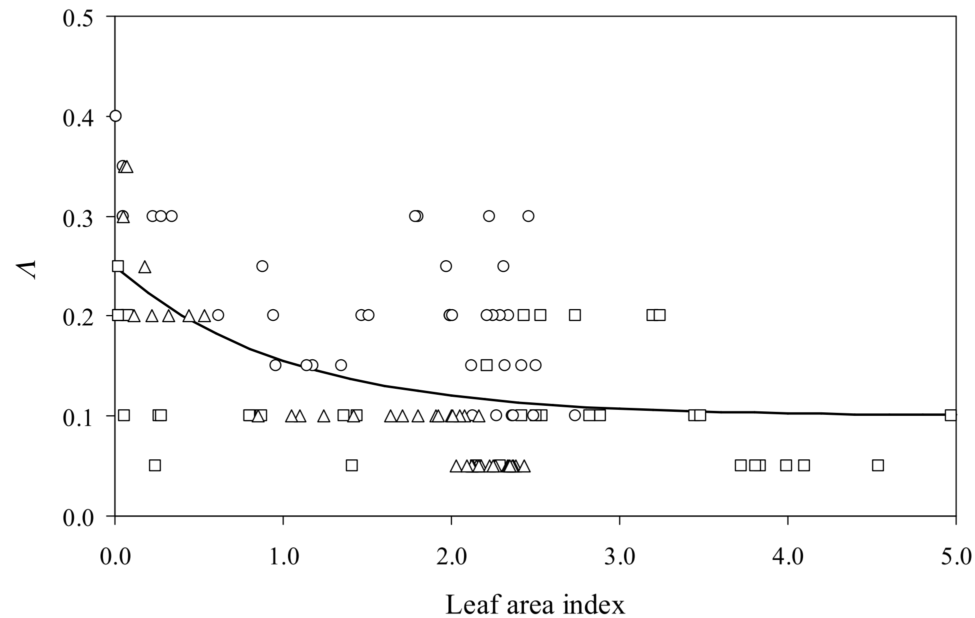

Fig. 3.8 – Scatter plot of calibration factor for indirect absorbed solar radiation Λ as a function of leaf area index L: □, Experiment 1; ○, Experiment 2; △, Experiment 3; the line is according to $\Lambda = 0.10 + 0.15 \exp(-L)$

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

As a result of cover property variations, 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} increases considerably especially at low leaf area index (**Fig. 3.4**). At 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 less than 0.1°C, 0.3°C and 0.03 kPa, respectively (**Tables 3.3** and **3.4**). 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 differed less than 0.1°C, 0.2°C and 0.01 kPa, respectively (**Tables 3.3** and **3.4**).

Table 3.3 – 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 $\Lambda = 0.1$

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, W m^{-2}	125	117	6	41	138	126	9	49	135	132	2	55
	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

In the model, the radiation calibration factor Λ was determined by fitting calculated to measured T_{Air} during the daytime. No compensation was given for the rate of released heat by the soil surface to the air that might increase T_{Air} during 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} satisfactory (**Fig. 3.7**) with the mean values of the calculated state variables T_{Air} and D_{Air} close to the measured ones (**Table 3.3**). 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 3.4**).

Table 3.4 – 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 percent error; calculations were with calibration factor for indirect 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

3.5. Conclusions

The climate inside the experimental greenhouses was close to the outdoor climate due high ventilation openings. The effect of the different greenhouse covering materials within the range on greenhouse climate 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 radiation calibration factor Λ of 0.1, but with higher error at a low leaf area index. The model performance 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 reduces 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 (NIR) reflecting greenhouse coverings obviously makes sense when a higher amount of NIR is reflected without loosing 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 tropical lowland in Indonesia.

4

The effects of cover properties, greenhouse dimensions, and crop transpiration on tropical lowland greenhouse climate supporting greenhouse design

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The effects of cover properties, greenhouse dimensions and crop transpiration on tropical lowland greenhouse climate supporting greenhouse design.

Abstract

Designs of naturally ventilated greenhouse in the tropical lowland of Indonesia were studied according to climatic conditions simulated using a simple greenhouse climate model (GCM). Dimensions of field-tested prototype greenhouses (ground area of 9.6 m by 15 m or 144 m^2, average height of 5.72 m, standard sidewalls ventilation opening of 2.75 m, covering surface of 387 m^2) were used as basis for the design. The design optimized effects of: (i) greenhouse near infrared radiation (NIR) transmission (0.0-0.77, with reference 0.69) affecting the amount of energy input, (ii) greenhouse ground areas (144 m^2–14400 m^2) influencing ventilation rates, (iii) leaf area index L (0.02–5.0) determining transpirations, and (iv) boundary conditions (hot, humid, and moderate wind speed; hot, humid, and higher wind speed; and hot, dry, and lower wind speed). The performance of the greenhouse design was analyzed based on the differences between maximum greenhouse air temperature calculated using GCM and outdoor maximum air temperature data ($\Delta T_{A\text{-}O}$). Critical conditions ($\Delta T_{A\text{-}O} > 0$) generally occur when L is low. Values of $\Delta T_{A\text{-}O}$ at L 0.02 under greenhouse with reference plastic and standard ventilation opening reached as high as 1.4°C (under 9.6 m by 15 m or 144 m^2 greenhouse) and 8°C (under 96 m by 150 m or 14400 m^2 greenhouse). At higher L, the problems with high T_{Air} diminished as transpiration process takes dominant effect on cooling greenhouse air. Above L 1, maximum T_{Air} mostly became lower than maximum T_{Out}. Simulations revealed that application of plastic having low NIR transmission could reduce greenhouse air temperature, crop temperature and crop transpiration. Effect of NIR reduction on reducing T_{Air} was more significant under smaller L, bigger greenhouse, and humid conditions. Meanwhile, at high L, transpiration cooling alone was able to keep T_{Air} low. An even lower T_{Air} was simulated from a more intensive transpiration cooling under hot and dry boundary conditions. Present study indicated that naturally ventilated model greenhouses of up to size of 14400 m^2 were capable to create suitable climate ($\Delta T_{A\text{-}O}$ close to or lower than zero) when the greenhouse crops had L of higher than 0.5.

4.1. Introduction

In the tropical lowland regions in Indonesia, open field crop cultivation is the most common but faces harsh outdoor conditions. Protection of these conditions by greenhouses with transparent cladding and insect net materials in the ventilation openings offers an alternative for the crop production system. However, there is a major deficiency in the naturally created climate under the tropical lowland greenhouse as the cover, being a barrier against air exchange with the ambient, can cause heat accumulation, especially during periods of high solar radiation which is commonly coupled with high outdoor air temperatures. This imminently leads the greenhouse air temperature to become too high (Bailey, 2006). Under such conditions, cooling the greenhouse compartment has always been necessary for greenhouse operation in warm climates in order to create a suitable microclimate around the crop. The cooling can be realized by combination of the following methods: (1) reducing radiative heat load by the application of a) near infrared radiation (NIR) reflecting cladding materials (Hoffmann & Waaijenberg, 2002; Hemming *et al.*, 2006a, 2006b) by application of shading (Kittas *et al.*, 2003) or by whitewashing (Kittas *et al.*, 1999; Baille *et al.*, 2001; Luo *et al.*, 2005); (2) removing excess heat from the greenhouse compartment, which is typically accomplished by ventilation, either mechanically, via exhaust fans, or naturally, via wind and buoyancy (Willits, 2003; Montero *et al.*, 2001; Harmanto *et al.*, 2006); and (3) increasing the fraction of energy conversion into latent heat by evaporative cooling via crop transpiration (Katsoulas *et al.*, 2002; Ajwang & Tantau, 2005; Impron *et al.*, 2007, 2008), misting or fogging (Katsoulas *et al.*, 2001; Arbel *et al.*, 2003), or cooling pads (Kittas *et al.*, 2003). Other cooling methods were also studied in literature, such as employing heat exchanges between soil and greenhouse air (Ghosal & Tiwari, 2006).

Designing naturally ventilated greenhouses for the tropical lowland conditions therefore requires inclusion of parameters most influential to the cooling processes: solar radiation, natural ventilation, and crop transpiration (Impron *et al.*, 2007, 2008). The static design of geometry and ventilation openings can be accomplished by the use of computational fluid dynamics (CFD) as a powerful tool to simulate airflow and temperature distribution based on static greenhouse characteristics and prevailing static boundary conditions (Campen, 2005). The dynamical behaviour including the influential parameters can be simulated by a lumped parameter greenhouse climate model (GCM) with dynamic climate data as boundary conditions. This GCM is based on the dynamically changing greenhouse energy balance equations relating the state variables and the exogenous variables, crop conditions, and characteristics of greenhouse cover transmission and ventilation (Bot, 1983; Boulard & Baille 1993, 1995; De Zwart, 1996; Boulard & Wang, 2000; Abreu *et al.*, 2005; Kittas *et al*, 2005).

To calculate the climate conditions in a naturally ventilated greenhouse in the tropical lowland a GCM was developed and presented earlier (Impron *et al.,* 2007). This GCM was calibrated and validated with experimental data under a wide range of conditions and gave satisfactory results (Impron *et al.,* 2008). In this paper the GCM is used to survey the sensitivity of the growth conditions in naturally ventilated greenhouses for tropical lowland in Indonesia for the effects of cover properties, ventilation and crop transpiration at prevailing outdoor climate conditions.

4.2. The simple greenhouse climate model

The simple GCM (Impron *et al.,* 2007) was developed on the basis of hourly average 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 hourly average outdoor climate data; (iii) solar radiation imposes heat fluxes to the greenhouse cover, the greenhouse structural elements, and the soil surface; (iv) mentioned absorbed solar radiation fluxes are released as sensible heat (with some delay) for a determined part to the greenhouse air; (v) crop transpiration is calculated according to a Penman–Monteith type model. The greenhouse cover has known optical properties defined in the relevant spectral regions of photosynthetically active radiation (PAR) and NIR.

The GCM employed three underlying sub models: 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 with the outdoor vapour pressure D_{Air} in Pa), and average canopy temperature T_{Can} in K. A complete description of the GCM, including the estimation of all model parameters was given in Impron *et al.* (2007), the calibration and validation was presented in Impron *et al.* (2008).

4.3. Greenhouse design

4.3.1. Dimensions of the prototype single span experimental greenhouse

The original dimensions of the prototype experimental greenhouse were designed applying CFD (Campen, 2005). The result was a greenhouse with both sidewall and "jack roof" ventilation openings to ensure high ventilation capacity and acceptable temperature distribution. The width of the ventilation openings in the sidewalls was designed at 2.75 m. In the roof, the width of the horizontal ventilation opening below the lifted central part of the cover was 2 m. All ventilation openings were covered with insect nets Mononet 600. The greenhouse had width of 9.6 m, length of 15 m, ground area of 144 m^2, volume of 823 m^3, average height of 5.72 m, average roof angle of 27.5^o, and covering surface of 387 m^2. The prototype greenhouse had ratio of ventilation opening to greenhouse covering (RVC) of 0.43 and ratio of ventilation opening to greenhouse ground area (RVG) of 1.15. The greenhouse floor was soil, not concretized. Plastic mulches were used for bedding and run-off medium for the excess irrigation. A full description is given in Impron *et al.* (2007).

4.3.2. Selection of boundary conditions for the sensitivity analysis

Based on the GCM testing (Impron *et al.*, 2008) higher air temperature inside naturally ventilated greenhouses was related to higher global irradition S, lower wind speed U, higher outdoor temperature T_{Out}, and lower vapour pressure difference with outside D_{Out} especially when the grown crop was still young. For a crop with high leaf area index, the greenhouse climate was moderated by transpiration cooling. Accordingly, boundary conditions for greenhouse design have to be implemented with the following importance sequence: S, U, T_{Out} and D_{Out} and these design boundary conditions have to be extracted from the full data set for some characteristic days for the operational climate conditions. The collected data was divided into three periods: Period 1 was from the beginning of the rainy season (October 2003) till mid-way the rainy season (January 2004). Period 2 was started mid-way the rainy season (February 2004) and ended at the end of the rainy season (June 2004). Period 3 was between the beginning of the dry season (July 2004) and the end of the dry season (October 2004).

The daily data for *S*, T_{Out} maximum, D_{Out} maximum, and *U* averages during the three successive experimental periods are presented in **Fig. 4.1.**

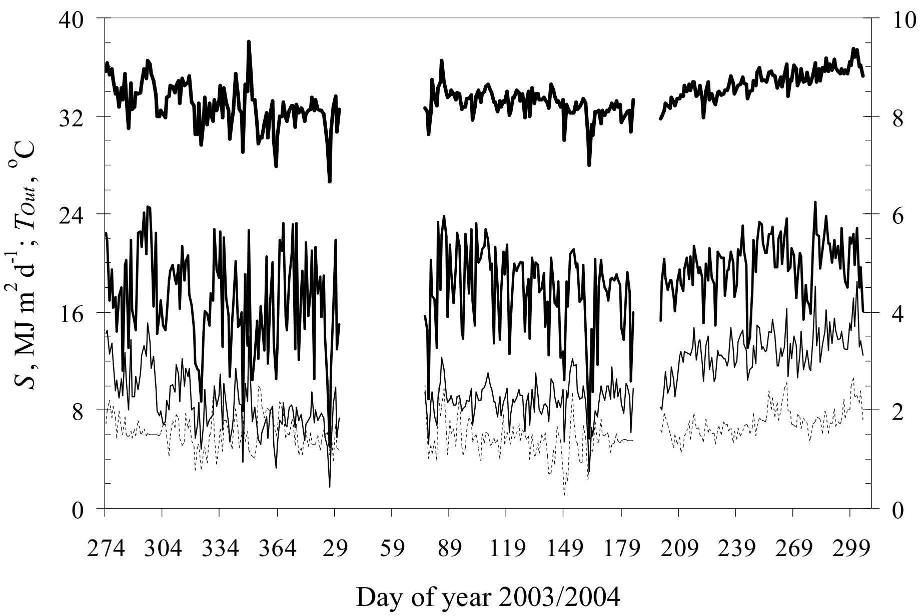

Fig. 4.1 – Representation of outdoor climates: ▬▬, maximum air temperature T_{Out}; ――, daily sum of global radiation *S*; ——, maximum air water vapour pressure deficit D_{Out}; ------, average wind speed *U*

The ranges of the daily values over the three periods were: *S* 5.1-25.0 MJ m^{-2} d^{-1}, T_{Out} maximum 26.6-38.1^{o}C, D_{Out} maximum 0.4-4.6 kPa, and *U* average 0.3-2.7 m s^{-1}. The highest values of the maximum T_{Out} of 38.1, 36.5, and 37.5^{o}C were associated with the occurrences of high daily *S* of 22.6, 22.3, and 22.3 MJ m^{-2} d^{-1}, respectively for Periods 1, 2, and 3.

If compared to the wet season Periods 1 and 2, the dry season Period 3 was indeed characterised by much drier air and generally coupled with higher *S* and T_{Out}, thus represented high evaporative demand. According to Kittas *et al.* (2003), evaporative cooling systems are efficient for dry conditions, but not really for humid conditions. Therefore, in the design of naturally ventilated greenhouse, the low D_{Out} is also a relevant constraint. From the data three typical days are chosen. The highest daily *S* values in Periods 1, 2, and 3 of 24.6, 23.9 and 25.0 MJ m^{-2} d^{-1} occurred on 23 October 2003, 26 March 2004, and 6 October 2004; and notated as B_1, B_2, and B_3 respectively.

Looking to T_{Out}, D_{Out} and U at these days, the weather of B_1 can be described as a typical day with hot, humid, and lower wind speed; B_2 as a typical day with hot, humid, and higher wind speed; and B_3 as a typical day with hot, dry, and moderate wind speed. Therefore the data on these dates are selected as boundary conditions for the sensitivity analysis with the GCM. The diurnal courses of these data are given in **Fig. 4.2.**

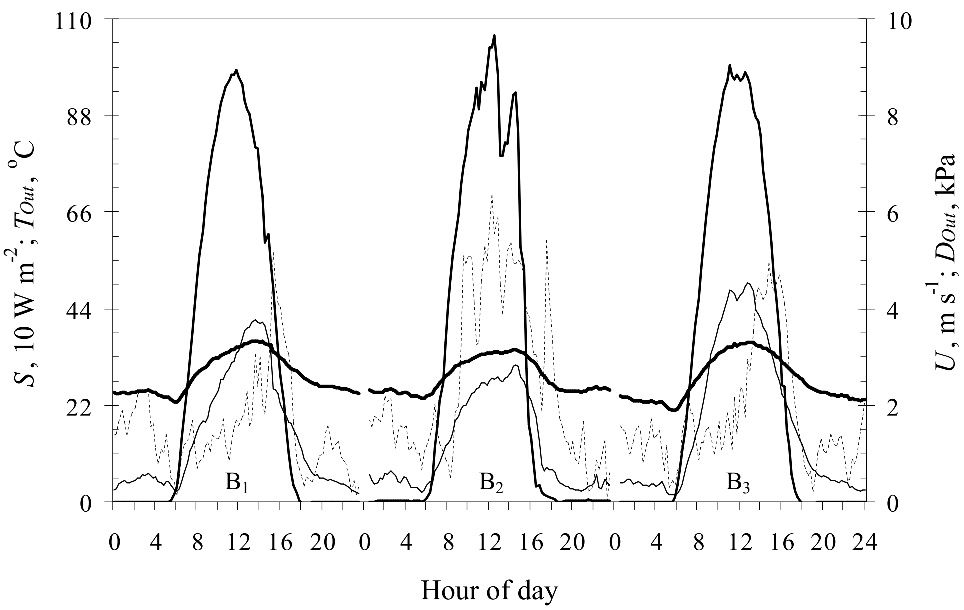

Fig. 4.2 – Diurnal course of the data on 23 October 2003 (B_1), 26 March 2004 (B_2), and 6 October 2004 (B_3) selected as boundary conditions for the GCM model: ▬▬, air temperature T_{Out}; ——, global radiation S; ——, air water vapour pressure deficit D_{Out}; ------, average wind speed U

The highest global radiation intensities at noon were 983, 1063, and 996 W m^{-2}; maximum T_{Out} were 36.5, 34.7, and 36.3°C, maximum D_{Out} were 3.8, 2.8, and 4.5 kPa; highest U were 5.2, 6.3, and 4.9 m s^{-1}; and average U were 1.5, 2.4, and 1.8 m s^{-1}; respectively for the B_1, B_2, and B_3. Diurnally, calmest wind usually was observed during night times and the strongest speed usually occurred in the afternoon at 13:00–16:00. With regards to the climate inside the greenhouses, this wind pattern provides strong ventilation cooling for the naturally ventilated greenhouse during the hottest hours of the day.

4.3.3. Sensitivity parameters

Scenarios for the design of naturally ventilated greenhouses reflects choices of variation of solar radiation heat load by varying NIR transmission of the plastic cover, variation of natural ventilation by varying greenhouse dimensions and variation of crop transpiration by varying leaf area index, at the most characteristic boundary conditions of the chosen days B1, B2 and B3.

Variation of NIR transmission. A reference plastic cover used in the field-tested prototype greenhouses has perpendicular direct NIR transmission coefficient τ_{NIR_dir} of 0.9. According to GCM calculation, variation of plastic cover τ_{NIR_dir} of 1.0–0.0 corresponds to greenhouse transmission for total NIR of 0.77–0.0. Effect of this variation on greenhouse climate is accounted in the radiation distribution submodel.

Variation of greenhouse dimensions. Variation of greenhouse dimensions can be achieved by increasing greenhouse size; by multiplying the greenhouse ground area to enlarge greenhouse sizes. Effect of different greenhouse sizes on greenhouse climate is calculated in the ventilation submodel.

Variation of leaf area index. Growing crops inside the greenhouse changes seasonal value of leaf area index L. Effect of L variation on greenhouse climate is quantified in the transpiration submodel. The range was chosen starting with 0.02 to include the leaf area index of a just planted crop. If the growth conditions are hostile at the start of the cultivation the production will fail.

Characteristic boundary conditions. Climates in the model greenhouses are evaluated for the three characteristic days B1, B2, and B3, respectively.

The growth conditions in the tropical lowland greenhouse were studied according to scenarios presented in **Table 4.1**. The bigger, multi span greenhouses were accomplished by multiplying the original greenhouse length and width with a same multiplier number, to a maximum of 10 times the original, representing a model of a big tropical lowland greenhouse with ground area of 14400 m^2.

Table 4.1 – Scenario of greenhouse design based on variation near infrared radiation (NIR) transmission; variation of greenhouse dimension aspects: greenhouse length (L) and greenhouse width (W); variation of leaf area index L; and variation of boundary conditions. The original greenhouse has ventilation opening height of 2.75 m in all sidewalls and horizontal ventilation opening below the lifted cover at both sides at the width of 2 m over the full length of the greenhouse

Aspects	Original	Scenario	Example of notation and its meaning	
NIR transmission	0.69	0.77–0.0	$N_{0.1}$	Set greenhouse NIR transmission to 0.1
L, m	15.0	Increase	L_5	Increase L by factor of 5
W, m	9.6	Increase	W_5	Increase W by factor of 5
L	0.02–4.97	0.02–5.0	L_1	Leaf area index of 1
Variation of boundary conditions			B_1	Data on 23 October 2003
			B_2	Data on 26 March 2004
			B_3	Data on 6 October 2004

The model greenhouse was notated according to the chosen parameter values. For example, $N_{0.1}L_{10}W_{10}\mathit{L}_1B_1$ represented a model greenhouse with NIR transmission of 0.1 ($N_{0.1}$), with – if compared to the original dimensions of the prototype greenhouse – length and width increased 10 times ($L_{10}W_{10}$), and the GCM model run with leaf area index 1 (L_1) under weather data on 23 October 2003 (B_1).

The performance of the greenhouse design was analyzed based on the differences between maximum greenhouse air temperature calculated using GCM and outdoor maximum air temperature data ($\Delta T_{A\text{-}O}$). This criterion is logical as lowering the maximum temperature represents the most crucial control problem for naturally ventilated tropical lowland greenhouses (Bailey, 2006). Assuming that most local crop is suited to local climate, critical conditions of the design of naturally ventilated tropical lowland greenhouse occur when $\Delta T_{A\text{-}O} > 0$. Model parameters and calibration factor for the GCM previously established (Impron *et al.*, 2007, 2008) were assumed to be valid and applicable for the design of bigger multi span greenhouses.

4.4. Results and discussion

4.4.1. General climate conditions inside the model greenhouse

According to the calibration and validation (Impron *et al.*, 2008) the GCM reliably simulates the greenhouse climate conditions for given variations of cover property, ventilation, crop transpiration at prevailing outdoor climate conditions. The climate in the single span 144 m^2 model greenhouse with NIR transmission of 0.69 on day B1 ($N_{0.69}L_1W_1B_1$) with natural ventilation is illustrated in **Fig. 4.3** for different *L***.** It shows a strong coupling between indoor and outdoor climate conditions. In the early morning, T_{Air} closely follows the rise of T_{Out}. Starting around 8:00 AM, T_{Air} increased faster than T_{Out} and with T_{Air} being higher for the smaller *L*. It appeared that maximum ($T_{Air} - T_{Out}$) generally occurs before noon, before T_{Out} and T_{Air} reach their maximum values in the early afternoon. This can be attributed to the increasing ventilation linked to the increasing wind speed. **Fig. 4.3** illustrates that ($T_{Air} - T_{Out}$) can be used to characterise the performance of the greenhouse system at the given parameter values. It also illustrates the effect of *L*. The small just planted crop meets the most harsh greenhouse climate conditions. At $L = 1$ the maximum temperature difference equals 1 ^{o}C during this day, compared to 2.2 ^{o}C at $L = 0.02$.

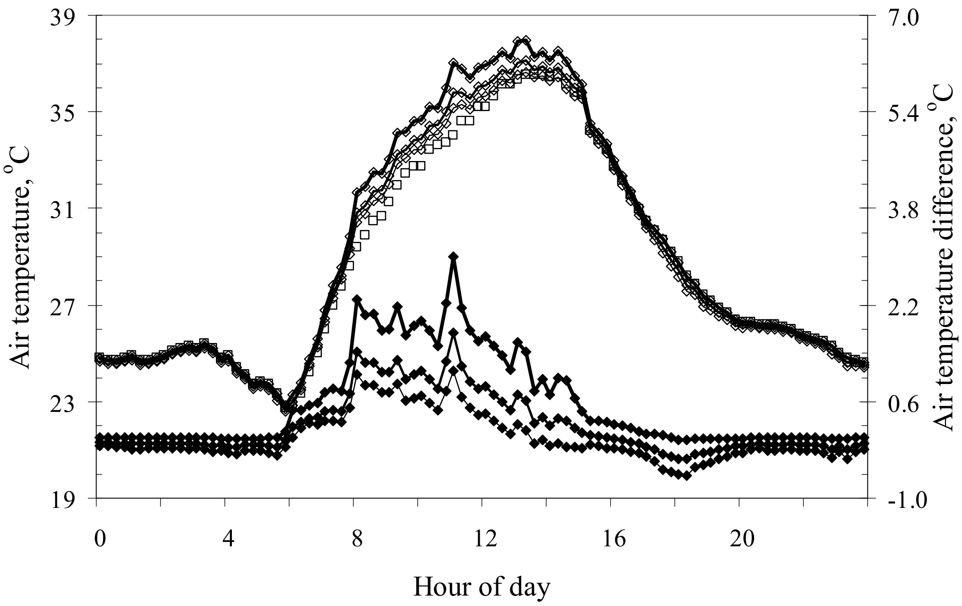

Fig. 4.3 – Diurnal traces of outdoor air temperature data T_{Out} (□), greenhouse air temperature calculated T_{Air} (◇), and air temperature difference $T_{Air} - T_{Out}$ (◆) under standard 144 m^2 model greenhouse with boundary condition on 23 October 2003 ($N_{0.69}L_1W_1B_1$) and different leaf area index: ▬▬, 0.02; ___, 0.5; ——, 1; Greenhouse notations are according to Table 4.1

4.4.2. Effects of variation of NIR transmission

The effect of variation of NIR transmission is one of the basic questions in our research. The effect on the maximum indoor-outdoor temperature difference in the prototype greenhouse (original 144 m^2 greenhouse) is presented in **Fig. 4.4** on the three days B_1, B_2 and B_3 for L varying from 0.02 till 1. For the different days and different L the decrease of $\Delta T_{A\text{-}O}$ is about 0.5 °C over the full range of greenhouse NIR transmission, so in the model greenhouse the effect is relatively small. This can be attributed to the high ventilation rate in the prototype greenhouse imposing the outdoor climate on the greenhouse.

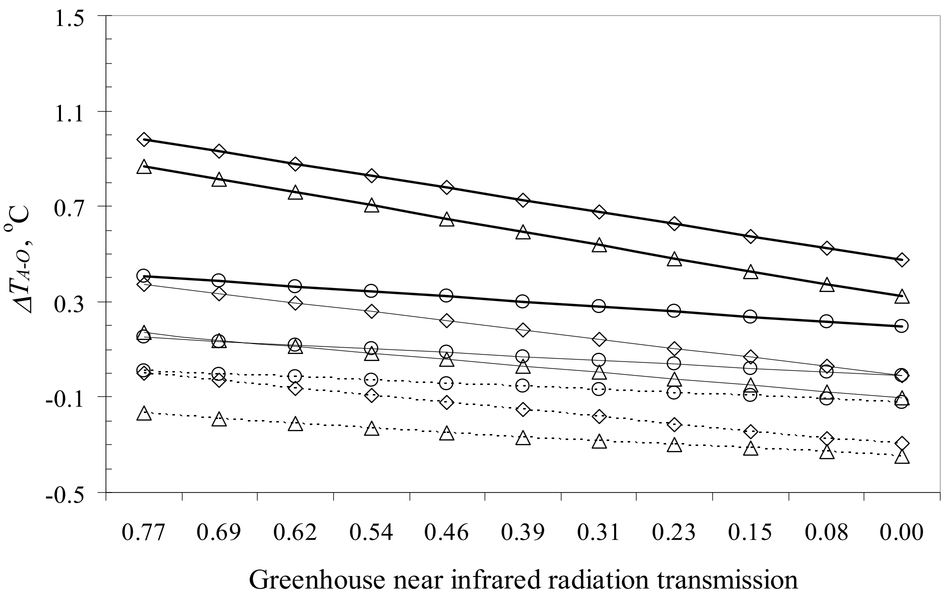

Fig. 4.4 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ for original 144 m^2 greenhouse at various greenhouse near infrared radiation transmissions with different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3); and leaf area index: ━━, 0.02; ——, 0.5; - - - - - -, 1

4.4.3. Effects of greenhouse dimensions

Increasing greenhouse sizes decrease the ratio of the ventilation opening area to the greenhouse cover area (RVC) or the ratio of ventilation opening area to greenhouse ground area (RVG) and therefore the ventilation rate *N*. This decrease of RVC and RVG is illustrated in **Fig. 4.5** together with the decrease of *N* calculated with the ventilation submodel (Impron *et al.*, 2007) for the given geometry of the ventilation openings. *N* is the daily average ventilation rate for the days B_1, B_2 and B_3 for the given greenhouse dimension. For increasing greenhouse dimensions RVC or RVG, and therefore also *N*, approach a constant value. Therefore the 14400 m^2 greenhouse represents also larger greenhouses. Values of *N* for B_2 were higher than for B_1 and B_3, which is related to higher average wind speeds during B_2 compared to B_1 and B_3 as can be read from **Fig. 4.2**. Increased RVC or RVG can also be realised by enlarging the ventilation openings in the side walls and/or the roof of the prototype greenhouse. However then static greenhouse design applying CFD has to be performed again to find out the ventilation rate for this new geometry.

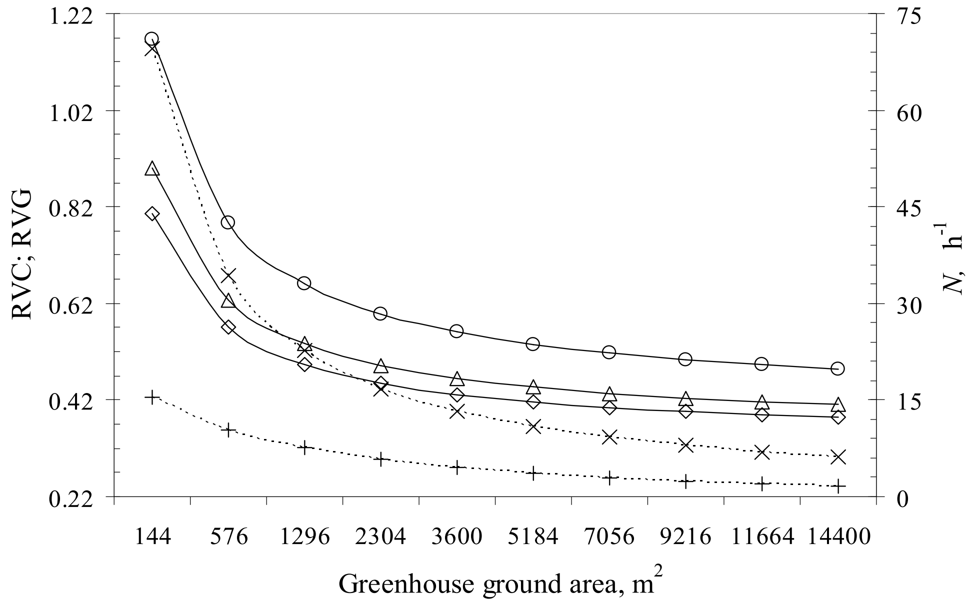

Fig. 4.5 – Calculated ratio of ventilation opening to greenhouse covering (RVC, – –+– –), ratio of ventilation opening to greenhouse ground area (RVG, – –×– –) and average ventilation rate *N* (——) in renewals per hour for various greenhouse sizes with greenhouse near infrared radiation transmission of 0.69, with standard ventilation opening of 2.75 m in the sidewalls and with different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3)

These characteristics affect $\Delta T_{A\text{-}O}$ for increasing greenhouse dimensions, however, at given boundary conditions, this behaviour also depends on the transpiration, so on L of the greenhouse crops. In **Fig. 4.6** $\Delta T_{A\text{-}O}$ is given for the reference plastic cover with NIR transmission coefficient of 0.9 for the three days B_1, B_2 and B_3 for varying leaf area index L from 0.02 till 1. At low L of 0.02, the cooling of the greenhouse air primarily relies on ventilation and convection and therefore $\Delta T_{A\text{-}O}$ increases as greenhouse size increases. During B_2 the temperature difference between greenhouse air and ambient air $\Delta T_{A\text{-}O}$ is lower than during B_3 and B_1. At higher L, transpiration becomes more significant in cooling the greenhouse air. Hot and dry conditions during B_3 provide higher driving force for transpiration than hot and humid conditions during B_2 and B_1; therefore $\Delta T_{A\text{-}O}$ at high L during B_3 was lower than during B_2 and B_1.

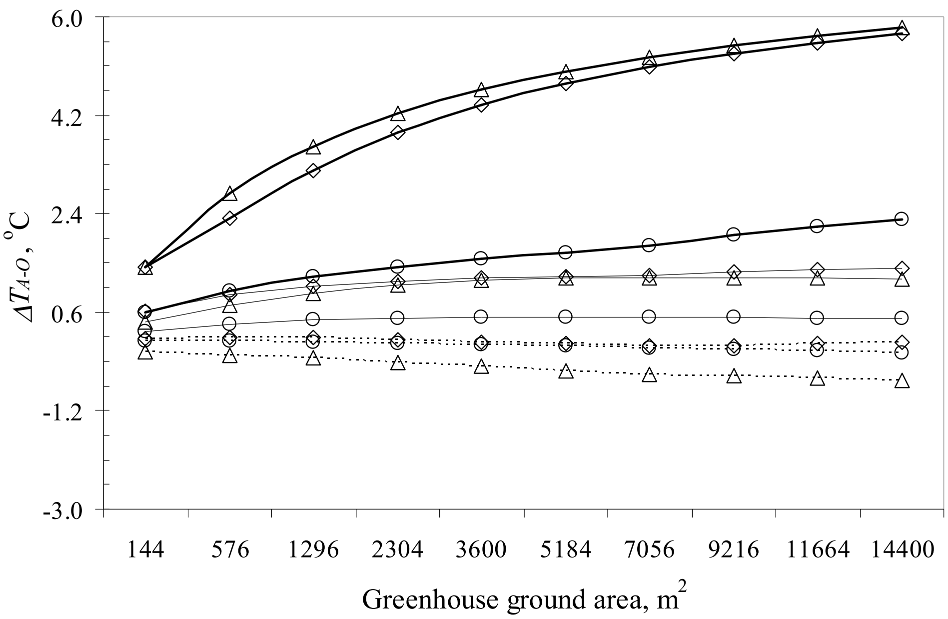

Fig. 4.6 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ for various greenhouse sizes under greenhouses near infrared radiation transmission of 0.69, standard ventilation opening of 2.75 m in the sidewalls, different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3); and different leaf area index: ▬, 0.02; ——, 0.5; ------, 1

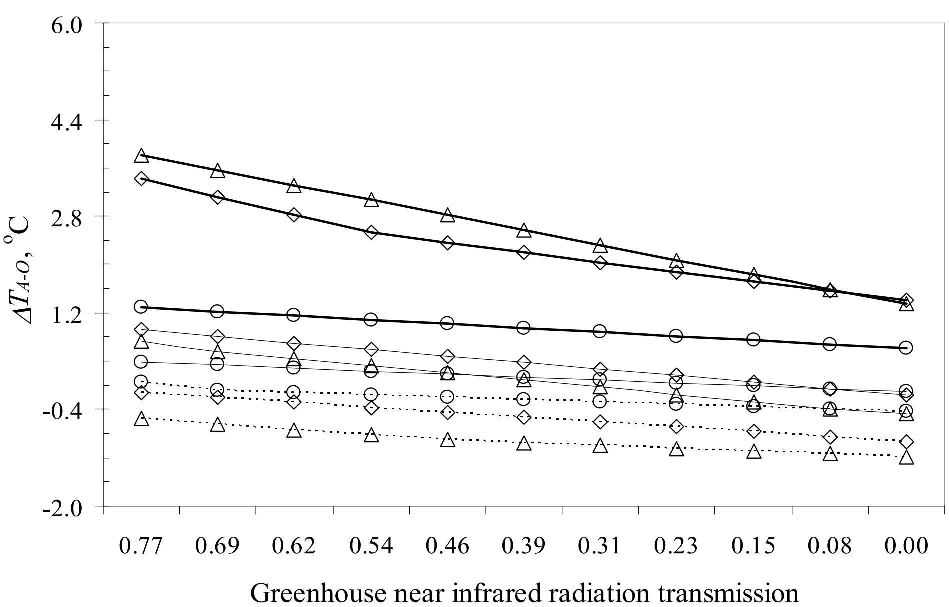

Fig. 4.7 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ for 3600 m^2 greenhouse (L_5W_5) at various greenhouse near infrared radiation transmissions with different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3); and leaf area index: ▬, 0.02; ——, 0.5; ------, 1; Greenhouse notations are according to Table 4.1

While the relative effect of ventilation and transpiration cooling change for increasing greenhouse dimensions the question is if the effect of NIR transparency also changes for increasing dimensions. Therefore in **Fig. 4.7** $\Delta T_{A\text{-}O}$ is represented for the days B_1, B_2 and B_3 for varying L in a 3600 m^2 multi span greenhouse and in **Fig. 4.8** for a 14400 m^2 multi span greenhouse. These figures demonstrate a more dominant effect of NIR reduction on lowering the air temperature in bigger greenhouses, at lower wind speed during days B_1 and B_3, and smaller L. Bigger greenhouses and lower wind speed reduce ventilation and smaller L reduces transpiration; therefore, in bigger greenhouses greenhouse cooling is more effective by reduction of NIR input. Therefore at given boundary conditions lower NIR transparent plastic covers can compensate for lower transpiration (young crops) and lower ventilation (larger greenhouses).

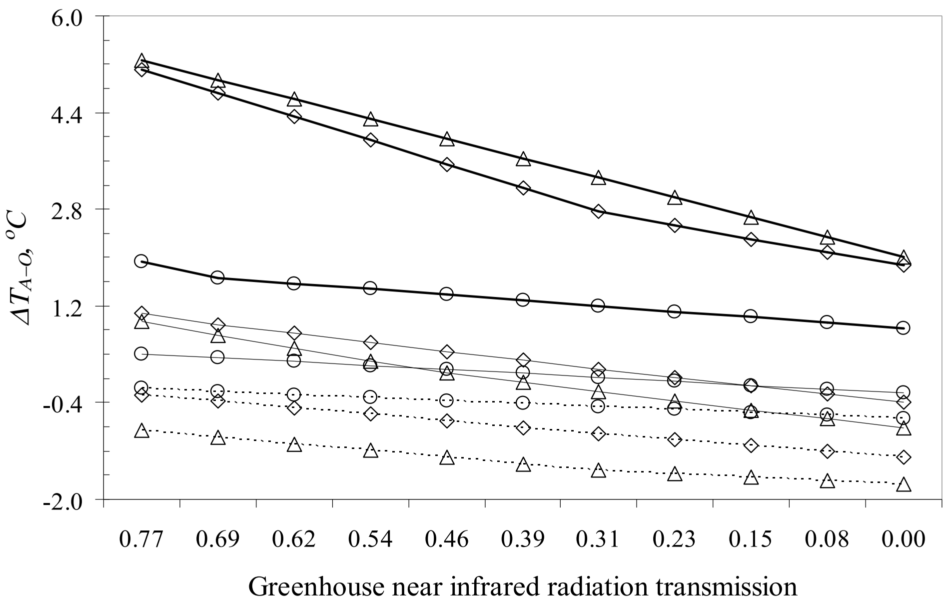

Fig. 4.8 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ for 14400 m^2 greenhouse ($L_{10}W_{10}$) at various greenhouse near infrared radiation transmissions with different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B2); △, 6 October 2004 (B_3); and leaf area index: ▬▬, 0.02; ——, 0.5; ------, 1; Greenhouse notations are according to Table 4.1

While NIR transparency directly affects the heat load to the greenhouse it can be expected that also crop temperature and crop transpiration will be affected. In **Fig. 4.9** crop temperature and crop transpiration are shown for the 144 m^2 prototype greenhouse and leaf area index L of 1 for the three days B_1, B_2 and B_3. Reduction of NIR transmission indeed reduces crop transpiration and crop temperature.

At this leaf area index L_1, every reduction of greenhouse NIR transmission by 10% reduces crop transpiration by 2%. Transpiration is higher on a typical day with hot and dry air (B_3) than on typical day with hot and humid air (B_2 and B_1). Simulation also shows that transpiration is lower at lower wind speed (B_2) than at higher wind speed (B_1). **Fig. 4.9** clearly shows that at the same greenhouse NIR transmission higher transpiration is accompanied with lower crop temperature.

4.4.4. Effects of variation of leaf area index

Variation of leaf area index primarily affects transpiration cooling. In sections 4.4.2 and 4.4.3 leaf area indexes for young crops ($L < 1$) were chosen as parameter in the description of the effects of NIR transparency and greenhouse dimensions. Then lower L correlate to larger temperature differences with the ambient air $\Delta T_{A\text{-}O}$ as shown in **Figs. 4.3–4.8**.

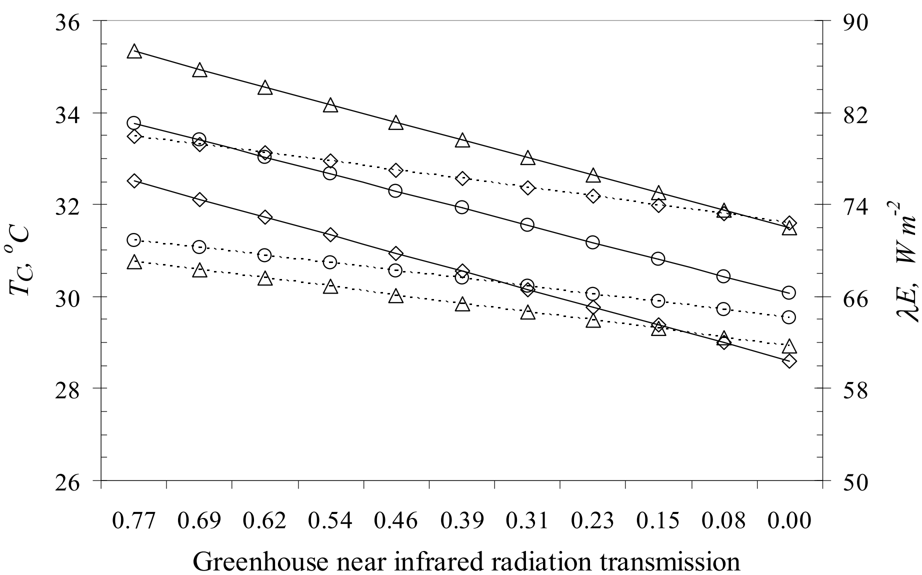

Fig. 4.9 – Calculated maximum canopy temperatures T_c (------) and average crop transpiration λE (——) for 144 m^2 greenhouse (L_1W_1) at various greenhouse near infrared radiation transmissions with different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B2); △, 6 October 2004 (B_3); and at leaf area index 1

For mature crops L can increase till about 5. For the larger range of L, the effect of L on $\Delta T_{A\text{-}O}$ is shown in **Fig. 4.10** for the three greenhouse sizes: the original 144 m^2 ($N_{0.69}L_1W_1$), 3600 m^2 ($N_{0.69}L_5W_5$), and 14400 m^2 ($N_{0.69}L_{10}W_{10}$) with greenhouse NIR transmission of 0.69 and in **Fig. 4.11** for greenhouse NIR transmission of 0.08. In general, $\Delta T_{A\text{-}O} > 0$ occurs when L is low as was seen already in **Figs. 4.3–4.8**. In the 144 m^2 model greenhouse, the greenhouse climate during B_2 was already moderate with the maximum $\Delta T_{A\text{-}O}$ at $L = 0.02$ of approximately 0.6 K due to higher average wind speed U resulting in higher average ventilation rate. As the air was more humid, transpiration cooling by the growing crop was slowly taking effect, therefore the period with condition of $\Delta T_{A\text{-}O} > 0$ was relatively longer. During B_3, the greenhouse climate at $L = 0.02$ worsened with the maximum $\Delta T_{A\text{-}O}$ reaching approximately 1.4 K due to lower average U; however, as the air was drier, the transpiration from a growing crop, so increasing L, was more rapidly a dominant effect in cooling the greenhouse air.

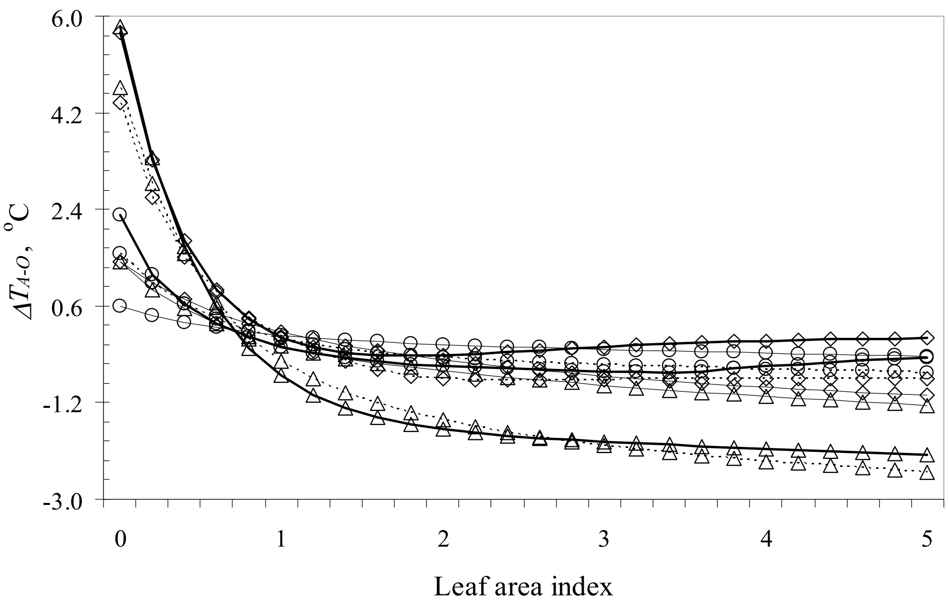

Fig. 4.10 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ at various leaf area index under greenhouses with near infrared radiation transmission of 0.69, standard ventilation opening of 2.75 m in the sidewalls, different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3); and different greenhouse sizes: ——, 144 m^2 (L_1W_1); ------, 3600 m^2 (L_5W_5); ▬▬, 14400 m^2 ($L_{10}W_{10}$); Greenhouse notations are according to Table 4.1

For low NIR transparency (**Fig. 4.11**) the difference with high NIR transparency is dominant at low L, for $L > 1$ there is still some effect but the cooling effect of crop transpiration is dominant.

4.4.5. Design synthesis

Current simulations evaluated reduction of T_{Air} in naturally ventilated greenhouses by means of: (i) reducing solar radiation input into the greenhouse by lowering NIR transparency of the plastic cover (**Figs. 4.4**, **4.7**, **4.8** and **4.9**), (ii) increasing the removal of heat from greenhouse compartment via ventilation airflow by increasing ratio of ventilation openings (**Figs. 4.5** and **4.6**), and (iii) increasing the fraction of energy conversion into latent heat via crop transpiration by keeping leaf area index L high (**Figs. 4.10** and **4.11**). Simulations also depicted climate-related processes attributable to lowering greenhouse air temperature: (i) higher wind speed U creates higher ventilation air exchange expressed in higher ventilation rate N and also higher sensible heat transfer between the greenhouse and outdoor air via the cover due to external convection; (ii) higher air water vapour pressure deficit D drives higher transpiration.

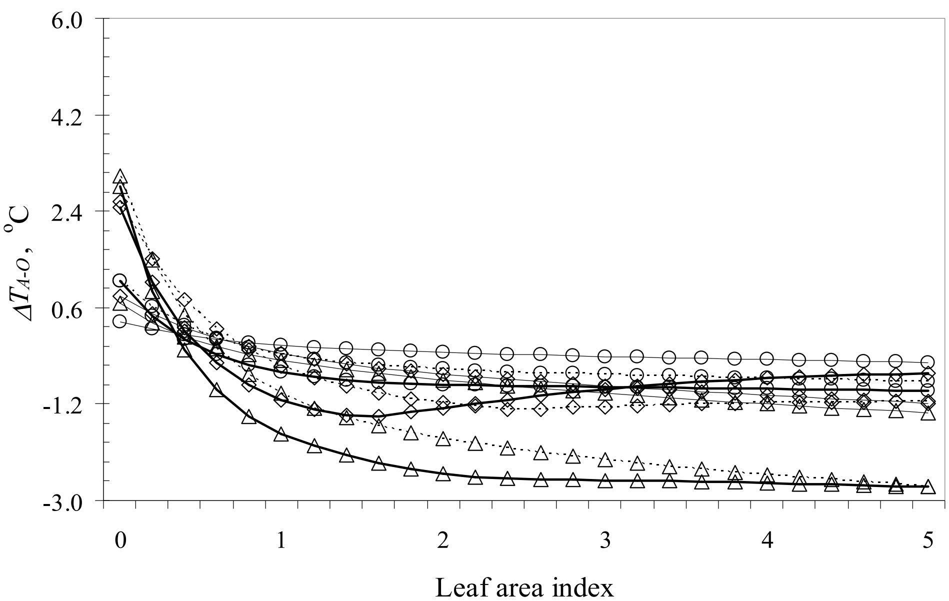

Fig. 4.11 – Differences between maximum greenhouse air temperatures calculated and outdoor maximum air temperature data $\Delta T_{A\text{-}O}$ at various leaf area index under greenhouses with near infrared radiation transmission of 0.08, standard ventilation opening of 2.75 m in the sidewalls, different boundary conditions: ◇, 23 October 2003 (B_1); ○, 26 March 2004 (B_2); △, 6 October 2004 (B_3); and different greenhouse sizes: ——, 144 m^2 (L_1W_1); ------, 3600 m^2 (L_5W_5); ▬▬, 14400 m^2 ($L_{10}W_{10}$); Greenhouse notations are according to Table 4.3

On model greenhouses with varying sizes from the original 144 m^2 (L_1W_1) to multi span 14400 m^2 ($L_{10}W_{10}$), the temperature $\Delta T_{A\text{-}O} > 0$ generally occurs when L was low so in the early growing period. Therefore, attempts to reduce T_{Air} by individual or combination of the above methods (i, ii and iii) are important within this early growing period especially for bigger greenhouses. Application of the plastic cover having low NIR transmission seems possible to lower T_{Air}. Higher U such as during B_2 warrants higher N to further reduce T_{Air}. Due to small leaf area of young crops, it might be difficult to attain high L, except by planting crops at high density. But later this introduces more laborious work to adjust the growing crops to a proper density to match crops growth. However it is common practice in greenhouse production in moderate climates to plant the starting crop at high density in a single span greenhouse with large relative ventilation opening and then transport it to a multi span greenhouse when $L > 0.5$–1. Another possibility is by alternating blocks of crops at different ages to form series of a block of older crops having high L followed by a block of young crops having low L. This last alternative assumes colder air from older crops having high L will mix well with the warmer air from young crops having low L. However, light conditions are affected negatively for the young crop due to shading by the mature crop so the first alternative of dense growing of the seedlings is advisable.

At higher L, the problems with high T_{Air} diminishes as transpiration process takes dominant effect on cooling greenhouse air. It appears that a high L alone will already be able to keep T_{Air} low. In big greenhouses of 3600 m^2 (L_5W_5) and 14400 m^2 ($L_{10}W_{10}$) with reference plastic at $L = 0.5$; maximum T_{Air} was only 1.6^{o}C higher than maximum T_{Out}. This might impose limited harmful effects for tropical greenhouse crops because the possible occurrence of the critical temperature is only for a short period in the late morning as shown in **Fig. 4.3**. For $L > 1$, maximum T_{Air} will be lower than maximum T_{Out}, which might be advantageous for the crop. An even lower T_{Air} could be created from a more intensive transpiration cooling under hot and dry boundary conditions.

Simulation demonstrated that reduction of NIR transmission reduces greenhouse air temperature at lower L, but crop temperature and crop transpiration are reduced also for higher L. The reduction of crop transpiration is also confirmed by practical experiments conducted by Kempkes *et al.* (2008) in The Netherlands with a rose crop. It can be concluded that one of the advantages of applying ideal low NIR transparent plastic could be related to water saving.

Present study indicates that naturally ventilated model greenhouses of up to size of 14400 m^2 are capable to create suitable climate when the greenhouse crops had L of higher than 0.5. As long as the greenhouse crops have high L, values of $\Delta T_{A\text{-}O}$ will be close to or lower than zero. In small crops a reduction of NIR is useful in these larger greenhouses (**Figs. 4.6–4.8**), in order to keep temperatures on an acceptable level.

4.5. Conclusions

A simple greenhouse climate model (GCM) was used to simulate climatic conditions of model greenhouses by optimizing effects of: (i) near infrared radiation (NIR) transmission of the plastic cover, (ii) leaf area index L, (iii) greenhouse dimensions at given boundary conditions characteristic for tropical lowland. The performance of the greenhouse was analyzed based on the differences between maximum greenhouse air temperature calculated using GCM and outdoor maximum air temperature data ($\Delta T_{A\text{-}O}$). Critical conditions ($\Delta T_{A\text{-}O} > 0$) generally occur when leaf area index L is low. At low L, reduction of greenhouse air temperature T_{Air} can be achieved primarily by two methods. Firstly, by reducing NIR transparency of the plastic cover to decrease radiation heat load into the greenhouse compartment. Effect of NIR transparency reduction on lowering T_{Air} at low L was more significant for bigger greenhouses with lower relative ventilation opening and humid conditions. Secondly, by high relative ventilation opening to remove excess heat out of the greenhouse. Higher wind speed is attributable to lowering T_{Air} by increased cooling due to ventilation air exchange and by increased convective sensible heat flux between the greenhouse and outdoor air via the plastic greenhouse cover. At high L, transpiration process dominates the cooling of greenhouse air. Transpiration cooling is more intensive under hot and dry boundary conditions. Reduction of NIR transmission reduces crop transpiration and therefore could be used as a water saving measure. This study indicated that large size multi span naturally ventilated greenhouses are capable to create $\Delta T_{A\text{-}O}$ close to or lower than zero when the greenhouse crops have L higher than 0.5. Starting crops with normally $L < 0.5$ could be planted in single span greenhouses at high planting density, so then higher L, and then transplanted to large multi span greenhouses at $L > 0.5$.

This study showed that it is possible to use a simple greenhouse climate model to analyse the importance and interaction of different greenhouse design parameter for tropical greenhouses. That way the greenhouse design can be further optimised in the future.

5

Growth and development of a determinate tomato crop under tropical lowland greenhouse conditions: observations, simulation and scenario studies

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Growth and development of a determinate tomato crop under tropical lowland greenhouse conditions: observations, simulation and scenario

Abstract

Three successive experiments, together lasting a full year, were conducted with determinate tomato crops greenhouses in the tropical lowlands of Indonesia. Effects of three plastic films (standard plastic, and lower and higher near-infrared radiation (NIR) reflecting pigment plastics) on growth and development were studied, and analyzed with the INTKAM crop growth model. More advanced plastic films reduce global radiation inside the greenhouse by up to 15%. However, this did not create distinct other climatic conditions due to the greenhouses' high natural ventilation capacity. Total dry matter production and truss formation rate did not differ among plastic film types. Truss pruning, however, caused profound differences in fruit production. Crops with a higher number of trusses produced higher total and fruit dry matter. A determinate tomato crop grown in a tropical greenhouse has a higher fruit abortion in later appearing trusses, resulting in a decreasing number of fruits per truss over time. This can partly be explained by the low source – sink ratio of around 0.4 during the productive period. Scenario studies revealed that the average fruit production under an ideal cover with zero NIR transmittance was approximately 3% higher than under standard cover. With a constant number of fruits per truss, two crops yearly produce 6% more fruit weight than three crops per year do. However, this effect is lost if the number of fruits per truss decreases over time. Then, production can be 12% lower, because of the longer period towards the end of the season with a low number of fruits per truss. The most significant increase of fruit production can be achieved by increasing the number of fruits per truss, which requires adequate crop management that is aimed at finding the appropriate source – sink balance.

5.1. Introduction

Most highly populated main cities in Indonesia are located in the tropical lowlands. Their inhabitants need continuous supply of safe and high-quality fresh fruits and vegetables. Currently, such products come from open fields in peri-urban areas and from greenhouse and outdoor cultivation in mountainous areas. Outdoor cultivation is risky as crops are exposed to high levels of pest and disease pressure, to heavy rainfall and strong winds during the rainy season, and to water shortage during the dry season. These factors limit production, and total crop loss is common. Products from mountainous areas require a relatively long transport time to reach urban markets.

Protected cultivation nearby urban areas in the tropical lowlands therefore may offer certain advantages in terms of reduced environmental stress, increased yield, sustainable year-round production, and transport. This type of protected cultivation, however, is not common as it requires specific adaptation of the greenhouse construction to the tropical lowland climate, where high greenhouse air temperatures that are adverse to the crop prevail.

Knowledge with regards to greenhouse constructions that are suitable for tropical lowland areas has recently been generated (Campen, 2005; Hemming *et al.*, 2006a). In contrast, information on growth and development of greenhouse fruits and vegetables under tropical lowland conditions is scarce (Kleinhenz *et al.*, 2006; Harmanto, 2006; Mutwiwa, 2007), and for Indonesia virtually non-existent.

The main problem with greenhouses in tropical lowlands is the high indoor temperature caused by high radiation levels, which may negatively influence the crop. For example, tomato fruit set is temperature-sensitive (see below). Adaptation of the optical properties of plastic covering material by addition of near-infrared radiation (NIR) reflecting pigment (Hoffmann & Waaijenberg, 2002; Hemming *et al.*, 2006a) in combination with natural ventilation (Campen, 2005; Impron *et al.*, 2007, 2008) have enabled the lowering of the thermal load of the greenhouse. Insect nets have to be applied in the ventilation openings to prevent pest infestation. A greenhouse climate model has been set up to study the effects of adapted optical cover properties and restricted natural ventilation by the nets on the greenhouse climate dynamics (Impron *et al.*, 2007, 2008).

An essential part of designing a greenhouse is the study of the growth and development of the greenhouse crop. In this study, tomato (*Lycopersicon esculentum* Mill.) was selected as the example crop for two reasons. Firstly, tomato is considered an important cash crop in Indonesia. Tomato ranks number five in the production and wholesale value of vegetables in Indonesia (Mather *et al.*, 2002), and total annual production in 2009 was 829,927 tonnes on 50,000 ha (FAO, 2010). This implies an annual fresh production of 16.6 t ha^{-1}. Secondly, tomato can be grown at a wide temperature range of 10–40 ^{o}C, but its fruit set is optimal in the range of 14–17^{o}C (night) and 19–24^{o}C (day) (Geisenberg & Stewart, 1986). Fruit set of most tomato varieties fails at a constant daytime temperature of 32^{o}C (Sato *et al.*, 2000). In a warm climate, fruit number and weight reduce (*e.g.* Willits & Peet, 1998), and the growth period shortens (*e.g.* De Koning, 1994; Perry *et al.*, 1997).

Two related research questions can be formulated: Is it possible to design a greenhouse for tropical lowland conditions that realizes an indoor climate that is suitable for tomato growth and development? Given this crop growth and development, what are avenues for production optimization?

The objectives of this study were to investigate growth and development of a determinate tomato variety grown in the tropical lowlands of Indonesia in naturally ventilated greenhouses, to analyze crop physiological responses to greenhouse climate conditions, especially to radiation and air temperature, and to investigate ways to increase production through optimizing greenhouse construction and cultivation methods.

5.2. Materials and methods

5.2.1. Experimental set-up

Site, growing seasons and greenhouse characteristics

The site of the experiments is located in Purwakarta (107°30'E, 6°30'S, altitude 25 m), West Java, Indonesia. The site is climatologically characterized by two distinct seasons: a dry season from June to October and a wet season from November to May. Experimental data were collected for three successive growing seasons that represented a full-year of variation of outdoor climatic conditions. Planting and final harvest dates of Experiment 1 were 23/10/2003 (onset of wet season) and 27/1/04 (middle of wet season), respectively. Respective dates for Experiment 2 were 22/03/2004 (middle of the wet season) and 22/6/2004 (end of the wet season), and for Experiment 3 23/7/2004 (onset of dry season) and 26/10/2004 (middle of the dry season).

Experiments were carried out in six identical greenhouses. A detailed description of the greenhouse dimensions, arrangements, ventilation nets and covering properties of three plastic types is given in Impron *et al.* (2007, 2008). The plastic types were one control plastic without NIR reflection (N0) and two newly developed plastics with two different concentrations of NIR reflecting pigments (N1 and N2, respectively). The radiometric properties of the plastic films in terms of diffuse and direct transmission coefficient of ultra violet radiation (UVR), photosynthetically active radiation (PAR), and NIR are summarized in **Table 5.1**. A lower NIR transmission implies reduction of the radiation load to the greenhouse which is expected to lower greenhouse temperature, and alteration of spectral band ratios that affect quantity and quality of light.

Table 5.1 – Diffuse and direct transmission coefficient τ for the plastics. Bold values were measured, the other values were estimated

Plastic type	Diffuse radiation			Direct perpendicular radiation		
	UV	PAR	NIR	UV	PAR	NIR
N0	0.14	**0.77**	0.76	**0.16**	**0.90**	**0.89**
N1	0.11	**0.73**	0.63	**0.13**	**0.81**	**0.74**
N2	0.10	**0.68**	0.57	**0.12**	**0.77**	**0.67**

Crop characteristics and cultural practices

In the lowland tropics, most farmers use determinate tomato varieties, which are adapted to the local climate. In this study, plants of the determinate cultivar Lentana (PT East West Seed Indonesia, Purwakarta) were grown in black poly-ethylene bags filled with burned rice husks as the growing medium. Plants were arranged in a double-row high-wire system at a density of 2.94 plants m^{-2} on five beddings covered with plastic mulch (silver colour upside, black downside). Row spacing within a bed was 60 cm and plant spacing within a row 40 cm. Each of the 10 rows contained 33 plants, resulting in 330 plants per greenhouse. Row orientation was east-west.

The architecture of a determinate tomato plant differs from that of an indeterminate high-wire tomato plant. Each determinate plant has one stem with 7 to 8 leaves at planting. When reaching 9 to 10 leaves, a second stem is formed (the term 'stem' is used here to distinguish from the smaller side shoots). Side shoots are formed at each node of each of the two stems. These side shoots are self-terminating, but fairly large in size nevertheless, resulting in a bushy architecture. The first truss appears right above the formation point of the second major stem. Further on, trusses are formed at the two stems and several side shoots. This results in approximately double the amount of trusses as compared to an indeterminate tomato plant. Side shoots that grow in axils between leaves and stems may have poorly developed fruits, and are mostly pruned.

The main difference in cultural practice between the experiments was the number of trusses being retained at the main stems (**Table 5.2**). The number of cumulative trusses in Experiments 1 and 3 was 33 and 34, respectively; whereas in experiment 2, the cumulative number of trusses was reduced to 15, in an attempt to reduce fruit abortion. In all experiments, side shoots and some leaves below the lowest maturing trusses were pruned. Pollination was promoted by manually vibrating the flower once a day generally around midday.

Table 5.2 – Dates of planting and final harvest and some cultivation information for Experiments 1, 2, and 3

Experiments	Planting	Harvest 1st fruit	Final harvest	# trusses at final harvest	Pruning side shoots	Duration of experiment (days)
Experiment 1	23/10/03	24/12/03	27/01/04	33	low	97
Experiment 2	22/03/04	22/05/04	22/06/04	15	high	92
Experiment 3	23/07/04	19/09/04	26/10/04	34	high	95

Water and nutrient application, pest and disease management, and other management practices were similar for all treatments. Water and nutrients were supplied by drip irrigation without re-circulation. A standard nutrient solution with EC 2–2.5 dS m^{-1} and with pH 5.5–6.0 was applied. Substrate humidity in the poly-ethylene bags was frequently checked visually during daytime to avoid water shortage. The beddings were covered with black plastic mulch to allow excess irrigation water to drip via a 3-inch gutter (half PVC pipe) to the drainage collector outside the greenhouse.

Insect nets in the ventilation opening considerably reduced insect pressure, although some caterpillar and spider mites were observed. Insects were scouted regularly, and pests were mainly controlled manually. Diseases such as powdery mildew were controlled by removing the infected leaves. Only in some instances, pests and diseases were chemically controlled.

5.2.2. Greenhouse climate

Global radiation *S*, PAR, air temperature and relative humidity were measured outside and inside the greenhouses, as described in detail by Impron *et al.* (2007, 2008). Frequent values of outdoor *S*, indoor PAR, NIR and UVR (all radiation terms are in W m^{-2}), greenhouse air temperature T_{Air} in °C, vapour pressure deficit D_{Air} in kPa and ambient carbon dioxide concentration *C* in ppm are required by the crop simulation model. Indoor values of solar radiation components (direct and diffuse PAR, NIR, and UVR) were simulated using the Simple Greenhouse Climate Model (Impron *et al.*, 2007, 2008). CO_2 concentration was not measured, and was assumed at a constant level of 350 ppm.

5.2.3. Crop growth and development

Destructive plant samples were taken at fortnightly intervals, from planting to final harvest. With a crop cycle of approximately 95 days, this resulted in seven sampling dates. One extra row of plants was placed beside a wall in each greenhouse and used for replacement of removed plants. One plant of each of the eight rows per greenhouse was randomly selected at each of the periodic harvests. Plant height and numbers of leaves, trusses, flowers and fruits per truss, and nodes were determined. Plant samples were separated in roots, leaves, stems, fruits and senesced leaves, and their fresh weights were determined immediately. Six representative mature fruits from each greenhouse were selected for fruit dry matter content measurements. Organs samples were dried at 105°C for two days, and dry weights were determined.

From each sampled plant, 2–3 fresh leaves were cut from the upper, middle, and lower leaf layers and immediately weighed and scanned using a flatbed CanonScan D646U ex scanner (Canon Inc., Japan). The leaf images were analyzed to calculate their area (cm^2). These leaf samples then were dried to determine leaf dry mass (g). The specific leaf area *SLA* in cm^2 g^{-1} was obtained and the leaf area of each investigated plant was calculated. Leaf area index *L* in m^2 m^{-2} was calculated as the product of the average leaf area per plant and plant density. Interception of PAR by the crop canopy *PARi* in W m^{-2} (instantaneous) or MJ m^{-2} (per time period) was estimated using a negative exponential relationship, by taking *L* as measured and an extinction coefficient for diffuse PAR of 0.78 (Goudriaan & Van Laar, 1994).

Truss appearance was tracked by tagging all trusses of 24 (Experiments 1 and 2) and 18 (Experiment 3) randomly selected plants per greenhouse. Fruit development from setting to maturity was expressed in degree-days *DD* in ^{o}C d according to **Eq. (5.1)**:

$$DD = \sum_{t=fruit\_setting}^{t=fruit\_maturity} (T_{Ave} - T_b) \qquad \textbf{(5.1)}$$

where: t is time in d; T_{Ave} is the average daily air temperature in ^{o}C; and T_b is the base temperature in ^{o}C. Reported values for the base temperature for tomato vary from 3.5 ^{o}C to 10 ^{o}C (*e.g.* Perry *et al.*, 1997; Adams *et al.*, 2001). This study used T_b of 4^{o}C, which has often proven to result in good simulation of truss formation rate.

Mature fruits were harvested two or three times per week. At each harvest, fresh weight and number of harvested fruit per row were measured. Calculation of dry weight of fruits was based on average measured fruit dry matter content of 0.066 g g^{-1}, which is within the range reported by others (Heuvelink, 1996; Li *et al.*, 2001; Cooman, 2002, Van der Ploeg, 2007).

5.2.4. Crop growth model description and parameterization

Growth and development were analyzed with the INTKAM crop simulation model. The INTKAM model simulates crop growth and plant-water relations (Elings *et al.*, 2004; Marcelis *et al.*, 2009). Leaf photosynthesis is computed with a biochemical model (Farquhar *et al.*, 1980). Instantaneous crop photosynthesis rate is computed from instantaneous leaf photosynthesis rates at various canopy depths (Goudriaan, 1986), and is integrated to daily crop photosynthesis rate. Daily dry matter partitioning and organ growth rates are based on the sink strengths of various organs and assimilate availability. Daily leaf area expansion is computed from leaf growth rate and maximum and minimum values of the specific leaf area (Gary *et al.*, 1995) that depends on the radiation level (Heuvelink, 1999). Instantaneous leaf transpiration rate is calculated with the Penman-Montheith equation, and applies the stomatal conductance model described by Nederhoff and De Graaf (1993). Water requirements for fresh mass growth are based on fixed values for dry matter content of roots, shoot and leaves, and a fruit dry matter content as a function of EC and day number (De Koning, 1994).

The default INTKAM model was developed and parameterized for an indeterminate tomato crop grown under temperate greenhouse conditions. Most underlying processes in the model are generic and can be assumed valid for a determinate tomato crop under tropical lowland greenhouse conditions as well, but three processes required to be re-parameterized on the basis of the observed data, viz. truss appearance rate, fruit number per truss, and *SLA*. In addition, several parameter values associated with differences in cultivation (*e.g.* pruning and photosynthesis rate associated with senescence) and cultivar characteristics were based on matching simulated with observed data. The INTKAM model was run at the assumed CO_2 level of 350 ppm. It should be noted that if CO_2 concentration is raised by for instance 10%, simulated dry matter production would increase by approximately 5%.

5.2.5. Scenarios

Scenario studies were conducted with the INTKAM model to investigate ways to increase tomato production under tropical lowland greenhouse conditions through optimizing greenhouse construction and cultivation methods. Greenhouse construction was optimized through the effects of greenhouse plastic cover (standard and ideal). Cultivation methods were optimized through the effects of crop characteristics (determinate and indeterminate tomato types, number of fruits per truss), and the number of crops per year.

A standard greenhouse plastic cover (NS) was assumed to have fractions of 0.76 diffuse and 0.89 direct perpendicular NIR transmittances, while an ideal greenhouse plastic cover (NI) has zero NIR transmittance.

Cultivation of a determinate tomato crop was simulated with three (C3) and two (C2) consecutive growing seasons per year; and an indeterminate tomato crop with one 11-month (C1) growing season per year. Whereas an indeterminate variety can be grown for a full year, this is not possible for a determinate variety.

A seasonal constant number of fruits per truss (*FRNC*) was varied from one to six, for both the determinate and indeterminate types. A decreasing number of fruits per truss (*FRND*) with increasing truss number was only applied to the determinate type, following observations (see Section 5.3.2).

Determinate and indeterminate growth types are described by different parameter values associated with architectural, growth, and developmental characteristics. Climate data sets under naturally ventilated single-span greenhouse with the NS and NI covers were generated using a Simple Greenhouse Climate Model (Impron *et al.*, 2007, 2008). A year-long reference outdoor climate was composed by combining existing data. Missing data were estimated from climate measurement on nearby dates. A standard L of the crop was assumed to compute D_{Air}. In combination with crop growth scenarios with slightly deviating L patterns, this approach effectively resulted in a one-step iteration of the effect of crop transpiration on the indoor climate. Previous experience has learned that it is sufficient to account for the effects of crop L on air temperature. A maximum L of 3 $m^2\ m^{-2}$ was assumed in the scenario studies.

In summary, 40 scenarios were computed that combine the effects of two greenhouse cover types (NS, NI), three number of crops per year (C3, C2, C1), 6 levels of *FRNC* (determinate and indeterminate tomatoes), and 1 additional effect of *FRND* (determinate tomato) (see **Table 5.8**).

5.3. Results

5.3.1. Climatic conditions

Daily means of climatic conditions are given in Table 5.3. Levels of outdoor S and PAR were 5.1–25.0 and 2.2–10.8 MJ m^{-2} d^{-1}. Average outdoor PAR during the dry season in Experiment 3 was 13% and 6% higher than in Experiments 1 and 2, respectively. Seasonal differences in indoor radiation were smaller. The amounts of S and PAR in N0 were 8.8% and 15.1% higher, respectively, than in N1, and 9.1% and 12.1% higher, respectively, than in N2, as a result of different covering properties. The lowest daily means of S and PAR were 9.3 and 4.4 MJ m^{-2} d^{-1} in N2 of Experiment 1.

Table 5.3 – Seasonal averages of climate characters for the three greenhouses (N0, N1, N2) and the outside environment (Out): daily sum of global radiation S and photosynthetically active radiation PAR, maximum air temperature T_{Max}, minimum air temperature T_{Min}, average air temperature T_{Ave}, average air relative humidity RH, and average air water vapour pressure deficit D

	Experiment 1				Experiment 2				Experiment 3			
	Out	N0	N1	N2	Out	N0	N1	N2	Out	N0	N1	N2
S, MJ $m^{-2}d^{-1}$	16.7	11.3	10.2	9.5	18.0	12.3	11.4	10.6	20.0	12.8	11.6	10.8
PAR, MJ $m^{-2}d^{-1}$	7.3	5.1	4.7	4.4	7.9	5.7	5.2	5.1	8.4	5.7	5.1	5.0
T_{Min}, °C	23.7	23.8	23.8	23.8	23.5	23.7	23.7	23.7	22.2	22.4	22.5	22.4
T_{Max}, °C	32.6	32.7	32.1	32.3	33.1	34.4	34.0	33.9	34.8	34.9	35.0	34.8
T_{Ave}, °C	27.0	27.0	26.8	27.0	27.3	27.8	27.7	27.6	27.5	27.5	27.5	27.5
RH, %	83.0	84.6	85.9	85.5	81.6	82.5	83.9	83.9	72.5	75.8	76.7	76.5
D, kPa	0.70	0.63	0.58	0.59	0.8	0.78	0.71	0.71	1.20	1.07	1.03	1.04

Average greenhouse air temperature was 26.9 °C, 27.7 °C, and 27.5 °C, respectively, for Experiments 1, 2, and 3. Average greenhouse relative air humidity was 85, 83, and 76 % respectively, for Experiments 1, 2, and 3. In general, the climatic conditions – except radiation – were similar among the greenhouses. More detailed climate descriptions and processes are given elsewhere by Impron *et al.* (2007, 2008).

5.3.2. Model parameterization

Determinate tomato type

Truss appearance rate TAR in number of trusses per day for determinate lowland tomato grown with two stems at T_{Ave} of 27.4°C, TAR can be described by a linear equation:

$$TAR = \{0.00845\,(T_{Ave} - T_b)\} \times \mathrm{N};\ R^2 = 0.86 \qquad \textbf{(5.2)}$$

with N number of stems per plant.

The number of fruits per truss decreased as truss number increased. The decline in the three experiments was similar, and independent from film type, with a lower number of fruits per truss in Experiment 2 (**Fig. 5.1**). Because of the uncertainty in physiological understanding, number of fruits per truss was model input.

Average *SLA* of a young crop was 0.02–0.03 m^2 g^{-1}, and decreased to 0.01–0.02 m^2 g^{-1} for a mature crop (**Fig. 5.2**). Values of *SLA* in Experiments 2 and 3 were similar to each other and did not show an end-of-season increase. There was a noticeable increase of *SLA* toward the end of Experiment 1. On the average, *SLA* can be described with the following equation:

$$SLA = SLA_F\,(0.0408 - 0.00578\ \ln(DAP));\ R^2 = 0.63 \qquad \textbf{(5.3)}$$

where: SLA_F is experiment-dependent parameter, with an overall value of 1, and specific values of 1.1 (Experiment 1), 0.87 (Experiment 2) and 1.0 (Experiment 3); and *DAP* is day after planting in day.

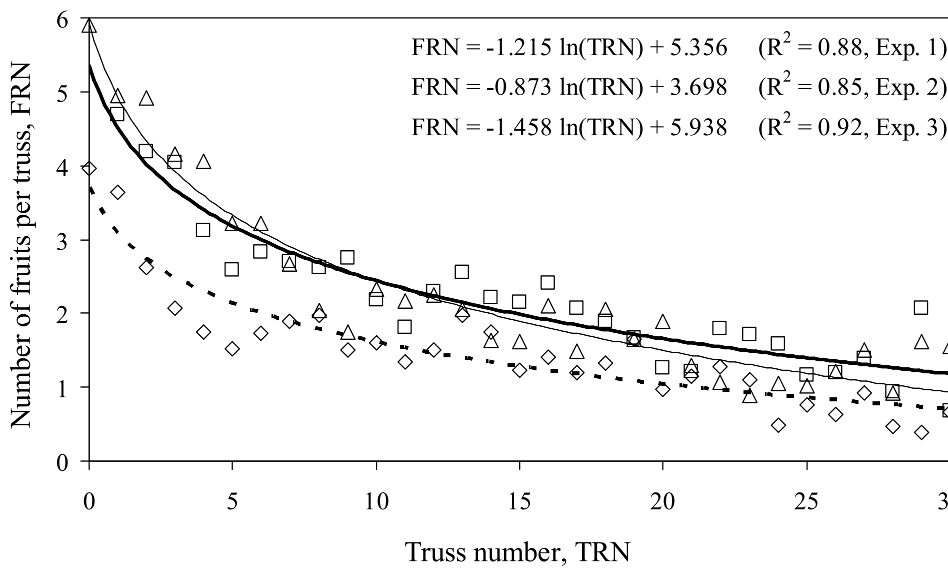

Fig. 5.1 – Number of fruits per truss (*FRN*) as function of truss number (*TRN*) in three experiments: □ ▬, Experiment 1; ◇ ▪▪▪, Experiment 2; △ –, Experiment 3. The lines represent logarithmic fits

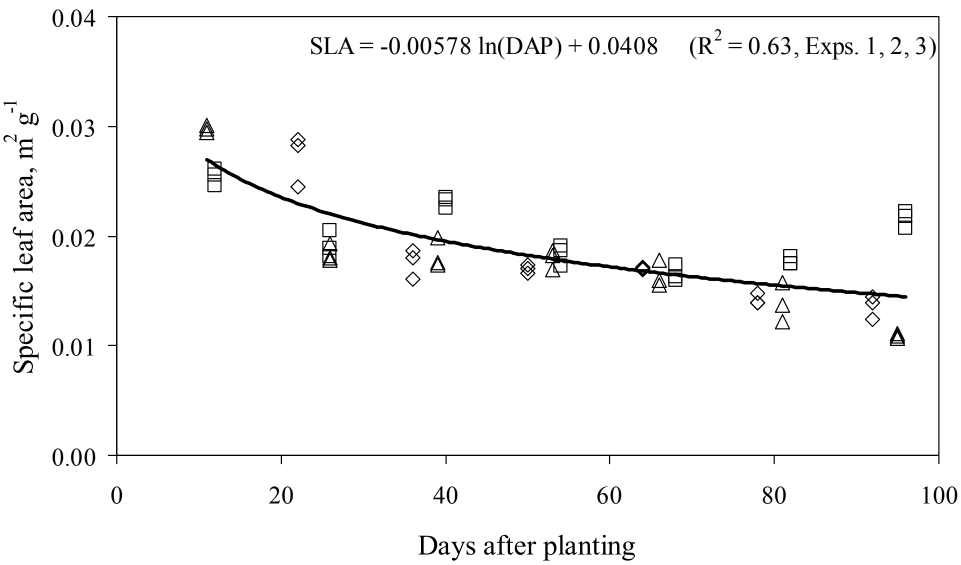

Fig. 5.2 – Specific leaf area (*SLA*) as function of day after planting (DAP) in three experiments: □, Experiment 1; ◇, Experiment 2; △, Experiment 3. The line ▬ represents a logarithmic fit for all data.

Time courses of *L* are given in **Fig. 5.3**. Fluctuations in *L* can be related to leaf senescence, and to shoot and leaf pruning. The latter was done before full maturity of the associated truss, and was simulated when the associated truss had acquired 80% of its temperature sum to maturity. Increasing *L* in the last stage of Experiment 1 was caused by more leaves at the side shoots that were retained after *DAP* 82. Decreasing *L* in the late stage of the Experiments 2 and 3 was due to leaf senescence. An initial *L* of 0.02 m^2 m^{-2} was used in the model. Simulated and observed *L* were in good agreement (figure not shown) when the parameter for fraction of leaves and shoots pruned (LSrem) was set at 0.2, 0.8, and 0.8 for Experiments 1, 2, and 3, respectively.

Initial dry weights at planting for roots, stems, and leaves were 0.77, 0.48, and 0.33 g m^{-2}, respectively for Experiments 1, 2, and 3. The initial rate of root growth was 0.10 g $plant^{-1}$ d^{-1}, which represented the average value from planting to the first destructive samples. Within the vegetative organs, the overall average ratios of leaf, stems, and root to vegetative weight (VOR, vegetative organ ratios) were 0.50, 0.45, and 0.05 (**Table 5.4**). The fraction of dry matter partitioned to the fruits (HI, harvest index) in Experiments 1, 2, and 3, was 0.56, 0.30, and 0.50, respectively (**Table 5.4**).

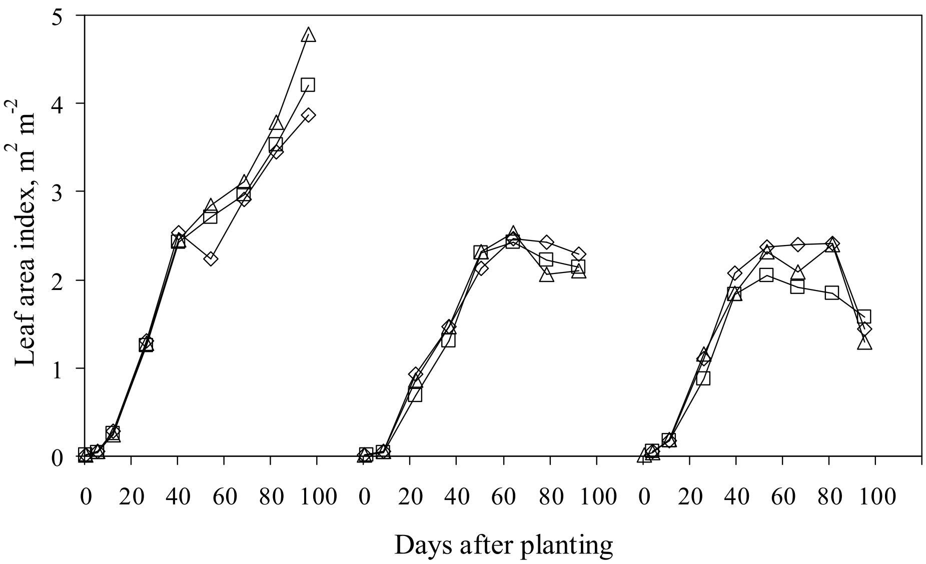

Fig. 5.3 – Time courses of average leaf area index in Experiments 1 (left), 2 (middle), and 3 (right): □, N0; ◇, N1; △, N2

Table 5.4 – Dry matter partitioning (%) to the roots (Rt), stems (St), leaves (Lv) and fruits (Fr) for the three consecutive experiments

	Experiment 1				Experiment 2				Experiment 3			
	Rt	St	Lv	Fr	Rt	St	Lv	Fr	Rt	St	Lv	Fr
N0	3	19	23	56	3	35	32	29	2	21	26	51
N1	3	19	21	57	3	34	31	32	2	22	26	50
N2	3	20	24	54	4	34	32	30	2	23	27	49
Average	3	19	22	56	3	35	32	30	2	22	26	50
5% LSD	1	5	3	7	1	6	6	9	1	5	5	4
VOR	0.07	0.43	0.50		0.05	0.50	0.45		0.04	0.43	0.52	

LSD, least significant difference; VOR, average vegetative organ ratio

Dry matter increase declined slightly after *DAP* 60, which can be due to leaf senescence and a lower photosynthesis rate. The decline was more pronounced in Experiments 2 and 3 than in Experiment 1. This decline was realized in the model by lowering linearly the photosynthesis capacity from 100% at *DAP* 60 to 80% (Experiment 1) or 70% (Experiments 2 and 3) at final harvest.

Average temperature sum to fruit maturity was 1010, 1028, and 989 ^{o}C d, respectively, for Experiments 1, 2, and 3. In the model, the overall average value of 1009 ^{o}C d was used. A list of experiment specific parameters values used in the INTKAM model for the simulation is given in **Table 5.5**.

Table 5.5 – Experiment specific parameters values used in the INTKAM model for simulation of determinate tomato

Parameter	Experiment		
	1	2	3
Plant density (plant m^{-1})	---------------	2.94	---------------
Ratio of leaf to vegetative partitioning	---------------	0.50	---------------
Ratio of stems to vegetative partitioning	---------------	0.45	---------------
Ratio of root to vegetative partitioning	---------------	0.05	---------------
Physiological age of fruit to harvest (^{o}C d)	---------------	1009	---------------
Photosynthesis capacity until *DAP* 60 (%)	---------------	100	---------------
Photosynthesis capacity at final harvest (%)	80	70	70
SLA factor	1.1	0.87	1.0
Sink strength ratio of one vegetative unit to one fruit	1.63	3.00	1.83
Fraction of shoots and leaves pruned at 80% fruit maturity	0.2	0.8	0.8

DAP, day after planting; *SLA* specific leaf area

Scenario studies

Model parameters for scenario studies with determinate tomato were as described in Section 5.3.2. The decreasing number of fruits per truss with increasing truss number (*FRND*) for the determinate was described by a function truss number (*TRN*) as shown in **Fig. 5.1** for Experiment 1, namely:

$$FRND = 5.356 - 1.215 \ln(TRN);\ R^2 = 0.88 \qquad \textbf{(5.4)}$$

Most model parameters and variables for indeterminate tomato were assigned INTKAM default values, with the exception of the ones mentioned below.

Truss appearance rate for indeterminate tomato was taken from Heuvelink (1995):

$$TAR = \{-0.0616 + (0.0104\ T_{Ave})\} \times \text{number of stems per plant} \qquad \textbf{(5.5)}$$

At T_{Ave} = 27.4 ^{o}C, *TAR* in **Eqs. (5.5)** and **(5.2)** is 0.22 and 0.39 trusses d^{-1}, respectively. The approximate double rate is due to the fact that for the determinate crop trusses are formed at two stems.

For temperate regions, *SLA* is set as a function of day of the year, which reflects the radiation-dependent sinusoidal pattern. For the tropical lowlands, *SLA* of indeterminate tomato was simplified according to **Eq. (5.3)**, omitting the radiation-dependent sinusoidal pattern.

The default physiological age of fruit to harvest for indeterminate tomato is of 940 ^{o}C d, which is lower than the observed value for determinate tomato. The observed value of 1009 ^{o}C d for both types was used for the scenario studies.

Leaf area index was simulated to a maximum value of 3 m^2 m^{-2} for all scenarios, anticipating a management practice that would aim for this value. This was achieved via the process of leaf pruning (LSrem) when the associated truss had acquired 80% of its temperature sum to maturity.

A list of model parameters for the scenario studies is given in **Table 5.6**.

Table 5.6 – Model parameters for scenario studies

	Number of crops per year		
	3	2	1
Crop type	determinate	determinate	indeterminate
Duration of each crop scenario (days)	122	183	366
Plant density (plant m^{-1})	---------------------- 2.94 ----------------------		
Ratio of leaf to vegetative partitioning	------------- 0.50 -------------		0.60
Ratio of stems to vegetative partitioning	------------- 0.45 -------------		0.27
Ratio of root to vegetative partitioning	------------- 0.05 -------------		0.13
Physiological age of fruit to harvest (^{o}C d)	---------------------- 1009 ----------------------		
Photosynthesis capacity until *DAP* 60 (%)	----------------------- 100 -----------------------		
Photosynthesis capacity at final harvest (%)	----------------------- 80 -----------------------		
SLA factor	----------------------- 1.0 -----------------------		
Sink strength ratio of one vegetative unit to one fruit	------------- 1.80 -------------		3.00
Fraction of shoots and leaves pruned	-------------------- 0.8–1.0 --------------------		
Number of fruits per truss as truss number increases	decreasing	decreasing	constant
Constant number of fruit per truss	---------------------- 1– 6 ----------------------		

DAP, day after planting; *SLA* specific leaf area

Some model parameters for determinate and indeterminate have similar values. The differences in parameter values reflect cultivation differences and cultivar characteristics.

5.3.3. Crop growth and development: observations and simulation

Specific leaf area and leaf area index

Leaf area index and *SLA* are closely linked. Specific leaf area courses were well simulated with *L* as model input (data not shown), and both *L* and *SLA* could be simulated adequately if the experiments were parameterized separately. An optimum generic parameterization for all three experiments resulted in adequate *L* simulation up to 60 *DAP*, after which simulated *L* showed an end-of-season over-estimation, particularly for Experiment 2. Specific leaf area then was slightly over-estimated for Experiments 1 and 3.

Dry matter production and partitioning

Observed cumulative total dry matter production was similar in Experiments 1 and 3, and was greater than in Experiment 2. This can be related to the amount of intercepted radiation. The higher PAR_i in Experiment 3 than in Experiment 2 was caused by a slightly higher PAR (**Table 5.3**, on average 5.33 vs. 5.27 MJ m^{-2} d^{-1}), a slightly longer growing season (95 vs. 92 days **Table 5.2**), and small differences in *L*. The *L* in Experiment 1, exceeding 3 m^2 m^{-2}, did not contribute to an increase in PAR_i, but the relatively low PAR incident resulted in a lower PAR_i. This resulted in higher radiation use efficiencies ε (**Table 5.7**) in Experiments 1 (3.34 g MJ^{-1} PAR_i) and 3 (3.12 g MJ^{-1} PAR_i) than in Experiment 2 (2.95 g MJ^{-1} PAR).

Although PAR transmitted by greenhouse cover in N0 was higher than in N1 and N2, no differences in total dry matter production were observed among plastics within each experimental period. Amounts of cumulative PAR_i across greenhouses were also similar (**Table 5.7**), which can be related to variation in *L*.

Dry matter partitioning to the fruits in truss-pruned crops (29–32%, Experiment 2) was substantially lower than in not-truss-pruned crops (54–57%, Experiment 1; 50–51%, Experiment 3).

Dry matter partitioning to the fruits was greatest, to the root smallest, and to the stems and to the leaves of similar magnitudes in experiments 1 and 3 (**Table 5.4**, **Fig. 5.4**). Partitioning to the stems, leaves and fruits were of similar magnitudes in Experiment 2. Partitioning within vegetative organs among leaves, stems, and roots were in the ratio of 8:6:1, 10:11:1, and 13:11:1 for Experiments 1, 2, and 3, respectively.

Although simulated *L* and SLA were slightly ove-restimated after parameterization of sub-processes, simulated total dry matter production (**Fig. 5.4**) and ε generally agreed well with observed values. The relative difference between observed and simulated values of total dry matter production and ε were similar, i.e. -2%, 9%, and 3% in Experiments 1, 2, and 3, respectively. Simulations gave comparable dry matter partitioning among organs, and organ weights **(Fig. 5.4)**.

Truss appearance rate, fruit development and fruit production

The first truss appeared at DAP 11, 15 and 12, respectively, in Experiment 1, 2 and 3. At an average temperature of 27.4 ^{o}C, a truss appearance rate of 0.39 trusses d^{-1} was measured. A fruit took an average of 1009 $d^{o}C$ (43 days) from setting to maturity. The average cumulative number of trusses that was observed and simulated was 33 and 32 in Experiments 1, and 34 and 32 in Experiment 3.

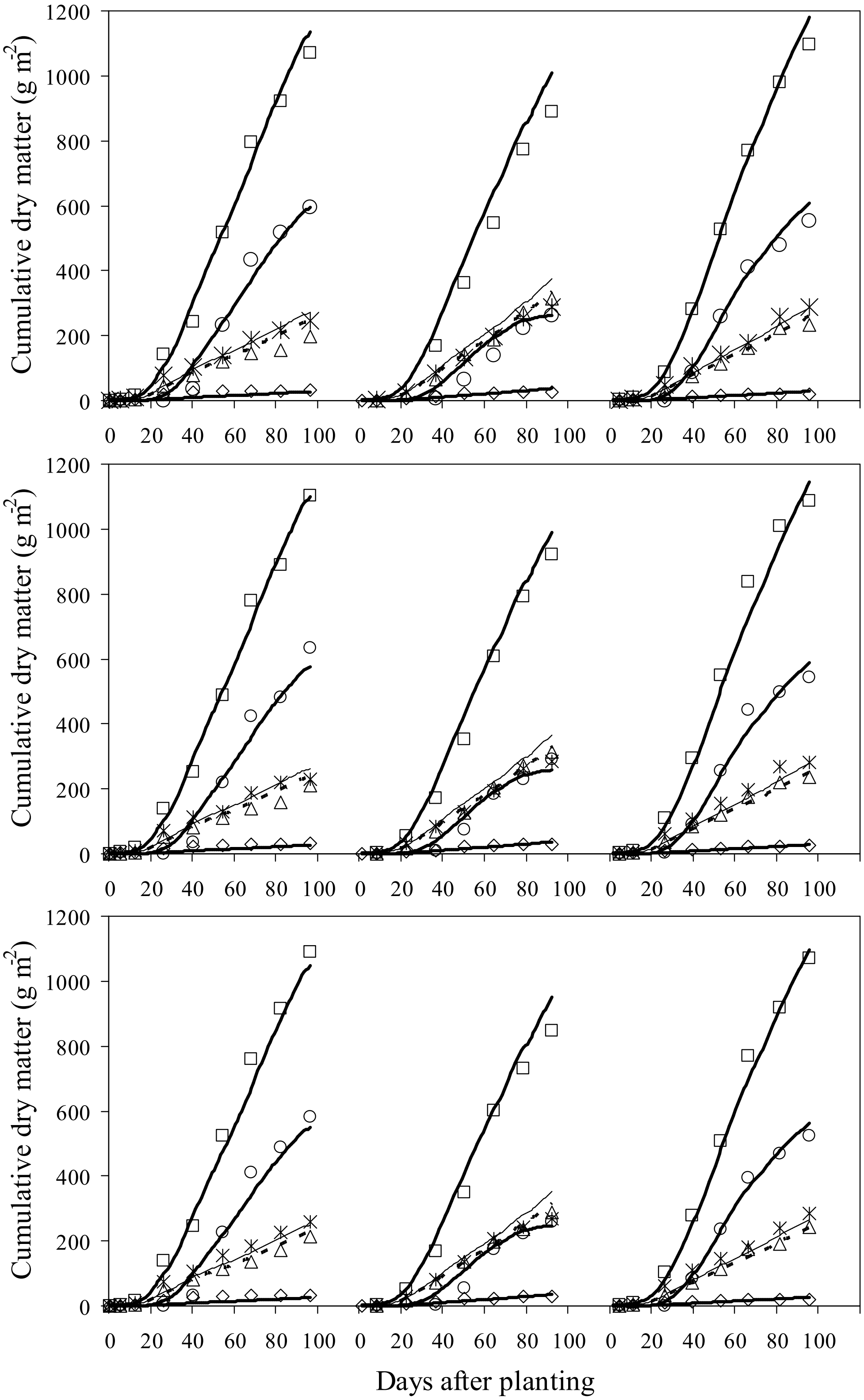

Fig. 5.4 – Observed (symbols) and simulated (lines) cumulative weights of total dry matter and plant organs in Experiments 1 (left), 2 (middle), 3 (right) for treatments N0 (top), N1 (middle), N2 (bottom). Symbols and lines: □ ▬ total, ○ ▬ fruits, ✳ – leaves, △ ▪▪▪ stems, ◇▬ roots

The differences between observed and simulated values are a consequence of the generic function applied. In Experiment 2, truss pruning resulted in a cumulative number of trusses of 15, both observed and simulated.

Average cumulative dry fruit weight in Experiments 1, 2, and 3 was 604, 269, and 542 g m^{-2} (**Table 5.7**).

Table 5.7 – Cumulative observed dry matter production *DM* (g m^{-2}), total calculated intercepted PAR by the crop PAR_i (MJ m^{-2}), radiation use efficiency ε of the crop (g total dry matter MJ^{-1} PAR_i), fruit dry matter *Fr* (g m^{-2}) and fresh fruit harvest *FrH* (t ha^{-1}). PAR_i was calculated with observed *L*

	Experiment 1					Experiment 2					Experiment 3				
	DM	PAR_i	ε	*Fr*	*FrH*	*DM*	PAR_i	ε	*Fr*	*FrH*	*DM*	PAR_i	ε	*Fr*	*FrH*
N0	1070	334	3.21	599	67	891	302	2.95	258	35	1095	343	3.19	553	71
N1	1104	328	3.37	629	71	922	307	3.00	295	36	1087	359	3.03	543	72
N2	1090	316	3.45	584	67	847	293	2.90	254	33	1070	340	3.15	524	69
Average	1088	326	3.34	604	69	887	301	2.95	269	35	1084	347	3.12	542	71
5% LSD	187	66	0.60	125	1	132	10	0.40	82	2	113	39	0.60	94	1

Their simulated values were 573, 255, and 585 g m^{-2}, respectively. By taking observed dry matter content of 0.066 g g^{-1}, the cumulative fresh fruit weight in Experiments 1, 2, and 3 was 97, 43, and 99 t ha^{-1}. Observed cumulative harvested fresh fruit weight in Experiments 1, 2, and 3 was 69, 35, and 71 t ha^{-1} (**Table 5.7**) with simulated values of 68, 36, and 66 t ha^{-1}, respectively. The average share of marketable fruits in Experiment 3 was 66% (no observations were taken in Experiments 1 and 2). The remaining 34% was formed by small parthenocarpic fruits that had angular shape and blossom end root.

Source – sink ratio

The high truss formation rate of 0.39 trusses per day per plant resulted in a high number of potential assimilate sinks. Simulation results (data not shown) indicate average sink strength of approximately 19 g $plant^{-1}$ d^{-1} and average source strength of approximately 6 g $plant^{-1}$ d^{-1} during the period of fruit production. This resulted in an average source – sink ratio of approximately 0.4. For comparison, simulation of a standard indeterminate tomato crop with 7 fruits per truss and an approximate truss load of 7 trusses per plant, under representative climate conditions in The Netherlands, gave average sink strength of approximately 13 g $plant^{-1}$ d^{-1} and average source strength of 8 g $plant^{-1}$ d^{-1}, resulting in source – sink ratio of approximately 0.6. The source – sink ratio in our experiments was therefore relatively low.

5.3.4. Scenarios

The fraction leaves and stems pruned (LSrem) was similar for all scenarios, which, in combination with different sink strengths caused by variable numbers of fruits per truss (FRNC), caused different partitioning of dry matter to the leaves. This caused variation in *L*, which explains a generally higher PAR_i and hence higher total dry matter production under lower fruit loads (**Table 5.8**).

Table 5.8 – Yearly simulated values of PAR interception PARi (MJ m^{-2} yr^{-1}), cumulative dry matter production DM (g m^{-2} yr^{-1}), radiation use efficiency ε (g MJ^{-1}), cumulative fraction of dry matter to fruits fFr (-), cumulative fruit dry matter production Fr (g m^{-2} yr^{-1}), and cumulative dry matter fruit harvest FrH (g m^{-2} yr^{-1}) for various scenario conditions. Fruit number per truss is set constant to 1 to 6, and set according to decreasing fruit number function

Fruit number per truss	Ideal greenhouse plastic cover						Standard greenhouse plastic cover					
	One crop per year, indeterminate tomato											
	PAR_i	DM	ε	fFr	Fr	FrH	PAR_i	DM	ε	fFr	Fr	FrH
1	1632	6099	3.74	0.15	896	848	1630	5906	3.62	0.15	895	841
2	1632	5684	3.48	0.32	1791	1695	1630	5426	3.33	0.33	1790	1683
3	1624	5051	3.11	0.49	2450	2321	1617	4885	3.02	0.48	2368	2227
4	1591	4962	3.12	0.55	2749	2603	1581	4779	3.02	0.55	2645	2488
5	1557	4848	3.11	0.61	2935	2780	1546	4673	3.02	0.60	2827	2658
6	1526	4753	3.11	0.65	3068	2906	1514	4575	3.02	0.65	2951	2776
	Two crops per year, determinate tomato											
1	1595	5263	3.30	0.32	1684	1491	1585	5117	3.23	0.33	1689	1466
2	1557	5253	3.37	0.48	2521	2229	1543	5076	3.29	0.49	2487	2177
3	1519	5173	3.41	0.58	3000	2633	1500	4974	3.31	0.58	2885	2558
4	1475	5040	3.42	0.64	3226	2850	1455	4832	3.32	0.64	3092	2760
5	1437	4916	3.42	0.69	3392	2980	1414	4696	3.32	0.69	3240	2874
6	1399	4782	3.42	0.72	3443	3046	1377	4572	3.32	0.73	3338	2940
Decreasing	1513	5087	3.36	0.44	2238	2054	1494	4885	3.27	0.44	2149	1981
	Three crops per year, determinate tomato											
1	1478	5139	3.48	0.30	1542	1211	1468	4989	3.40	0.31	1547	1183
2	1448	5165	3.57	0.46	2376	1846	1435	4988	3.48	0.46	2294	1792
3	1416	5095	3.60	0.55	2802	2203	1397	4895	3.50	0.55	2692	2127
4	1380	4985	3.61	0.61	3041	2413	1358	4768	3.51	0.62	2956	2319
5	1347	4870	3.62	0.66	3214	2540	1321	4638	3.51	0.66	3061	2429
6	1314	4749	3.61	0.70	3324	2614	1288	4516	3.51	0.70	3161	2495
Decreasing	1395	5006	3.59	0.50	2503	2098	1374	4795	3.49	0.50	2398	2011

A more profound effect on fruit harvest weight is caused by the number of not-mature fruits (**Table 5.8**). Planting one crop per year (C1) enabled a harvest of 95% of the fruits as mature fruits, leaving only 5% of the fruits not mature. The share of not-mature fruits increased to 12% in C2 and to 22% in C3, respectively. In case of a determinate tomato crop with FRND, the share of not-mature fruits was lower, i.e. 8% (C2) and 16% (C3).

Effect of fruit load

Dry matter partitioning to the fruits was largely determined by the total number of fruits on the plant (**Table 5.8**, **Fig. 5.5**). In case of simulation with FRNC 1 for determinate and with FRNC 2 for indeterminate tomatoes, fruit production was low, accounting for less than 35% of total dry matter production (**Table 5.8**). As FRNC was increased to 6, the fraction dry matter partitioned to the fruits increased substantially, reaching 0.65 (C1), 0.72 (C2), 0.70 (C3). For a determinate tomato with FRND, average dry matter partitioning to the fruits was 0.44 (C2) and 0.50 (C3).

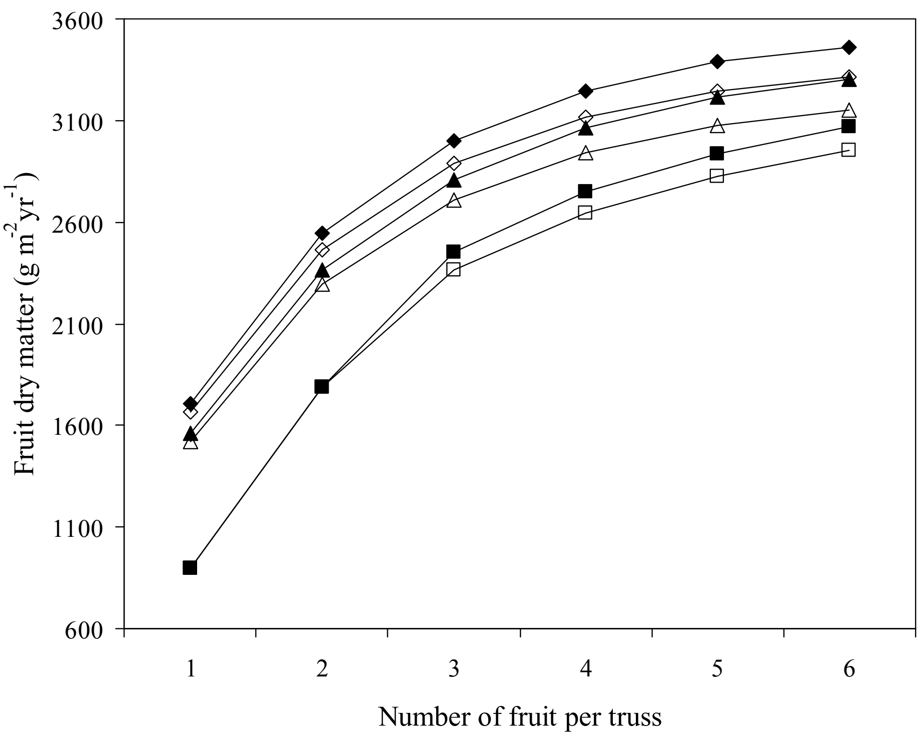

Fig. 5.5 – Simulated annual fruit dry matter production as a function of the number of fruit per truss. Scenarios for an idealized greenhouse are given by closes symbols (■,◆,▲), and for a standard greenhouse by open symbols (□, ◇, △). Scenarios for an indeterminate tomato crop with 1 (■, □), and for determinate tomato crops with 2 (◆, ◇) and 3 (▲, △) plantings per year are presented

A tomato crop with a certain number of fruits per truss has higher simulated fruit dry matter production if two crops per year are assumed, than if three crops per year are assumed (**Table 5.8**). This is caused by the fact that on an annual basis, the productive period is longer with two crops than with three crops per year. The lower fruit dry matter production by the year-long grown indeterminate tomato crop was due to lower fruits load caused by the lower truss appearance rate (**Eq. 5.5**) and therefore the lower generative sink strength. A determinate tomato crop with FRND produced on an annual basis less fruit dry matter under C2 than under C3 because of the longer period towards the end of the season with a low number of fruits per truss. The level of production of determinate tomato with FRND was comparable to the production achieved with a constant FRNC of around 3 (C1) or 2 (C2 and C3).

5.4. Discussion

The possibility of designing greenhouses that can realize a suitable climate for crop growth and development, and the feasibility of cultivating a good producing crop under the realized greenhouse climate are essential elements in generating knowledge for the introduction of protected cultivation in tropical lowland regions. Several greenhouses were introduced in tropical regions, such as in high altitude tropics of the Bogota Plateau, Colombia (Cooman, 2002; Cooman *et al*., 2005) and in Thailand (Kleinhenz *et al*., 2006; Harmanto, 2006; Mutwiwa, 2007). Recently, prototypes of the tropical lowland greenhouse constructions have been established in Indonesia (Campen, 2005; Impron *et al*., 2007, 2008) and Malaysia. The present study focuses on growth and development of a tomato crop grown in the prototype greenhouses and on understanding the underlying processes through the use of the INTKAM crop growth model. Such information is scarce as yet, and for Indonesia virtually non-existent. Furthermore, the three successive growing seasons were also aimed to evaluate the potential of a full-year crop production under tropical lowland greenhouse conditions, and to form the basis of scenario studies.

Growth dynamics of determinate tomato

Climate differences between the three periods were small (**Table 5.3**), but crop management practices, in particular truss pruning, caused relatively great differences in crop growth. Effects of varying climate and crop management practices over the three experimental periods on growth and development were analyzed with the crop model INTKAM. Some of the modelled processes were re-parameterized for determinate tomato in lowland tropics, resulting in a good agreement between simulation and observations of growth and development.

SLA of a mature crop in a tropical lowland greenhouse averaged 0.01–0.02 $m^2\ g^{-1}$. Leaves in a high-radiation environment are relatively thick, as was also observed in Thailand (Kleinhenz *et al.*, 2006) and under summer condition in the Netherlands (Heuvelink, 1996). Also, whereas SLA in a temperate climate follows a radiation-dependent sinusoidal pattern (Heuvelink, 1996), this is different for the lowland tropics close to the equator where radiation is relatively stable over time. SLA at the crop level decreased with crop age, independent of the season. An explanation is the decrease over time of the fraction of young leaves with higher SLA leaves. Generic model parameterization for all experiments resulted in a slight end-of-season over-estimation of SLA and *L*. This did not have a serious impact on simulated crop growth as this hardly affected the amount of intercepted radiation.

Crop growth rate is related to the amount of PAR intercepted by the crop canopy (PAR_i), which is a function of PAR outside the greenhouse, PAR transmitted by greenhouse cover (I_{PAR}) and *L*. Although I_{PAR} was 9 % and 12% higher in N0 than in N1 and N2, respectively, variation in *L* resulted in similar amounts of cumulative PAR_i across greenhouses within experimental periods (**Table 5.7**). Under these conditions, in each experimental period, the plastic type had no significant effect on any of the studied crop growth parameters. Due to the strong passive ventilation capacity of the greenhouses, differences in air temperature were very small, resulting in similar truss appearance rates (**Eq. 5.5**).

Total dry matter production in Experiment 2 was lowest, and also dry matter partitioning to the fruits was approximately 50% lower than in Experiments 1 and 3. The lower total dry matter production is explained by the low PAR_i, which was caused by slightly lower values in PAR and duration of the growing season. The lower dry matter partitioning to the fruits can be explained by the high level of truss pruning in Experiment 2. The low dry matter partitioning to the fruits in Experiment 2 was associated with a greater dry matter partitioning to stems and leaves (**Table 5.4**). On average, pruned crops in Experiment 2 had approximately 18% lower total dry matter production and 11% lower PAR_i than non-pruned crops (**Table 5.7**). The lower PAR_i was the consequence of a lower *L* in combination with a lower total radiation.

Observed values of ε of 2.95–3.34 g MJ^{-1} PAR were within the reported range of 2.6–4.04 g MJ^{-1} PAR, depending on cultivation treatments (Heuvelink, 1996; Kleinhenz *et al.*, 2006). In the present experiment over a whole growing season in greenhouse grown tomatoes, the smaller ε in pruned crops can be related to the lower fruit load. It appears therefore that in terms of radiation use efficiency, no differences exist between tomato cultivated in the tropics and temperate climates. Differences are predominantly the consequence of differences in greenhouse design and cultivation method.

Determinate tomato crops grown in tropical greenhouses exhibit a higher fruit abortion for later appearing trusses, resulting in a decreasing number of fruits per truss over time. This was also reported by Estrada *et al*. (2009) for a tomato cultivar with an indeterminate growth that has a short growth cycle. In our case, one possible explanation can be found in Van der Ploeg *et al.* (2007): "at high temperature plants produce more fruits and increased sink fruit sink strength, however early fruit will grow at the expense of vegetative parts and as developing and flowering trusses are weaker sinks than fruiting trusses this may cause a delay in growth of newly set fruit and might even lead to flower and fruit abortion". For lack of clear understanding of the physiological mechanisms, the abortion process itself could not be simulated in an explanatory manner. When imposing the decreasing number of fruits per truss with increasing truss number, the simulated source – sink strength ratio of determinate tomato was approximately 0.4. In Experiment 2, retaining only the first 15 appearing trusses did not increase observed fruit set, simulated sink strength and simulated source – sink ratio. This is likely caused by a high fruit load attained at earlier moment for short growing season of determinate tomato with high truss appearance rate. The accumulated number of fruits of the first 15 trusses account for 60–65% of the total number of fruits per plant for the whole growing season (**Fig. 5.1**), which realizes a large sink for the entire growing season.

High fruit abortion has been reported to be associated with prevailing high temperature (Geisenberg & Stewart, 1986; Bertin, 1995; Peet *et al*. 2003, Kleinhenz *et al.*, 2006). Observed average greenhouse temperatures during night time were mostly higher than 20 ^{o}C, and during day time between 9 A.M. and 15 P.M mostly above 30 ^{o}C (**Table 5.3**), which are above the maximum air temperature for tomato fruit set (Geisenberg & Stewart, 1986). Therefore, it is possible that high prevailing temperatures also played a role in fruit abortion.

Greatest fresh fruits harvest was in the order of 70 t ha^{-1} as obtained in Experiments 1 and 3 (**Table 5.7**). Therefore, on a yearly basis with three consecutive planting, an estimated annual fresh fruit production of 210 t ha^{-1} year^{-1} should be possible. Under ventilated plastic greenhouses in the humid tropics of Thailand, Kleinhenz *et al.* (2006) reported a fresh fruits production of 9.5 kg m^{-2} on 4.2 stems m^{-2} over 19 weeks after planting, which is approximately equal to 260 t ha^{-1} year^{-1}. Our results are also comparable to tomato (cultivar Rengo) production under acrylic-covered greenhouses in Kuwait of 258 t ha^{-1} year^{-1} (Albaho & Al-Mazidi, 2005).

Options for better production systems

The scenario studies revealed that (i) fruit production under NI is slightly higher than under NS, (ii) at a constant number of fruit per truss, fruit production of a determinate tomato crop is higher in case of two seasons than three seasons per year, and (iii) increasing the number of fruits per truss is the most significant factor to increase fruit production.

The small effect of plastic type can be explained by the fact that both crops under NI and NS receive the same amount of PAR and are exposed to almost similar climate conditions. Average fruit production under NI was approximately 3% higher than under NS (**Table 5.8**). This small production gain by an improved greenhouse cover NI was obtained under 144 m^{2} ventilated greenhouse where climates under NI and NS are almost similar. The similar temperature and relative air humidity were caused by the large passive ventilation capacity of the greenhouse. However, simulation using the

Simple Greenhouse Climate Model (see Chapter 4) shows that for bigger greenhouses the air temperature under NI is lower than under NS. Under such condition, larger production gain under NI than under NS is possible. If, for example, air temperature is assumed to be reduced by 1 ^oC, simulated maintenance respiration reduces and simulated production increases by 3%.

An increased fruit number per truss increases fruit production, although the increase reduces with increasing numbers of fruits per truss (**Fig. 5.5**). With six fruits per truss, simulated annual fresh fruit production of an indeterminate tomato crop is 464 t ha^{-1} yr^{-1}, that of two determinate tomato crops per year 522 t ha^{-1} yr^{-1}, and that of three determinate tomato crops per year 503 t ha^{-1} yr^{-1} (**Table 5.8**). For reference, fruit production attained under Dutch greenhouses can reach well above 500 t ha^{-1} yr^{-1} (Elings *et al.*, 2005; Heuvelink *et al.*, 2005).

At a constant number of fruits per truss, an increased annual fruit production can be expected if the production period per crop is lengthened, as is illustrated in **Fig. 5.6**.

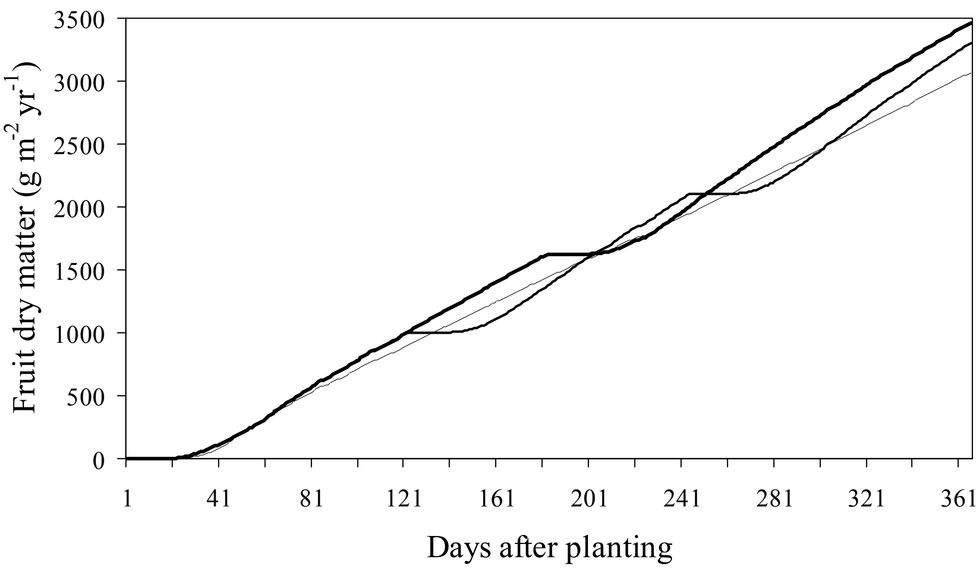

Fig. 5.6 – Illustrating the effect of number of crops per year on fruit dry matter production in indeterminate tomato: -----, one crop per year; and determinate tomato: ▬▬, two crops per year; ——, three crops per year. Simulation was run with 6 fruits per truss with NI greenhouse plastic cover

Fewer crops per year reduce the number of unproductive period between planting to the onset of fruit growth. Also, the fraction not-mature fruits is also smaller in case of fewer crops. Simulations showed that two crops per year produce 6% more fruits than three crops per year. However, this effect is lost if the number of fruits per truss decreases over time. The periods with relatively low number of fruits per truss gain dominance. Simulations showed that then, on a yearly basis the production can be 12%

lower in case of two crops per year than in case of three crops per year (**Table 5.8**). Therefore, management methods have to be developed that prevent fruit abortion.

Literature (*e.g.* Sato *et al.,* 2001; Peet *et al.*, 2003; Firon *et al.*, 2006) reported that the high daily temperatures potentially decrease fruit set, which could also be the case for indeterminate tomato (Kleinhenz *et al.,* 2006, Estrada *et al*., 2009). However, our experimental data indicate that high temperatures are not likely to be the main cause of the decreasing fruit set over time, as temperatures were also high at the beginning of the season, when abortion was relatively low. Increasing fruit load also means increasing sink strength, which requires a higher source strength. Marcelis and Pascale (2009) recently highlighted ways to improve greenhouse crop production. Relevant to our study is increased source strength, through for example a higher *L*.

In short, simulations indicate that the high potential of fruit production under tropical lowland greenhouse requires high number of fruits per truss, and that therefore crop management practices should be directed towards a long-term source – sink balance that reduces fruit abortion.

5.5. Conclusions

The present experiments did not show significant differences in crop growth and developmental responses to differences in plastic films. Cultural practices, in particular truss pruning, caused more profound difference in crop growth. Crops with a low number of trusses produced substantially lower fruit dry matter and hence fruit yield than crops with high number of trusses. Determinate tomato grown in tropical greenhouses exhibit higher fruit abortion for later appearing trusses, resulting a characteristic of number of fruits per truss decrease as truss increase. This might be related to the low source – sink strength ratio and high prevailing temperatures.

The scenario studies revealed that fruit production by a determinate tomato crop characterized by a decreasing number of fruits per truss can be increased slightly by using zero NIR transmittance plastic film and by planting three crops per year (which is current practice). However, when the number of fruits can be maintained constant through appropriate crop management measures, the crop production would increase with increasing fruit load and lengthening production period.

6

Discussion and concluding remarks

6.1. General approach

To judge the applicability of greenhouses at tropical outdoor climate the first question was if the outdoor climate conditions allow the realisation of optimum conditions for greenhouse horticultural crops. These conditions may be achieved if excessive greenhouse temperatures can be avoided. In this study, the greenhouse cooling is passive and primarily depends on three natural processes: reduction of radiation input by application of near infrared radiation (NIR) reflecting plastics, removing hot air from the greenhouse compartment by natural ventilation, and increasing latent heat flux by transpiration. The overall balance of various energy flows in the greenhouse system – as described in detail in Chapter 2 – determines the greenhouse climate. In this study, the greenhouse climate is expressed in the state variables of greenhouse air temperature T_{Air}, canopy temperature T_{Can} and water vapour pressure deficit D_{Air}. To analyze the system experiments were conducted during the three seasons typical for the tropical lowland. In the current study T_{Can} was not measured but this factor could be related to the experimental data applying the simple greenhouse climate model (GCM). This model was designed to analyse the effect of single factors, such as greenhouse near infrared radiation (NIR) transmission, greenhouse ventilation and leaf area index L, on the mentioned greenhouse climate state variables at given outdoor weather conditions.

6.2. Limitations of the simple greenhouse climate model

The physical basis of the model was derived from literature, where some of the equations and parameters in the model were empirical (Chapter 2). Independent data sets were used in model development and in model validation (Chapters 2 & 3).

The model assumes a well-mixed greenhouse compartment (Roy *et al.*, 2002). In fact, climate variables show spatial variation within the greenhouse (Bojaca *et al.*, 2009), which requires a different approach to be modelled. In fact this approach was followed by the basic design of the greenhouse geometry and ventilation openings, applying CFD (Campen, 2005). In our approach the aim is the analysis of the (slow) dynamics following the daily variation of the outdoor weather during a growth season. Then the greenhouse compartment can be considered as well mixed if the spatial distribution of climate variables does not strongly vary. However some variation in spatial distribution will occur, especially driven by the ventilation rate. With higher ventilation rate the spatial distribution will homogenize. A common feature in our experimental data was the increase of wind velocity, and so ventilation rate, during the day with increasing outdoor temperature, driven by the increasing atmospheric buoyancy. So during the most critical parts of the day at the highest outdoor temperatures the spatial distribution was minimal allowing the consideration of the greenhouse compartment as well mixed for the analysis of the critical greenhouse climate.

While the model only considers the greenhouse air compartment it assumes that a defined part Λ of the solar radiation is released as sensible heat to the greenhouse air. This can be justified by the fact that first solar radiation is absorbed by the greenhouse cover, the greenhouse structural elements and the soil surface and then released (with some delay) to the air. This considerably simplifies the heat exchange between various parts of the greenhouse which was justified because the model was aimed at design for static conditions of the greenhouse climate following the slow daily dynamics of the outdoor weather during the succeeding days of the growth season. Calibrating this released solar radiation part Λ from the experiments resulted in Λ = 0.1 with large variation and decreasing during the growth season. If the effect of increasing leaf area index during the growth season was taken into account, an exponential term in Λ gave satisfactory agreement between measurements and calculation of T_{Air} and D_{Air}. The variations in Λ will be dependent on the experimental set-up while the varying delay in released heat from the opaque greenhouse parts is not measured. This dependency on the experimental set-up as was also experienced by Boulard & Baille (1993) and Boulard & Wang (2000) when using a dimensionless calibration factor in simple greenhouse climate models. Thus, when applying the GCM to evaluate greenhouse climate dynamics or to design greenhouses (Chapter 4), the results should be interpreted with caution. For example, the size and geometry of the ventilation openings realising the designed ventilation has to be determined subsequently by *e.g.* CFD modelling.

Regardless of the above shortcomings, a good agreement between experimental data and simulation results was evident under extensive experimental conditions. Simulation errors of T_{Air} and D_{Air} were less than 2% and 10%, respectively. The conclusion is that the results enable the model to be used in the design of the optimum greenhouse system for tropical lowland.

6.3. Single factors

6.3.1. Ventilation capacity

As expected measurements showed that in general T_{Air} and D_{Air} were higher inside an empty greenhouse than outdoor. Additional closing of ventilation openings amplified these differences. In greenhouses with growing crops inside, the difference between indoor and outdoor air temperature became smaller due to the effect of transpiration cooling. Then the difference between indoor and outdoor air water vapour pressure deficit became much higher when the ventilation walls were partly closed, due to reduced water vapour removal. These conditions indicate that ventilation is crucial for removing the warm and moist air from the greenhouse compartment.

A high ventilation capacity tends to make the climate between outdoor and indoor highly coupled, showing that passive control of greenhouse climate by natural ventilation can avoid significant increase in T_{Air}. According to these findings, a high ventilation capacity is crucial for a tropical lowland greenhouse.

6.3.2. Applying plastic covering material having low NIR transmission

It was expected that NIR reflectivity would affect greenhouse air temperature due to the of reduction of radiation heat input (Brown, 1939; Morris *et al.*, 1958; Tanaka, 1997). Simulations revealed that application of plastic having low NIR transmission could reduce T_{Air}, T_{Can} and crop transpiration (Hemming *et al.*, 2006c). A high reduction in NIR transmission is needed in order to affect T_{Air} and T_{Can}. Simulations with GCM showed similar results. The effect of NIR reduction on reducing T_{Air} was more significant under small leaf area index *L,* bigger greenhouse size and humid conditions. The conclusion is that for young crops lower NIR transparent plastic covers can potentially compensate for low transpiration rates at given boundary conditions, and therefore help maintaining a relatively low air temperature, which usually helps avoiding water shortages. However, a significant reduction in NIR transmission is needed for that. Moreover a reduction in NIR may compensate for lower ventilation (which could be related to a very low outdoor wind speed, a smaller ventilation opening and/or a larger greenhouse) if NIR reduction is significant. Experiments and simulations showed that for full grown crops, having $L \geq 1$ the effect of NIR reflectivity on greenhouse air temperature was low, but the effect on crop transpiration was significant. For a 144 m^2 greenhouse and at $L = 1$, every reduction of greenhouse NIR transmission by 10% reduces crop transpiration by 2%. This result can be compared to results of Kempkes *et al*. (2008 and 2009) which showed a reduction in crop transpiration by NIR reflection screens used on roses in The Netherlands. In their experiments 20% reduction in energy load resulted in 30% reduction in transpiration of roses, while showing almost no differences in T_{Can} since the absorbed solar energy by the crop had been fully translated into latent heat. This decrease is much higher than found in our study while their ventilation is very low.

The conclusion for the results in a greenhouse in tropical lowland of Indonesia is that for full grown crops plastic coverings with a low NIR transmission will not significantly reduce greenhouse air temperature but can be applied to reduce transpiration rate as had been shown in the simulation results and thereby prevent crop stress. Moreover water can be saved important for areas with water shortage. Plastic films with a low reduction in NIR transmission are not sufficient to have a significant effect as had been shown in the experimental results

6.3.3. Increasing transpiration cooling

Growing crops inside the greenhouse increases the energy conversion into latent heat and increases the air water vapour content. In later stages of crop growth with a high leaf area index L, the effect of transpiration on decreasing greenhouse T_{Air} is more significant and the maximum T_{Air} was often lower than the maximum outdoor air temperature T_{Out}. The differences of T_{Air} between the experimental greenhouses with different NIR covers diminished at high L as transpiration took more dominant effect on lowering T_{Air}.

At high L, transpiration cooling alone was able to keep T_{Air} low. At very dry boundary conditions an even lower T_{Air} was simulated. It was simulated that leaf area index L had the highest impact on T_{Air}, implying that then a large amount of cooling is achieved by the crop itself. So the conclusion is that for full grown crops transpiration cooling in combination with sufficient ventilation for removal of water vapour (latent heat) is essential in preventing too high greenhouse air temperatures. For young crops transpiration is too low and ventilation is essential for removal of sensible heat. Dense planting of young crops could help in preventing extreme conditions during this crop stage.

6.3.4. Taking advantage of favourable outdoor climates

According to GCM simulation, the following processes are attributable to lowering greenhouse air: (i) higher wind speed U creates higher ventilation rate N and higher sensible heat transfer between the greenhouse and outdoor air via the cover due to external convection; (ii) higher vapour pressure deficits D drives higher transpiration. As was observed during the experiments, at the most critical outdoor climate conditions (maximum outdoor temperature) the wind speed appeared to have its daily maximum. Obviously this is due to the maximal atmospheric buoyancy then. So this helps in preventing critical greenhouse climate conditions.

6.4. Crop production in tropical lowland greenhouse: a case for tomato crops

For a determinate tomato crop, we observed a combination of high truss appearance rate as a consequence of the crop architecture, and decreasing number of fruits per truss with increasing truss number The latter was associated with high fruit abortion, which may have been associated with the availability of assimilates for young developing fruits. The benefit of having a higher truss appearance rate is nullified by the overall low number of fruits per truss, as crop production is highly influenced by the number of fruits per m^2.

Scenario studies indicated that increasing fruit load is the most significant factor to increase fresh fruit production, up to 439 t ha^{-1} yr^{-1} for an indeterminate and 462 t ha^{-1} yr^{-1} for a determinate tomato crop, both with 6 fruits per truss. On the one hand, on an annual basis a determinate tomato crop has a shorter productive period because of the multiple plantings and therefore multiple unproductive young crop phases, but on the other hand, an indeterminate tomato crop has a lower fruit load caused by the lower truss appearance rate. On balance, the indeterminate tomato crop has a disadvantage.

Fruit abortion must therefore be minimized. Tomato plants are sensitive to high temperatures, with flowering and fruit set being the most sensitive stages (Wahid *et al*., 2007). As fruit set in tomato under high temperatures is related to adaptability problems (Rudich, 1986), this requires breeding for a cultivar with higher temperature tolerance. However, many existing tomato cultivars lack in genetic variation to temperature, which is typical of self-pollinating crops; thus breeders may consider utilizing alternative sources of variation from wild cultivars (Van der Ploeg *et al.*, 2007).

Greenhouse tomato production could be increased slightly by elongating the productive crop period (and therefore reducing the number of crops per year) and by using zero NIR transmittance plastic film. However, when determinate characteristics are not altered (a high truss appearance rate, a decreasing number of fruits per truss with increasing truss number) the simulation favoured a higher fresh fruit production under three (318 t ha^{-1} yr^{-1}) than two (311 t ha^{-1} yr^{-1}) consecutive plantings a year. Leaf area index was simulated to a maximum value of 3 m^2 m^{-2}. The small difference of fruit productions might be negligible.

Fresh tomato production in prototype greenhouses can reach around 70 ton/ha per growing season of around 95 days. This production is much higher compared to the average national production of around 16.6 t ha^{-1} (FAO, 2010). This production level requires optimum water and nutrient supply trough drip irrigation and ventilation through nets that prevent infestation by insects. If in two years seven consecutive crops are planted, an estimated annual fresh fruit production of 250 t ha^{-1} $year^{-1}$. This last figure deviates slightly from the achievable under simulation of 315 t ha^{-1} yr^{-1}.

6.5. Recommendations for further research

6.5.1. The need to investigate climates of bigger greenhouses

By combining all factors capable in lowering T_{Air}, *what is the optimum greenhouse design in the tropical lowland?* The answer to this question varies. If this is based on the achievable T_{Air} the lower the T_{Air} the better the greenhouse. Simulation showed that greenhouses with varying sizes from the original single span 144 m^2 (L_1W_1) to multi span 14400 m^2 ($L_{10}W_{10}$) experiences $\Delta T_{A\text{-}O} > 0$ when leaf area index L was low, and it get worst under calm and sunny outdoor weather. A single span 144 m^2 (L_1W_1) greenhouse is able to keep $\Delta T_{A\text{-}O}$ close to zero, especially under windy weather. Applying plastic cover having lower NIR transmission is of little advantage as most of the greenhouse cooling can be attributed to ventilation and with full grown crops, to transpiration. In bigger greenhouses of 3600 m^2 (L_5W_5) and 14400 m^2 ($L_{10}W_{10}$), applying idealized plastic reduces $\Delta T_{A\text{-}O}$ considerably at low leaf area index L and calm weather conditions. This scenario study indicates that naturally ventilated greenhouses of up to size of 14400 m^2 were capable to create better climate when the greenhouse crops had $L > 0.5$. As long as the greenhouse crops have high L, values of $\Delta T_{A\text{-}O}$ will be close to or lower than zero, mostly due to transpiration cooling. This is supported by recent experience with a three span greenhouse in tropical Malaysia (Elings, 2011).

These model-based climate characteristics for bigger greenhouses need to be tested in the field.

6.5.2. The need to develop a simulation model for fruit abortion and number of fruits per truss in determinate tomato crops

The need to develop a reliable simulation model for number of fruits per truss has long been expressed (Heuvelink, 1996), however the progress on this area is still limited. In the model, quantification of fruit and flower abortion are rarely investigated explicitly (Heuvelink, 1996) although fruit/flower abortions affect the number of fruits per truss that act as one of the important determining factors in the production of fruit horticultural crops such as tomato. Immediate research in quantifying the abortion in tomato in relation with non-optimal temperature conditions based on physiological processes is needed, and when integrated in the simulation, would extend crop model applicability (Heuvelink, 1996). The work at least requires extensive analyses on sink – source feedback mechanisms (Ho & Hewitt, 1986; De Koning, 1994; Heuvelink, 1996), cultivar characteristics (Rudich, 1986; Lohar & Peat, 1998; Sato *et al.* 2001; Firon *et al.*, 2006, Van der Ploeg *et al*., 2007), and integrating also effects of air temperature and air humidity (Bertin, 1995; Peet *et al*., 2003).

Study on the characteristic of fruit abortion in later appearing trusses observed in determinate tomato is essential. Low source – sink balance appeared to be an important determinant of this character.

6.6. Practical application of greenhouses in the tropical lowland

According to experimental results and simulation studies on the characteristic of greenhouse climates and on the growth and development of tomato crops, the prototype naturally ventilated greenhouse with plastic covering is applicable as basis for the operational greenhouse crop production system for the tropical lowland conditions. The indoor greenhouse climate appeared to be suitable for growing lowland horticultural crops such as determinate tomato.

Moderating climates in the tropical lowland greenhouse could be achieved simultaneously by application of NIR reflecting plastics with a very low NIR transmission, facilitating high ventilation capacity, and by increasing crop transpiration. The effect of each factor on lowering T_{Air} varies following from the crop stages and outdoor climate dynamics. The GCM developed is able to design greenhouse crop production systems for tropical lowland areas, not only in Indonesia but also for other countries having similar outdoor climate conditions.

The greenhouse design suggested in this study gives a lot of opportunities for tropical lowland areas. Experiments showed that greenhouse production gives advantages compared to outdoor crop production in terms of productivity and product quality but also in terms of reducing pests and diseases. The resulting reduction in the consumption of plant protection chemicals contributes to human health. A comparable design is currently tested in tropical areas of Malaysia with good results (Elings, 2011). Next to that the greenhouse design suggested in this study can be considered a clear improvement of current greenhouse designs which can be found in tropical areas in Indonesia (Rodenburg, 2011).

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Summary

Tropical lowland is characterized by harsh outdoor climate and high presence of pests and diseases which often cause severe damage to open field crops. Protected cultivation using a greenhouse with transparent plastic and insect nets could minimize environmental pressures and increase crop production. There is an opportunity to adopt a greenhouse crop production system especially for horticultural crops, in peri-urban areas to secure the supply for the urban population with safe and environmentally friendly horticultural products, to save water and to avoid water pollution. However, currently the biophysical knowledge required to support the adoption of greenhouse production systems for the tropical lowland is limited. As generally advances in greenhouse production systems are made in the regions having distinct different climatic conditions as compared to the tropical lowland climate, the adoption of the greenhouse design must be evaluated thoroughly. The challenges for the introduction of greenhouses in the tropical lowlands of Indonesia are to design greenhouses that are adapted to local climates in combination with the use of cladding materials and insect nets that are capable to create a manageable microclimate inside the greenhouse that is suitable for a range of crops. Within such a sphere of thoughts then this thesis is constructed.

The objectives of the research were: (1) to study the climate in a specially developed and adapted greenhouse type for the tropical lowland in Indonesia under the influence of outdoor conditions in interaction with cover properties, ventilation rate, and crop transpiration; and (2) to analyse the effects of greenhouse climate on growth, development, and yield of tomato as model crop and to asses ways to improve tomato production in tropical lowland greenhouses. These objectives were approached by; (1) developing a simple greenhouse climate (GCM) model based on physical relationships between outdoor conditions and the greenhouse elements including the crop, (2) a detailed analysis of crop growth and production of a determinate tomato, in particular with respect to its response to tropical lowland greenhouse climate and crop management. Greenhouse climate factors investigated were mainly solar radiation and air temperature as these are expected to have significant effects on the crop. Crop management actions investigated were pruning of leaves and trusses. The growth dynamics of the crop was analysed using the INTKAM crop simulation model. In combination with the GCM, the INTKAM model was also employed to investigate ways to improve tomato production in tropical lowland greenhouses.

In this study, six prototype plastic greenhouses having similar dimensions (ground area of 9.6 m by 15 m or 144 m^2, average height of 5.72 m, covering surface of 387 m^2) were built in Purwakarta (107°30′ E, 6°30′ S, altitude 25 m), Indonesia for field experimentation. In total, extensive data sets were collected of climate and tomato crop growth from six prototype greenhouses with three different plastics (reference, and two

levels of near infrared reflecting pigments); two ratios of ventilation openings to greenhouse covering area (0.223 and 0.427); a wide range of tomato leaf area indices L (0.01–4.97 m^2 m^{-2}); and for three crop growing periods that represent year-long tropical lowland climatic conditions.

In **Chapter 2**, the simple greenhouse climate model GCM was developed. The physical basis of the model was described in terms of solar radiation distribution, ventilation, and crop transpiration. The model optimises these three main factors and calculates only three state variables: average greenhouse air temperature T_{Air}, average greenhouse air water vapour pressure (expressed as air water vapour pressure deficit D_{Air}), and average canopy temperature T_{Can}. The model was parameterised, calibrated, and validated with separate data sets from the reference greenhouse. A consistent performance of the model was observed, both in the calibration and validation stages. Measurements and calculations of T_{Air} and D_{Air} agreed satisfactorily, with less than 5% errors.

In **Chapter 3,** effects of cover properties, ventilation rate, and crop leaf area on the tropical greenhouse climate are analysed. A more comprehensive validation of the GCM according to the remaining data sets was performed. The model with a calibration factor Λ for indirect absorbed solar radiation (indicating the part of the radiation absorbed by the greenhouse cover, structural elements and soil surface released to the air) of 0.1 satisfactory 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 L. Model performance was improved slightly by including the effect of L on the Λ as an exponential term. Under validated conditions, where greenhouse air temperature proved to be closely coupled with the outdoor, measurements and calculations demonstrated that T_{Air} was affected more by variation in ventilation and L than by the applied cover properties. L had the highest impact on greenhouse air temperature, implying that a high amount of cooling is achieved by the crop itself. 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 results as described in **Chapters 2** and **3** establish confidence in use of the model for scenario studies on optimum greenhouse systems for tropical lowland in Indonesia.

In **Chapter 4**, variation in the main parameters determining greenhouse climate were evaluated using the GCM to design naturally ventilated greenhouses in the tropical lowland of Indonesia. Dimensions of the prototype greenhouse were used as basis for the design. The design optimized effects of: (i) greenhouse near infrared radiation (NIR) transmission (0.0-0.77, with reference 0.69) affecting the amount of energy input, (ii) values of L (0.02–5.0) determining transpiration, (iii) greenhouse ground area (144 m^2–14400 m^2) and sidewalls ventilation opening (0–3.75 m, with standard of 2.75 m) influencing ventilation rates, and (iv) boundary conditions (hot, humid, and moderate wind speed; hot, humid, and higher wind speed; and hot, dry, and lower wind speed). The performance of the greenhouse design was analyzed based on the difference between maximum greenhouse air temperature calculated using GCM and outdoor maximum air temperature data ($\Delta T_{A\text{-}O}$). Critical conditions ($\Delta T_{A\text{-}O} > 0$) generally occur when L is low. At low L, reduction of greenhouse air temperature T_{Air} can be achieved primarily by two methods. Firstly, by reducing greenhouse near infrared radiation (NIR) transmission to decrease radiation input to the greenhouse compartment. The effect of greenhouse near infrared radiation (NIR) transmission reduction on lowering T_{Air} was more significant for bigger greenhouse and under humid conditions. Secondly, T_{Air} could be reduced by increasing ventilation openings to remove excess heat out of the greenhouse. Higher wind speed U was attributable to increase ventilation rate and increase sensible heat flux between the greenhouse and outdoor air via the plastic greenhouse cover due to convection, thus also lowering T_{Air}. At high L, transpiration dominated the cooling of the greenhouse air. The transpiration cooling is more intensive under hot and dry boundary conditions. This study indicated that naturally ventilated model greenhouses of up to size of 14400 m^2 were capable to create $\Delta T_{A\text{-}O}$ close to or lower than zero when the greenhouse crops had L higher than 0.5.

Regarding the possible application of the GCM as a tool to design a tropical lowland greenhouse, however, some care is required. Some model parameters, such as the dimensionless calibration factor Λ might be dependent on experimental set-up thus require further investigation to validate its applicability under different conditions. Also GCM is not capable of calculating the size and geometry of the ventilation openings realising the designed ventilation. This has to be determined subsequently by, *e.g.* CFD modelling.

Chapter 5 presents experimental results and simulation of growth of a determinate tomato crop under tropical lowland greenhouse conditions in Indonesia. The results of three successive experiments, each lasting about 95 days in the prototype greenhouses with three different plastic films (standard plastic, and lower and higher near infrared radiation (NIR) reflecting pigment plastics) and variation in leaf area and number of trusses were analyzed. Crop growth dynamics and scenario studies to investigate options to improve tomato production were evaluated using the INTKAM crop growth model. In general, the climatic conditions – except radiation – are similar between greenhouses. Such condition can be attributed to the high natural ventilation capacity of the greenhouses. The experiments did not show significant differences in crop response to the differences of the applied plastic films. Cultural practice, in particular truss pruning, caused more profound difference in crop growth, however, not in truss appearance rate and fruit development. Crops with low number of trusses produced substantially lower fruit dry matter and hence fresh fruit yield than crops with a high number of trusses. Determinate tomato clearly exhibits high fruit abortion and the number of fruits per truss decreases as truss number increases. This can be partly explained by the source – sink mechanism: determinate tomato in tropical lowland greenhouse showed a low source – sink ratio of around 0.4 during the productive period. Effort to increase tomato production might require adequate crop management that is aimed at finding the appropriate source – sink balance. The scenario study revealed that greenhouse tomato production could be increased slightly by elongating the productive crop period, by using zero NIR transmittance plastic film, and most significantly by increasing fruit load.

The field experiments demonstrated the suitability of the indoor greenhouse climate for growing lowland horticultural crops such as determinate tomato. It was observed that greenhouse production gives advantages compared to outdoor crop production in terms of productivity. These showed that the prototype naturally ventilated greenhouse with plastic covering is applicable as basis for the operational greenhouse crop production system for the tropical lowland conditions, not only in Indonesia but also for other countries having similar outdoor climate conditions.

Simulation studies with the GCM showed that moderating the climate in the tropical lowland greenhouse could be achieved simultaneously by application of NIR reflecting plastics with a very low NIR transmission, facilitating high ventilation capacity, and by increasing crop transpiration. The effect of each factor on lowering T_{Air} varies following from the crop stages and outdoor climate dynamics. The GCM is able to design bigger greenhouse crop production systems for tropical lowland areas. The climate characteristics for these model-based greenhouses need to be tested in the field.

Samenvatting

Tropisch laagland wordt gekarakteriseerd door een ruw buitenklimaat en veel ziekten en plagen waardoor dikwijls ernstige schade optreedt aan gewassen in open teelten. Door beschermde teelt in kassen voorzien van insectnetten kan de omgevingsdruk worden geminimaliseerd en de gewasproductie worden verhoogd. Gewasproductiesysteem in kassen kunnen in gebieden rond grote steden de stadsbevolking voorzien van veilige en milieuvriendelijke tuinbouwproducten waarbij water wordt bespaard en watervervuiling wordt voorkomen. Echter de biofysische kennis nodig om kasproductiesystemen toe te passen in het tropisch laagland is op het ogenblik beperkt. Omdat kasproductiesystemen vooral vooruitgang geboekt hebben in gebieden die nogal verschillen in klimaatcondities met het tropisch laagland moet het kasontwerp zorgvuldig worden geëvalueerd. De uitdaging bij de introductie van kassen in het tropische laagland van Indonesië is om kassen te ontwerpen die zijn aangepast aan het lokale klimaat waarbij met gebruik van geschikte kasdekmaterialen en insectnetten een beheersbaar binnenklimaat kan worden gerealiseerd dat geschikt is voor een verscheidenheid aan gewassen. Vanuit deze gedachtegang is dit proefschrift opgezet.

Het doel van het onderzoek was: (1) bestudering van het klimaat in een speciaal ontwikkeld en aangepast kastype voor het tropische laagland van Indonesië zoals beïnvloedt door de weerscondities buiten en als functie van de kasdekeigenschappen, het ventilatievoud en de gewasverdamping en (2) analyse van het effect van het kasklimaat op groei, ontwikkeling en opbrengst van tomaat als voorbeeldgewas, en het vinden van methoden om tomaatproductie in tropische laaglandkassen te verbeteren. Deze doelen werden bereikt door: (1) de ontwikkeling van een eenvoudig kasklimaatmodel (GCM) dat is gebaseerd op de fysische relaties tussen de buitenweercondities en de kasonderdelen, inclusief gewas, (2) een grondige analyse van de groei en productie van een determinate tomatengewas, vooral in relatie tot het klimaat in de tropische laaglandkas en het gewasmanagement. Vooral de kasklimaatfactoren zonnestraling en luchttemperatuur werden in het onderzoek betrokken omdat verwacht werd dat deze een significant effect op het gewas hebben. Voor wat betreft gewasmanagement werd snoeien van blad en trossen onderzocht. Het verloop van de gewasgroei in de tijd werd geanalyseerd met het INTKAM gewasgroeimodel. De combinatie van INTKAM en GCM werd ook gebruikt om te onderzoeken hoe de tomaatproductie in de tropische laaglandkas kan worden verbeterd.

Ten behoeve van de veldexperimenten in dit onderzoek werden zes prototype kassen met dezelfde afmetingen (grond oppervlakte 9.6 m bij 15 m dus 144 m^2, gemiddelde hoogte 5.72 m, buitenoppervlak 387 m^2) gebouwd in Purwakarta (107^{o}30′ E, 6^{o}30′ S, op hoogte 25 m), Indonesië. De zes prototype kassen waren voorzien van kasdekken met drie verschillende eigenschappen (referentie en twee niveaus van nabij

infrarood reflecterende pigmenten) waarbij twee verhoudingen tussen de oppervlaktes van de ventilatieopening en de kasvloer werden toegepast (0.233 en 0.427). In totaal werden uitgebreide datasets verzameld waarbij een breed gebied van de leaf area index L werd gerealiseerd (0.01–4.97 m^2 m^{-2}). De experimenten werden uitgevoerd gedurende drie teeltperiodes die samen de tropische laaglandklimaatcondities gedurende een jaar representeren.

In **Hoofdstuk 2** wordt het eenvoudige kasklimaatmodel ontwikkeld. De fysische grondslag van het model wordt beschreven in termen van verdeling van de zonnestraling, ventilatie en gewasverdamping. Het model optimaliseert deze drie voornaamste factoren en berekent slechts drie toestandsgrootheden: gemiddelde kasluchttemperatuur T_{Air}, gemiddelde waterdampspanning (uitgedrukt als dampspanningsdeficit D_{Air}) en gemiddelde gewastemperatuur T_{Can}. Het model werd geparametriseerd, gekalibreerd en gevalideerd met verschillende datasets uit de referentiekas. Er werd een consistent modelgedrag waargenomen zowel voor de kalibratie als de validatie. Metingen en berekeningen van T_{Air} en D_{Air} kwamen goed overeen met een fout binnen de 5%.

In **Hoofdstuk 3** worden de effecten van kasdekeigenschappen, ventilatievoud en leaf area index L op het tropische kasklimaat geanalyseerd. Er werd een uitgebreidere validatie van de GCM uitgevoerd met behulp van de nog niet gebruikte datasets. Met een kalibratiefactor Λ (het deel van de zonnestraling dat via de onderschepping aan de niet transparante delen van de kas wordt omgezet in een voelbare warmtestroom naar de kaslucht) gelijk aan 0.1 werd T_{Air} berekend met een fout binnen 2 % en D_{Air} met een fout binnen 10%. De fouten werden groter voor kleinere L. Het modelgedrag verbeterde iets als het effect van L op Λ als een exponentiele functie werd weergegeven. Binnen het validatiegebied waar de kasluchttemperatuur nauw gekoppeld bleek te zijn aan de buitentemperatuur, lieten de metingen en berekeningen zien dat T_{Air} meer werd beïnvloedt door variaties in de ventilatie en in L dan door de kasdekeigenschappen. L had de sterkste invloed op T_{Air} wat er op duidt dat gewasverdamping een grote bijdrage aan de koeling levert. De variatie in kasdekeigenschappen van de proefkassen was te klein om effecten hiervan waar te nemen. Er blijkt dat in een goed kasontwerp voor tropische laaglandcondities een hoog ventilatievoud nodig is. De resultaten van de hoofdstukken 2 en 3 geven vertrouwen in het gebruik van het model in scenariostudies naar een optimaal kassysteem voor de tropische laaglandcondities in Indonesië.

Om natuurlijk geventileerde kassen te ontwerpen voor het tropische laagland van Indonesië wordt in **Hoofdstuk 4** met behulp van GCM de variatie geëvalueerd van de belangrijkste parameters die het kasklimaat bepalen.De maten van het prototype kas waren daarbij uitgangspunt voor het ontwerp. Het ontwerp optimaliseerde de effecten van: (i) transmissie voor nabij infrarood (NIR) van het kasdekmateriaal (0.0-0.77, met referentie 0.69) die de energie-input beïnvloedt, waarden van L (0.02-5.0) die de verdamping beïnvloedt, (iii) kasoppervlak (144-1440 m^2), ventilatieoppervlak in de gevels (0-3.75 m^2 met 2.75 m^2 als referentie) die het ventilatievoud beïnvloedt en (iv) de randcondities (heet, vochtig bij gematigde windsnelheid; heet, vochtig bij hogere windsnelheid en heet, droog bij lage windsnelheid). Het kasontwerp werd beoordeeld op basis van de verschillen tussen de maximale kasluchttemperatuur zoals berekend met GCM en maximaal optredende buitentemperatuur($\Delta T_{A\text{-}O}$). Kritische condities ($\Delta T_{A\text{-}O}$ > 0) treden op bij lage L. Dan kan de kasluchttemperatuur op twee manieren worden verlaagd: ten eerste door de NIR transmissie te verlagen zodat de stralingsinput wordt verlaagd. Dit effect was sterker in grote kassen en vochtige condities. Ten tweede door de ventilatieopeningen te vergroten voor de afvoer van overtollige warmte. Een hogere windsnelheid U draagt bij aan een hogere ventilatie en een toename van de convectieve afvoer van warmte van het kasdek naar de buitenlucht, wat ook bijdraagt aan verlaging van de T_{Air}. Bij hoge L domineert verdamping de afkoeling. Transpiratiekoeling is sterker bij hete en droge omgevingscondities. Deze studie geeft aan dat natuurlijk geventileerde kassen tot een oppervlak van 14400 m2 in staat zijn om een $\Delta T_{A\text{-}O}$ vrijwel gelijk of kleiner dan 0 te realiseren als L groter is dan 0.5.

Bij de mogelijke toepassing van GCM als ontwerpgereedschap past een kanttekening. Er zijn modelparameters, zoals de dimensieloze kalibratiefactor Λ, die afhankelijk kunnen zijn van de experimentele opzet, zodat meer onderzoek vereist is om hun geldigheid onder verschillende condities te bepalen. Ook kan met GCM niet worden berekend wat de grootte en geometrie van de ventilatieopeningen moet zijn om een ontworpen ventilatievoud te realiseren. Deze moeten afzonderlijk met b.v. CFD modellering worden bepaald.

Hoofdstuk 5 laat de experimentele resultaten en de simulatie zien van de groei van een determinate tomaatgewas bij de tropische laaglandcondities in Indonesië. De resultaten werden geanalyseerd van drie opeenvolgende experimenten, die ieder ongeveer 95 dagen duurden, in de drie prototype kassen met drie verschillende plastic films (standaard, en lagere, respectievelijk hogere reflectie voor nabij infrarood) waarbij bladoppervlak en aantal trossen varieerde. Het INTKAM gewasgroeimodel werd gebruikt voor de evaluatie van het verloop van de gewasgroei en van methoden om de tomaatproductie te verbeteren. Door de hoge ventilatiecapaciteit zijn de klimaatcondities, met uitzondering van de straling, in de kassen vergelijkbaar. De experimenten lieten geen significante verschillen zien van de gewasrespons op de verschillende plastic films. Gewasmanagement, vooral trossnoei, leidde tot grotere verschillen in gewasgroei, hoewel niet in de snelheid van trosvorming en vruchtontwikkeling. Gewas met een laag aantal trossen produceerde merkbaar een lager totaal droge stof gewicht van de vruchten en dus versgewicht dan gewassen met een hoog aantal trossen. Determinate tomaatgewassen vertonen duidelijk een hoge vrucht abortie en het aantal vruchten per tros neemt af bij toename van het aantal trossen. Dit kan deels worden verklaard vanuit het source – sink mechanisme: gedurende de productieve periode heeft het determinate tomaatgewas in de tropische laaglandkas een lage source – sink ratio van ongeveer 0.4. Gewasmanagement gericht op verhoging van de tomaatproductie moet een juiste source – sink balans zien te vinden. De scenariostudie gaf aan dat de tomaatproductie wat verhoogd kan worden door de teeltperiode te verlengen, door plastic film toe te passen die geen NIR doorlaat en, het meest significant, door verhoging van de vruchtbelading.

De veldexperimenten toonden aan het kasklimaat geschikt is voor de teelt van laaglandgewassen, zoals determinate tomaten. Teelt in kassen gaf voordelen in termen van productiviteit ten opzichte van open teelten. Het prototype natuurlijk geventileerde kas met plastic kasdek bleek toepasbaar als uitgangspunt voor een bruikbaar kasproductiesysteem voor tropische laaglandcondities, niet alleen in Indonesië maar ook in andere landen met vergelijkbare klimaatcondities.

Simulatiestudies met de GCM toonden aan dat het klimaat in tropische kassen kan worden gematigd door zowel toepassing van een NIR reflecterend kasdek met een zeer lage NIR transmissie als door een hoge ventilatiecapaciteit en door toenemende verdamping. Het effect van iedere factor op het verlagen van T_{Air} is verschillend, afhankelijk van het gewasstadium en de dynamiek van het buitenweer. Met GCM konden grotere kasproductiesystemen voor tropische laaglandgebieden worden ontworpen. Het gedrag van deze modelgebaseerde kassen moet wel worden getest.

Ringkasan

Budidaya tanaman di lahan terbuka di wilayah dataran rendah tropika sering mengalami kerusakan yang parah akibat kondisi iklim yang tidak optimal bagi tanaman serta tingkat serangan hama dan penyakit tanaman yang tinggi. Budidaya tanaman terproteksi (*protected cultivation*) di dalam rumahkaca (RK) bertudung plastik (*plastic greenhouse*) yang dilengkapi kasa anti serangga dapat meminimalkan tekanan lingkungan tersebut, menghindari kerusakan dan bahkan dapat meningkatkan produksi tanaman. Ada potensi untuk mengadopsi sistem produksi tanaman di dalam rumahkaca (PTRK) khususnya untuk tanaman hortikultura, di daerah dekat perkotaan guna mengamankan pasokan bagi penduduk perkotaan dengan produk yang sehat dan ramah lingkungan, untuk menghemat pemakaian air, dan menghindari pencemaran air. Akan tetapi, pada saat ini pengetahuan mengenai aspek biofisik yang diperlukan untuk mendukung adopsi PTRK di wilayah dataran rendah tropika masih terbatas. Pada umumnya, kemajuan terkini dalam bidang PTRK ada di wilayah yang kondisi iklimnya secara nyata berbeda dengan iklim di wilayah dataran rendah tropika, oleh karena itu adopsi desain RK harus dievaluasi secara mendalam. Tantangan untuk introduksi RK di wilayah dataran rendah tropika adalah bagaimana mendesain bangunan RK khusus yang sesuai dengan iklim lokal dikombinasi dengan pemakaian tudung (atap dan dinding) plastik dan kasa anti serangga yang mampu menciptakan iklim mikro di dalam RK dapat dikontrol dan sesuai bagi tanaman. Dalam lingkup pemikiran itulah tesis ini disusun.

Tujuan dari penelitian ini adalah: (1) untuk mempelajari iklim RK yang khusus dikembangkan dan disesuaikan untuk wilayah dataran rendah tropika di Indonesia di bawah pengaruh kondisi-kondisi lingkungan luar (khususnya iklim/cuaca) melalui interaksi dengan sifat tudung, laju ventilasi, dan transpirasi tanaman; dan (2) untuk menganalisis pengaruh iklim RK pada pertumbuhan, perkembangan, dan produksi tomat sebagai tanaman model serta untuk mengalisis berbagai cara untuk meningkatkan produksi tomat yang dibudidayakan di dalam RK dataran rendah tropika. Tujuan ini dicapai melalui; (1) pengembangan model iklim rumahkaca (*greenhouse climate model*/GCM) yang didasarkan pada hubungan fisik antara kondisi lingkungan luar (khususnya iklim/cuaca) dan elemen RK termasuk tanaman, (2) analisis rinci pertumbuhan tanaman dan produksi tomat, khususnya dalam respon tanaman terhadap iklim RK dataran rendah tropika dan pengelolaan tanaman. Faktor iklim RK yang diteliti terutama radiasi matahari dan suhu udara karena kedua unsur tersebut diharapkan memiliki efek yang signifikan pada tanaman. Tindakan pengelolaan tanaman yang diteliti adalah pemangkasan daun dan tandan buah (*truss*). Dinamika pertumbuhan tanaman dianalisis dengan menggunakan model simulasi tanaman INTKAM. Melalui kombinasi dengan GCM, model INTKAM juga

digunakan untuk mencari cara-cara untuk meningkatkan produksi tomat yang ditanam di dalam RK tropika dataran rendah.

Pada penelitian ini, enam prototipe RK dengan dimensi yang sama (luas 9.6 m x 15 m atau144 m^2, rata-rata tinggi 5.72 m, luas tudung 387 m^2) telah dibangun di Purwakarta (107°30′ BT, 6°30′ LS, 25 mdpl), Indonesia untuk percobaan lapang. Data yang terkumpul dari percobaan ini mewakili kondisi iklim dan pertumbuhan tanaman tomat yang ekstensif dari dalam RK dengan tiga tipe tudung plastik (standar N0, dan dua tipe plastik dengan tingkat transmisi radiasi infra-merah (NIR) yang berbeda); dua rasio luas bukaan ventilasi terhadap luas tudung RK (0.223 dan 0.427); berbagai tingkat indeks luas daun L (0.01–4.97); dan tiga periode tanam yang melingkup kondisi iklim dataran rendah tropika sepanjang tahun.

Pada **Bab 2**, diuraikan secara rinti mengenai pengembangan GCM. Landasan fisika dari model mencakup proses distribusi radiasi matahari, proses ventilasi, dan proses transpirasi tanaman. GCM melakukan optimasi terhadap tiga factor utama tersebut untuk menghitung tiga peubah keadaan yaitu: rataan suhu udara dalam RK T_{Air}, rataan tekanan uap-air udara dalam RK (dinyatakan sebagai defisit tekanan uap-air udara D_{Air}), dan rataan suhu kanopi tanaman T_{Can}. GCM dikembangkan dengan data dari RK standar. Parameterisasi, kalibrasi, dan validasi GCM dilakukan dengan set data yang berbeda. Kinerja GCM menunjukkan konsistensi pada tahap kalibrasi dan validasi. Pengukuran dan perhitungan model terhadap T_{Air} dan D_{Air} menghasilkan tingkat kesesuaian yang memuaskan, dengan galat kurang dari 5%.

Pada **Bab 3** dijelaskan mengenai pengaruh sifat optik tudung plastik, laju ventilasi, dan luas daun pada iklim di dalam RK dataran rendah tropika. GCM divalidasi lagi dengan data yang lebih komprehensif. GCM, dengan faktor kalibrasi $\Lambda = 0.1$ (sebagai indikasi dari bagian radiasi yang diserap oleh tudung RK, oleh elemen struktur bangunan RK, dan oleh permukaan tanah yang selanjutnya dilepas ke udara di dalam RK) menghasilkan perhitungan T_{Air} dengan galat kurang dari 2% dan D_{Air} dengan galat kurang dari 10%. Galat perhitungan lebih besar terjadi pada nilai L yang rendah. Kinerja GCM sedikit lebih baik apabila pengaruh L pada Λ diperhitungan dalam suatu persamaan eksponensial. Dengan kondisi validasi model sekarang ini, dimana suhu udara di dalam RK terpengaruhi secara besar oleh suhu udara luar, pengukuran dan perhitungan menunjukkan bahwa T_{Air} lebih dipengaruhi oleh variasi laju ventilasi dan tingkat L daripada oleh sifat optik tudung plastik. Indeks luas daun mempunyai pengaruh paling besar pada suhu udara di dalam RK, yang mengimplikasikan bahwa sejumlah besar pendinginan dicapai oleh tanaman itu sendiri. Sedangkan variasi sifat optik tudung plastik yang saat ini dicobakan, tidak menghasilkan pengaruh yang nyata terhadap suhu udara di dalam RK. Hal ini berarti bahwa, desain RK untuk wilayah dataran rendah tropika memerlukan kapasitas ventilasi yang tinggi. Hasil analisis sebagaimana disajikan pada **Bab 2** dan **Bab 3** memberikan keyakinan untuk memanfaatkan GCM bagi studi skenario dalam merancang sistem RK yang optimum untuk wilayah dataran rendah tropika di Indonesia.

Pada **Bab 4**, berbagai variasi dari parameter utama yang menentukan iklim RK dievaluasi dengan GCM untuk merancang RK berventilasi alami di wilayah dataran rendah tropika di Indonesia. Dimensi dari protopipe RK telah digunakan sebagai dasar bagi perancangan. Desain mengoptimasi pengaruh-pengaruh: (i) tingkat transmisi radiasi infra-merah dari tudung plastik (0–0.77, dengan nilai standar 0.69) yang mempengaruhi input radiasi matahari, (ii) nilai L (0.02–5.0) yang menentukan transpirasi, (iii) luas bangunan RK (144 m^2–14400 m^2) dan luas bukaan ventilasi pada dinding RK (0–3.75 m, dengan standar 2.75 m) yang mempengaruhi laju ventilasi, dan (iv) kondisi iklim sekitar (panas, lembab, kecepatan angin moderat; panas, lembab, kecepatan angin tinggi; panas, kering, kecepatan angin rendah). Kinerja model RK dianalisa dari perbedaan antara maksimum suhu udara yang dihitung dengan GCM dengan maksimum suhu udara data ($\Delta T_{A\text{-}O}$). Kondisi kritis ($\Delta T_{A\text{-}O} > 0$) umumnya terjadi pada L rendah. Pada L rendah, penurunan T_{Air} dapat dicapai terutama melalui dua cara. Pertama, dengan mengurangi nilai transmisi NIR untuk menurunkan input radiasi ke dalam RK. Pengaruh penurunan nilai transmisi NIR dalam menurunkan nilai T_{Air} akan lebih nyata pada ukuran RK yang lebih besar dan kondisi udara lembab. Kedua, dengan memperbesar ukuran bukaan ventilasi untuk memindahkan kelebihan panas keluar dari ruangan RK. Kecepatan angin yang lebih tinggi meningkatkan laju ventilasi dan juga laju fluks panas terasa antara udara di dalam RK dengan udara di luar RK melalui tudung plastik akibat proses konveksi, yang juga menurunkan T_{Air}. Pada L yang tinggi, proses transpirasi mendominasi pendinginan udara di dalam RK. Pendinginan oleh proses transpirasi lebih intensif terjadi di bawah kondisi lingkungan yang panas dan kering. Studi ini mengindikasikan bahwa model RK berventilasi alami dengan ukuran sampai 14400 m^2 dapat mencapai keadaan $\Delta T_{A\text{-}O}$ mendekati atau lebih kecil dari nol jika L lebih besar dari 0.5.

Meskipun GCM dapat dipakai sebagai alat pendesain RK di wilayah dataran rendah tropika, akan tetapi penggunaannya harus disertai kehati-hatian. Beberapa parameter model dalam GCM, seperti faktor kalibrasi Λ mungkin nilainya tergantung pada *set-up* kondisi percobaan, dan nilainya dapat berbeda pada kondisi lapang yang berbeda. GCM juga tidak digunakan untuk mendesain ukuran dan geometri dari bukaan ventilasi yang merealisaikan desain ventilasi. Hal ini harus ditentukan lebih lanjut melalui, misalnya, model *Computational Fluid Dynamics* (CFD).

Bab 5 menyajikan hasil-hasil percobaan dan simulasi pertumbuhan tanaman tomat tipe determinat yang dibudidayakan di dalam prototipe RK di dataran rendah tropika. Hasil percobaan lapang dari tiga periode tanaman, masing-masing berlangsung sekitar 95 hari, dengan tanaman tomat determinat yang dibudidayakan di dalam RK dengan tiga tipe tudung dari plastik dengan nilai transmisi NIR yang berbeda, dan variasi tingkat L dan jumlah tandan buah telah dianalisa. Dinamika pertumbuhan tanaman dan berbagai cara untuk meningkatkan produkdi tomat di dalam RK dataran rendah tropika dianalisa dengan menggunakan model simulasi tanaman INTKAM. Secara umum – kecuali radiasi matahari – kondisi iklim antar RK relatif sama. Kondisi semacam ini dapat terjadi karena desain RK dengan kapasitas ventilasi alami yang besar. Percobaan tidak menunujukkan adanya pengaruh nyata dari tipe plastik terhadap tanaman. Metode budidaya, terutama pemangkasan memberikan pengaruh yang nyata pada perumbuhan, tapi tidak nyata pada perkembangan tanaman. Tanaman dengan jumlah tandan buah yang lebih rendah secara nyata memiliki hasil buah yang lebih rendah. Tomat determinat secara jelas menunjukkan tingkat aborsi buah yang tinggi dan karakteristik jumlah buah per tandan buah yang semakin menurun dengan meningkatknya jumlah tandan buah. Hal ini sebagian dapat dijelaskan oleh mekanisme sumber (*source*) – rosot (*sink*). Tomat determinat di dalam RK dataran rendah tropika mempunyai kekuatan rasio sumber – rosot yang rendah, yaitu sekitar 0.4, selama periode produktifnya. Upaya untuk meningkatkan produksi tomat memerlukan pengelolaan budidaya tanaman yang ditujukan untuk menemukan kesetimbangan sumber – rosot yang sesuai. Studi skenario menunjukkan bahwa produksi tomat dapat ditingkatkan sedikit dengan memperpanjang periode produktif dan dengan pemakaian plastik yang memiliki transmisi NIR rendah. Sedangkan peningkatan produksi secara nyata dapat dicapai melalui peningkatan jumlah buah.

Percobaan lapang menunjukkan adanya kesesuaian iklim dalam rumah kaca untuk budidaya tanaman hortikultura dataran rendah seperti tomat. Telah diamati bahwa produktivitas tanaman dalam rumah kaca lebih baik dibandingkan dengan tanaman di lahan terbuka. Ini menunjukkan bahwa prototipe rumah kaca dengan tudung plastik berventilasi alami dapat dipakai sebagai dasar operasionalisasi sistem produksi tanaman dalam rumahkaca untuk kondisi dataran rendah tropika, bukan hanya di Indonesia tetapi juga untuk negara-negara lain yang memiliki kondisi iklim serupa.

Studi simulasi dengan GCM menunjukkan bahwa iklim yang moderat dalam rumahkaca di dataran rendah tropika dapat dicapai secara simultan (1) melalui aplikasi plastik yang memantulkan NIR dan mempunyai transmisi NIR sangat rendah, (2) memfasilitasi kapasitas ventilasi tinggi, dan (3) dengan meningkatkan transpirasi tanaman. Efek dari setiap faktor pada penurunan T_{Air} bervariasi tergantung pada kondisi tanaman dan dinamika iklim luar ruangan. GCM mampu merancang sistem produksi tanaman dalam rumahkaca yang lebih besar untuk daerah dataran rendah tropika. Karakteristik iklim untuk rumah kaca berbasis model tersebut perlu diuji di lapangan.

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Back in 2002, I met Dr. Silke Hemming, Prof. Dr. Leo Marcelis, and Ing. Dries Waaijenberg in Bogor, Indonesia. They offered me to do a research on protected cultivation in tropical lowland of Indonesia (Procult Project). I was so excited. The timing was right because I was ready to do a research after I have just finished my final courses for my PhD study in Agroclimatology at Bogor Agricultural University (IPB). The topics closely related to my work as lecturer in agrometeorology/agricultural physics. Dr. Hemming constantly provided guidance during field experiments and thesis writing. I benefitted a lot from our discussions particularly on optical properties of the plastics used in the research and how these aspects are essential for tropical lowland greenhouse climate. Often she reminded me to take a coffee break. It is good to get occupied with the thesis writing, but it is better to refresh the mind regularly to keep the spirit high. Take a coffee break!

Dr. Anne Elings came to my rescue at the most critical time of my study. The work on the tomato crop manuscript required the use of crop simulation model to better explain the dynamics of the crop growth. It must have consumed a lot of his valuable time when he sat next to me, running the crop model, many times a whole afternoons. Every time I encountered a problem with the crop model, I would come to his office for help. Bugs got fixed fast. Your critical comments and corrections greatly improve the manuscript. I will always remember you saying: ”Impron, you must move on…”

I read PhD theses of Dr. H.F. De Zwart and Dr. C. Stanghellini; these inspired me in the development of the GCM. Regarding the tomato crop, I found many ideas from the PhD thesis of Dr. E. Heuvelink were useful for the crop manuscript in this thesis. Dr. J. A. Dieleman has made some critical suggestions in the crop manuscript.

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During my first stay to Wageningen, Dick Uenk and I one or twice went to visit tomato crops in some greenhouses. With Dries Waaijenberg, I went to see some big greenhouses. These trips showed me some of highly industrialised and advanced greenhouse crop production systems in The Netherlands. Very impressive and inspiring.

During three periods of my stay in Wageningen, the office of Wageningen UR Greenhouse Horticulture has moved several times. Wherever the place, the atmosphere is scientific, the support is encouraging, the service is excellent, and most importantly the people is friendly.

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Impron

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Curriculum Vitae

Impron was born on 15 March 1963 in Pekalongan, Central Java, Indonesia. In 1983 he was invited to study at Bogor Agricultural University (IPB), Bogor, Indonesia and graduated with diploma in Agrometeorology in 1987. During 1988 – 1989 he took Associate Diploma in Scientific Instrumentation at Bendigo College of Advanced Education Bendigo, Victoria, Australia. In 1990 he continued his master by research at Graduate School of Agriculture and Forestry, University of Melbourne, Australia. He obtained his M.Agr.Sc. degree from the University of Melbourne in 1994.

Between 1994 and 1997, he worked as a lecturer and Vice Dean for Student Affair at the Faculty of Agriculture, Mercu Buana University, Jakarta, Indonesia. Since 1995 he worked as a lecture at the Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB. He was appointed as Secretary of the Department from August 1997 to June 2000. Between October 2000 and December 2002 he was the Deputy Head of BIOTROP – Impact Center for Southeast Asia in Bogor, Indonesia.

In 2000 he started his doctoral study and enrolled to Agroclimatology Study Programme at Graduate School, IPB. In 2003, after finishing theoretical courses in Agroclimatolgy, he continued the PhD programme at Wageningen University and Research Centre, The Netherlands. From 14 January to 21 May 2003, he was at IMAG, Wageningen UR to prepare field experimentation. This research was conducted under the auspices of the Graduate School of Agricultural and Environmental Sciences. The field experiment itself was conducted in Purwakarta, Indonesia from June 2003 to November 2004. Since 2005 he worked on thesis writing, in Bogor and Wageningen. During his stay in Wageningen (10 October 2005 – 8 July 2006 and 14 January – 11 April 2009) he joined Wageningen UR Greenhouse Horticulture.

His present duties are teaching several courses and supervising researches for undergraduate and postgraduate students. His research interests are on agrometeorology, modeling of greenhouse climate and quantification of the relationship between climatic factors and crop growth in open-field and greenhouse crops. He is also actively involved in researches related to climate change adaptations.

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