MODELLING THE GREENHOUSE ENVIRONMENT

AND THE

GROWTH OF CUCUMBERS

(*Cucumis sativus* L.)

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ABSTRACT

Mathematical models which describe the greenhouse environment, and the growth of a crop of cucumbers, in that environment, have been developed and tested. The models have been used to predict: the response of the greenhouse to varying weather conditions, the growth of the crop leaf canopy, and the weight and number of fruit harvested.

The greenhouse environment has been modelled using a system of non-linear differential equations, derived from a consideration of the energy and mass balances of the glazing, internal structure, crop canopy, root media, floor, deep soil layers, and the greenhouse air space. The equations have been solved for five minute time steps, using measured values of outside weather conditions and control inputs as boundary values.

Entry of solar radiation into the greenhouse, and absorption by various surfaces, has been determined using transmission tables generated using a "ray-tracing" light transmission model. The light transmission model has been calibrated in a separate experiment. The incoming solar radiation has been partitioned between diffuse, direct, photosynthetically active and near infra-red radiation, for use in the crop model.

Validation experiments have been performed to test the greenhouse environment simulation model. The results of the validation exercise showed that the model was capable of predicting the temperatures in the greenhouse, within a few degrees. The mean errors were smaller for the crop canopy, root medium, and floor, than for the glazing or air temperature. Prediction errors for relative humidity and carbon dioxide concentration were more variable.

An existing model of cucumber development rate, and leaf expansion, has been modified and validated. This gave good results when adequate account was taken of leaf senescense, and initiation of lateral growths.

Sub-models for photosynthesis, respiration, and assimilate partitioning have been developed, and combined with the greenhouse environment and leaf expansion models. The combined model has been used to predict the course of growth of a cucumber crop over one growing season, and the number and weight of fruit harvested. The predictions have been compared to results from a test crop. This revealed that while the total number of fruit harvested was accurately predicted, the total weight of harvested fruit was not.

The models are intended to be used in the study of optimal control of the greenhouse environment.

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And finally I would like to express my gratitude to David, Denise, Daniel, Jeremy, Joshua, and James, for their love and support in times of desperation!

This thesis is dedicated to Karen, Amy-Lee, and Adam, who will at last have their husband and father to themselves again!

The Grand Academy of Lagado

The first man I saw was of meagre aspect, with sooty hands and face, his hair and beard long, ragged and singed in several places. His clothes, shirt and skin were all of the same colour. He had been eight years upon a project for extracting sunbeams out of cucumbers, which were to be put into vials hermetically sealed, and let out to warm the air in raw inclement summers. He told me he did not doubt that in eight years more he should be able to supply the Governor's gardens with sunshine at a reasonable rate.

..... from Guilliver's Travels
by Jonathon Swift

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SYMBOL IN TEXT	SYMBOL IN MODEL	DESCRIPTION	UNITS
A	ARM(I) or ARL(I)	area of a leaf	cm^2
A_{bot}	Abot	open area of bottom ventilators and doors	m^2
A_c	Ac	surface area of the crop canopy (one side only)	m^2
A_f	Af	area of the greenhouse floor	m^2
A_g	Ag	surface area of the greenhouse glazing	m^2
A_h	Ah	surface area of the greenhouse heating system	m^2
A_m	Am	exposed surface area of the root medium bags	m^2
A_s	As	surface area of the greenhouse structure	m^2
A_{top}	Atop	open area of top ventilator windows	m^2
$Age(i)$	AgeFruM(I) or AgeFruL(I)	age of the i-th fruit	day
Assim	Assim	assimilation rate of the crop	$mgCO_2.plant^{-1}.s^{-1}$
α	A	slope of the leaf pattern curve during the primordial phase of leaf development	$cm.cm^{-1}.day^{-1}$
α_d	Ad	delay value of parameter α	$cm.cm_{-1}.day_{-1}$
α_s	As	stationary (normal) value of parameter α	$cm.cm^{-1}.day^{-1}$
B_c	Bc	solar radiation absorbed by the crop per unit floor area	$W.m^{-2}$
$\overline{B}_c$	Bcave	average daily solar radiation intensity at the top of the crop	$W.m^{-2}$
B_f	Bf	solar radiation absorbed by the floor per unit floor area	$W.m^{-2}$
B_g	Bg	solar radiation absorbed by the glazing per unit floor area	$W.m^{-2}$
B_m	Bm	solar radiation absorbed by the root medium per unit floor area	$W.m^{-2}$
$\overline{B}_p$	Bpar	average daily photosynthetically active radiation at top of crop	$MJ.m^{-2}$
B_s	Bs	solar radiation absorbed by the greenhouse structure per unit floor area	$W.m^{-2}$
b	B	slope of the leaf pattern curve during the expanding phase of leaf development	$cm.cm^{-1}.day^{-1}$
b_d	Bd	delay value of parameter b	$cm.cm^{-1}.day^{-1}$

b_s	Bs	stationary (normal) value of parameter b	$cm.cm^{-1}.day^{-1}$
Cloud	Cloud	cloud cover fraction	-
C_{ao}	Cao	rate of sensible heat loss from greenhouse due to ventilation	$W.m^2$
C_{ca}	Cca	rate of convection from the crop to the inside air per unit floor area	$W.m^{-2}$
C_{fa}	Cfa	rate of convection from the floor to the inside air per unit floor area	$W.m^{-2}$
C_{ga}	Cga	rate of convection from the glazing to the inside air per unit floor area	$W.m^{-2}$
C_{go}	Cgo	rate of convection from the glazing to the outside air per unit floor area	$W.m^{-2}$
C_{ha}	Cha	rate of convection from the heating system to the inside air per unit floor area	$W.m^{-2}$
C_{ma}	Cma	rate of convection from the root medium to the inside air per unit floor area	$W.m^{-2}$
C_{pa}	Cpa	specific heat capacity of inside dry air	$J.g^{-1}.^{\circ}C^{-1}$
C_{pc}		specific heat capacity of the crop	$J.g^{-1}.^{\circ}C^{-1}$
C_{pcl}	Cpcl	specific heat capacity of clay minerals	$J.g^{-1}.^{\circ}C^{-1}$
C_{pf}		specific heat capacity of the dry fraction of the floor layer	$J.g^{-1}.^{\circ}C^{-1}$
C_{pgb}	Cpgb	specific heat capacity of the glazing bars	$J.g^{-1}.^{\circ}C^{-1}$
C_{pgl}	Cpgl	specific heat capacity of the greenhouse glazing material	$J.g^{-1}.^{\circ}C^{-1}$
C_{pm}		specific heat capacity of the dry fraction of the root medium	$J.g^{-1}.^{\circ}C^{-1}$
C_{po}	Cpa	specific heat capacity of outside dry air	$J.g^{-1}.^{\circ}C^{-1}$
C_{pom}	Cpom	specific heat capacity of organic matter	$J.g^{-1}.^{\circ}C^{-1}$
C_{ps}	Cps	specific heat capacity of the greenhouse structure	$J.g^{-1}.^{\circ}C^{-1}$
C_{pq}	Cpq	specific heat capacity of quartz minerals	$J.g^{-1}.^{\circ}C^{-1}$
C_{pv}	Cpv	specific heat capacity of water vapour	$J.g^{-1}.^{\circ}C^{-1}$
C_{pw}	Cpw	specific heat capacity of liquid water	$J.g^{-1}.^{\circ}C^{-1}$
C_{pl}	Cpl	specific heat capacity of the dry fraction of the 1st soil layer	$J.g^{-1}.^{\circ}C^{-1}$

C_{p2}	Cp2	specific heat capacity of the dry fraction of the 2nd soil layer	$J.g^{-1}.^{\circ}C^{-1}$
C_{p3}	Cp3	specific heat capacity of the dry fraction of the 3rd soil layer	$J.g^{-1}.^{\circ}C^{-1}$
C_{p4}	Cp4	specific heat capacity of the dry fraction of the 4th soil layer	$J.g^{-1}.^{\circ}C^{-1}$
C_{p5}	Cp5	specific heat capacity of the dry fraction of the 5th soil layer	$J.g^{-1}.^{\circ}C^{-1}$
C_{sa}	Csa	rate of convection from the greenhouse structure to the inside air per unit floor area	$W.m^{-2}$
CO_{2a}	CO2a	carbon dioxide concentration of the inside air	$\mu l.l^{-1}$
CO_{2o}	CO2o	carbon dioxide concentration of the outside air	$\mu l.l^{-1}$
c	C	logarithm of the relative length of the unfolding leaf	-
c_d	Cd	delay value of parameter c	-
c_s	Cs	stationary (normal) value of parameter c	-
D_m	BagD	diameter of the root medium bags	m
DM_c	DMc	total dry matter of the crop	gDM
d	D	characteristic dimension	m
E_{ao}	Eao	latent heat loss from the inside air due to ventilation per unit floor area	$W.m^{-2}$
E_{drain}	Edrn	advective energy loss from the root medium due to drainage per unit floor area	$W.m^{-2}$
E_{drip}	Edrip	advective energy loss from the glazing due to dripping per unit floor area	$W.m^{-2}$
E_{irr}	Eirr	advective energy addition to the root medium due to irrigation per unit floor area	$W.m^{-2}$
E_{up}	Eup	advective energy exchange between the root medium and the crop due to water uptake per unit floor area	$W.m^{-2}$
EOT	EOT	equation of time	minute
e_a	ea	vapour pressure of inside air	Pa
e_a'	esat	saturated vapour pressure of inside air	Pa
e_o	eo	vapour pressure of outside air	Pa
F	FDC	fraction of dividing cells in a leaf	-
F_{cc}	Fcc	self view factor of the crop	-

F_{cf}	Fcf	view factor of the crop to the floor	-
F_{cg}	Fcg	view factor of the crop to the glazing	-
F_{ch}	Fch	view factor of the crop to the heating system	-
F_{cm}	Fcm	view factor of the crop to the root medium	-
F_{cs}	Fcs	view factor of the crop to the structure	-
F_{fc}	Ffc	view factor of the floor to the crop	-
F_{fg}	Ffg	view factor of the floor to the glazing	-
F_{fh}	Ffh	view factor of the floor to the heating system	-
F_{fm}	Ffm	view factor of the floor to the root medium	-
F_{fs}	Ffs	view factor of the floor to the structure	-
F_{gsky}	Fgsky	view factor of the glazing to the sky	-
F_{hc}	Fhc	view factor of the heating system to the crop	-
F_{hf}	Fhf	view factor of the heating system to the floor	-
F_{hg}	Fhg	view factor of the heating system to the glazing	-
F_{hh}	Fhh	self view factor of the heating system	-
F_{hm}	Fhm	view factor of the heating system to the root medium	-
F_{hs}	Fhs	view factor of the heating system to the structure	-
F_{mc}	Fmc	view factor root medium to crop	-
F_{mf}	Fmf	view factor root medium to floor	-
F_{mg}	Fmg	view factor root medium to glazing	-
F_{mh}	Fmh	view factor root medium to heating system	-
F_{mm}	Fmm	self view factor of the root medium	-
F_{ms}	Fms	view factor root medium to structure	-
F_{sc}	Fsc	view factor of the structure to the crop	-
F_{sf}	Fsf	view factor of the structure to the floor	-
F_{sg}	Fsg	view factor of the structure to the glazing	-

F_{sh}	Fsh	view factor of the structure to the heating system	-
F_{sm}	Fsm	view factor of the structure to the root medium	-
F_{ss}	Fss	self view factor of the structure	-
F_{sun}	FracSun	fraction sunlit leaf area	-
FAI	FAI	exposed floor area index	-
$\mathcal{F}_{cg}$	SFcg	combined emissivity view factor from the crop to the glazing	-
$\mathcal{F}_{ch}$	SFch	combined emissivity view factor from the crop to the heating system	-
$\mathcal{F}_{cs}$	SFcs	combined emissivity view factor from the crop to the structure	-
$\mathcal{F}_{fc}$	SFfc	combined emissivity view factor from the floor to the crop	-
$\mathcal{F}_{fg}$	SFfg	combined emissivity view factor from the floor to the glazing	-
$\mathcal{F}_{fh}$	SFfh	combined emissivity view factor from the floor to the heating system	-
$\mathcal{F}_{fm}$	SFfm	combined emissivity view factor from the floor to the root medium	-
$\mathcal{F}_{fs}$	SFfs	combined emissivity view factor from the floor to the structure	-
$\mathcal{F}_{gsky}$	SFgsky	combined emissivity view factor from the glazing to the sky	-
$\mathcal{F}_{hg}$	SFhg	combined emissivity view factor from the heating system to the glazing	-
$\mathcal{F}_{hs}$	SFhg	combined emissivity view factor from the heating system to the structure	-
$\mathcal{F}_{mc}$	SFmc	combined emissivity view factor from the root medium to the crop	-
$\mathcal{F}_{mg}$	SFmg	combined emissivity view factor from the root medium to the glazing	-
$\mathcal{F}_{mh}$	SFmh	combined emissivity view factor from the root medium to the heating system	-
$\mathcal{F}_{ms}$	SFms	combined emissivity view factor from the root medium to the structure	-
$\mathcal{F}_{sg}$	SFsg	combined emissivity view factor from the structure to the glazing	-
f_{ao}	fao	rate of water vapour exchange between the inside and outside air per unit floor area	$g.m^{-2}.s^{-1}$

f_{ca}	fca	rate of water vapour exchange between the crop and the inside air per unit floor area	$g.m^{-2}.s^{-1}$
f_{drain}	fdrn	rate of water loss from the root medium by drainage per unit floor area	$g.m^{-2}.s^{-1}$
f_{drip}	fdrip	rate of water loss from the underside of the glazing by dripping per unit floor area	$g.m^{-2}.s^{-1}$
f_{fruit}	ffruit	rate of water loss from the crop by removal of fruit	$g.m^{-2}.s^{-1}$
f_{ga}	fga	rate of water vapour exchange between the glazing and the inside air per unit floor area	$g.m^{-2}.s^{-1}$
f_{irr}	firr	rate of water addition to the root medium by irrigation per unit floor area	$g.m^{-2}.s^{-1}$
f_{ma}	fma	rate of water vapour exchange between the root medium and the inside air per unit floor area	$g.m^{-2}.s^{-1}$
f_{up}	fup	rate of water uptake by the crop from the root medium per unit floor area	$g.m^{-2}.s^{-1}$
f_{gross}	FGross	rate of carbon dioxide removal from inside air by photosynthesis per unit floor area	$mgCO_2.m^{-2}.s^{-1}$
f_{growth}	FGrowth	rate of carbon dioxide addition to inside air by growth respiration per unit floor area	$mgCO_2.m^{-2}.s^{-1}$
f_{resp}	FResp	rate of carbon dioxide addition to inside air by maintenance respiration per unit floor area	$mgCO_2.m^{-2}.s^{-1}$
f_{vent}	Fvent	rate of carbon dioxide removal from inside air by ventilation per unit floor area	$mgCO_2.m^{-2}.s^{-1}$
$Field$	Field	field capacity of the root medium	$m^3H_2O.m^{-3}$
Gr	Gr	Grashof number	-
G_{fl}	Gfl	rate of conduction between the floor and the first soil layer per unit floor area	$W.m^{-2}$
G_{fm}	Gfm	rate of conduction between the floor and the root medium per unit floor area	$W.m^{-2}$
G_{12}	G12	rate of conduction between the 1st and 2nd soil layers per unit floor area	$W.m^{-2}$
G_{23}	G23	rate of conduction between the 2nd and 3rd soil layers per unit floor area	$W.m^{-2}$
G_{34}	G34	rate of conduction between the 3rd and 4th soil layers per unit floor area	$W.m^{-2}$

G_{45}	G45	rate of conduction between the 4th and 5th soil layer per unit floor area	$W.m^{-2}$
G_{5d}	G5d	rate of conduction between the 5th soil layer and the deep ground per unit floor area	$W.m^{-2}$
G_{sg}	Gsg	rate of conduction between the greenhouse structure and the glazing per unit floor area	$W.m^{-2}$
GAI	GAI	glazing area index	-
g	g	gravitational constant	$m.s^{-2}$
HAI	HAI	surface area of the heating system relative to the floor area	-
$\hat{H}_a$	Ha	enthalpy of the inside air per unit floor area	$J.m^{-2}$
$\hat{H}_c$	Hc	enthalpy of the crop canopy per unit floor area	$J.m^{-2}$
$\hat{H}_f$	Hf	enthalpy of the greenhouse floor layer per unit floor area	$J.m^{-2}$
$\hat{H}_g$	Hg	enthalpy of the greenhouse glazing per unit floor area	$J.m^{-2}$
$\hat{H}_m$	Hm	enthalpy of the root medium bags per unit floor area	$J.m^{-2}$
$\hat{H}_s$	Hs	enthalpy of the greenhouse structure per unit floor area	$J.m^{-2}$
$\hat{H}_1$	H1	enthalpy of the 1st soil layer per unit floor area	$J.m^{-2}$
$\hat{H}_2$	H2	enthalpy of the 2nd soil layer per unit floor area	$J.m^{-2}$
$\hat{H}_3$	H3	enthalpy of the 3rd soil layer per unit floor area	$J.m^{-2}$
$\hat{H}_4$	H4	enthalpy of the 4th soil layer per unit floor area	$J.m^{-2}$
$\hat{H}_5$	H5	enthalpy of the 5th soil layer per unit floor area	$J.m^{-2}$
h_{ao}	hao	advective heat transfer coefficient for ventilation heat loss	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cca}	hCca	convective heat transfer coefficient of the crop	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cfa}	hCfa	convective heat transfer coefficient of the floor	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cga}	hCga	convective heat transfer coefficient of the inside of the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cgo}	hCgo	convective heat transfer coefficient of the outside of the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cha}	hCha	convective heat transfer coefficient of the heating system	$W.m^{-2}.^{\circ}C^{-1}$

h_{Cma}	hCma	convective heat transfer coefficient of the root medium	$W.m^{-2}.^{\circ}C^{-1}$
h_{Csa}	hCsa	convective heat transfer coefficient of the greenhouse structure	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cfm}	hGfm	conductance between the floor and the root medium	$W.m^{-2}.^{\circ}C^{-1}$
h_{Cf1}	hGf1	conductance between the floor and the 1st soil layer	$W.m^{-2}.^{\circ}C^{-1}$
h_{C12}	hG12	conductance between the 1st and 2nd soil layers	$W.m^{-2}.^{\circ}C^{-1}$
h_{C23}	hG23	conductance between the 2nd and 3rd soil layers	$W.m^{-2}.^{\circ}C^{-1}$
h_{C34}	hG34	conductance between the 3rd and 4th soil layers	$W.m^{-2}.^{\circ}C^{-1}$
h_{C45}	hG45	conductance between the 4th and 5th soil layers	$W.m^{-2}.^{\circ}C^{-1}$
h_{C5d}	hG5d	conductance between the 5th soil layer and the deep ground	$W.m^{-2}.^{\circ}C^{-1}$
h_{Csg}	hGsg	conductance between the greenhouse structure and the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rcg}	hRcg	radiative heat transfer coefficient from the crop to the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rch}	hRch	radiative heat transfer coefficient from the crop to the heating system	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rcs}	hRcs	radiative heat transfer coefficient from the crop to the structure	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rfc}	hRfc	radiative heat transfer coefficient from the floor to the crop	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rfg}	hRfg	radiative heat transfer coefficient from the floor to the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rfh}	hRfh	radiative heat transfer coefficient from the floor to the heating system	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rfm}	hRfm	radiative heat transfer coefficient from the floor to the root medium	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rfs}	hRfs	radiative heat transfer coefficient from the floor to the structure	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rgsky}	hRgsky	radiative heat transfer coefficient from the glazing to the sky	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rhg}	hRhg	radiative heat transfer coefficient from the heating system to the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rhs}	hRhg	radiative heat transfer coefficient from the heating system to the structure	$W.m^{-2}.^{\circ}C^{-1}$

h_{Rmc}	hRmc	radiative heat transfer coefficient from the root medium to the crop	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rmg}	hRmg	radiative heat transfer coefficient from the root medium to the glazing	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rmh}	hRmh	radiative heat transfer coefficient from the root medium to the heating system	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rms}	hRms	radiative heat transfer coefficient from the root medium to the structure	$W.m^{-2}.^{\circ}C^{-1}$
h_{Rsg}	hRsg	radiative heat transfer coefficient from the structure to the glazing	$W.m^{-2}.^{\circ}C^{-1}$
I_{opdr}		intensity of direct PAR radiation above the crop	$W.m^{-2}$
I_{pbeam}	Ibeam	intensity of the direct PAR radiation beam absorbed in a layer of the crop	$W.m^{-2}$
I_{pdf}	Idf	intensity of diffuse PAR radiation absorbed in a layer of the crop	$W.m^{-2}$
I_{pdr}	Idr	intensity of direct PAR radiation absorbed in a layer of the crop	$W.m^{-2}$
I_{psc}		intensity of scattered PAR radiation absorbed in a layer of the crop	$W.m^{-2}$
I_{shd}	Ishd	intensity of PAR radiation absorbed by shaded leaves in a layer of the crop	$W.m^{-2}$
I_{sun}	Isun	intensity of PAR radiation absorbed by sunlit leaves in a layer of the crop	$W.m^{-2}$
i	I	leaf number	-
J		Julian day number	day
K_{bdf}	Kbdf	extinction coefficient for diffuse radiation in a stand of "black" leaves	-
K_{bdr}	Kbdf	extinction coefficient for direct radiation in a stand of "black" leaves	-
K_{d}	Kd	diffuse fraction index	-
K_{df}		extinction coefficient for diffuse radiation in real leaves	-
K_{dr}		extinction coefficient for direct radiation in real leaves	-
K_{ndf}	Kndf	extinction coefficient for NIR diffuse radiation in real leaves	-
K_{ndr}	Kndr	extinction coefficient for NIR direct radiation in real leaves	-
K_{pdf}	Kpdf	extinction coefficient for PAR diffuse radiation in real leaves	-

K_{pdr}	Kpdr	extinction coefficient for PAR direct radiation in real leaves	-
K_t	Kt	sky clearness index	-
k_f	kf	thermal conductivity of the floor	$W.m^{-1}.^{\circ}C^{-1}$
k_m	km	thermal conductivity of the root medium	$W.m^{-1}.^{\circ}C^{-1}$
k_1	k1	thermal conductivity of the 1st soil layer	$W.m^{-1}.^{\circ}C^{-1}$
k_2	k2	thermal conductivity of the 2nd soil layer	$W.m^{-1}.^{\circ}C^{-1}$
k_3	k3	thermal conductivity of the 3rd soil layer	$W.m^{-1}.^{\circ}C^{-1}$
k_4	k4	thermal conductivity of the 4th soil layer	$W.m^{-1}.^{\circ}C^{-1}$
k_5	k5	thermal conductivity of the 5th soil layer	$W.m^{-1}.^{\circ}C^{-1}$
Le	Le	Lewis number	-
L	LM or LL	length of a leaf	cm
L_i	LM(I) or LL(I)	length of the i-th leaf	cm
L_{i+1}		length of the i+1-th leaf	cm
L_R		reference length for a primordial leaf	cm
L_U		length of the unfolding leaf	cm
LAI	LAI	leaf area index	-
LCT		local civil time	hrs
LE_{ca}	LEca	rate of evaporative heat loss from the crop per unit floor area	$W.m^{-2}$
LE_{ga}	LEga	rate of evaporative heat loss from the glazing per unit floor area	$W.m^{-2}$
LE_{ma}	LEma	rate of evaporative heat loss from the root medium per unit floor area	$W.m^{-2}$
LST		local solar time	hrs
M_a	Ma	molecular mass of dry air	$gDA.mol^{-1}$
M_c		molecular mass of carbon dioxide	$gCO_2.mol^{-1}$
M_w	Mw	molecular mass of water	$gH_2O.mol^{-1}$
MAI	MAI	root medium surface area index	-
Nu	Nu	Nusselt number	-
Nu_{forced}	Nufor	Nusselt number for forced convection	-
Nu_{free}	Nufre	Nusselt number for free convection	-
N_{plant}	Nplant	number of plants in the greenhouse	plant
N_v	Nv	airchange rate	hr^{-1}

NC_i	NCM(I) or NCL(I)	relative number of cells along the mid-rib of the i-th leaf	cell.cell^{-1}
n	N	number of leaves below the unfolding leaf in which cell division is occurring	-
P_o	Po	barometric pressure	Pa
P		plastochron index of plant	-
P_{CO_2}	PCO2	carbon dioxide limited rate of photosynthesis for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
P_{en}	Pend	endogenous rate of photosynthesis for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
P_g		rate of gross photosynthesis for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
P_{gmax}	PGmax	maximum rate of gross photosynthesis for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
P_{nmax}	PNmax	maximum rate of net photosynthesis for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
P_{shd}	PGshd	rate of gross photosynthesis for a single shaded leaf	mgCO$_2$.m^{-2}.s^{-1}
P_{sun}	PGsun	rate of gross photosynthesis for a single sunlit leaf	mgCO$_2$.m^{-2}.s^{-1}
P_t	Pt	rate of gross photosynthesis for a layer of sunlit and shaded leaves	mgCO$_2$.m^{-2}.s^{-1}
PGR_f'	PGRFmax	maximum potential growth rate of a fruit	mgDM.s^{-1}
$PGR(i)_f$	PGRFruM(I) or PGRFruL(I)	potential growth rate of the i-th fruit	mgDM.s^{-1}
q	Q	rate of leaf initiation in the apex of a stem	leaves.d^{-1}
q_s	Qs	stationary rate of leaf initiation in the apex of a stem	leaves.d^{-1}
Re	Re	Reynolds number	-
R	R	universal gas constant	J.mol^{-1}.K^{-4}
R_{cg}	Rcg	rate of net radiation exchange between the crop and the glazing per unit floor area	W.m^{-2}
R_{ch}	Rch	rate of net radiation exchange between the crop and the heating system per unit floor area	W.m^{-2}
R_{cs}	Rcs	rate of net radiation exchange between the crop and the greenhouse structure per unit floor area	W.m^{-2}
R_d	Rd	dark respiration rate for a single leaf	mgCO$_2$.m^{-2}.s^{-1}
R_{d20}	Rd20	dark respiration rate for a single leaf at 20°C	mgCO$_2$.m^{-2}.s^{-1}
R_{gsky}	Rgsky	rate of net radiation exchange between the glazing and the sky per unit floor area	W.m^{-2}

R_{fc}	Rfc	rate of net radiation exchange between the floor and the crop per unit floor area	$W.m^{-2}$
R_{fg}	Rfg	rate of net radiation exchange between the floor and the glazing per unit floor area	$W.m^{-2}$
R_{fm}	Rfm	rate of net radiation exchange between the floor and the root medium per unit floor area	$W.m^{-2}$
R_{fs}	Rfs	rate of net radiation exchange between the floor and the greenhouse structure per unit floor area	$W.m^{-2}$
R_{hf}	Rhf	rate of net radiation exchange between the heating system and the floor per unit floor area	$W.m^{-2}$
R_{hg}	Rhg	rate of net radiation exchange between the heating system and the glazing per unit floor area	$W.m^{-2}$
R_{hs}	Rhs	rate of net radiation exchange between the heating system and the structure per unit floor area	$W.m^{-2}$
R_{mc}	Rmc	rate of net radiation exchange between the root medium and the crop per unit floor area	$W.m^{-2}$
R_{mg}	Rmg	rate of net radiation exchange between the root medium and the glazing per unit floor area	$W.m^{-2}$
R_{mh}	Rmh	rate of net radiation exchange between the root medium and the heating system per unit floor area	$W.m^{-2}$
R_{ms}	Rms	rate of net radiation exchange between the root medium and the structure per unit floor area	$W.m^{-2}$
R_{sg}	Rsg	rate of net radiation exchange between the greenhouse structure and the glazing per unit floor area	$W.m^{-2}$
RGR_{ci}		relative growth rate of cells along the mid-rib of the i-th leaf	$cell.cell^{-1}.day^{-1}$
RGR_{p}		relative growth rate of the plant per plastochron	$cm.cm^{-2}.plast^{-1}$
RGR_{pi}		relative growth rate of the i-th leaf per plastochron	$cm.cm^{-2}.plast^{-1}$
RGR_{t}		relative growth rate of the plant per unit time	$cm.cm^{-2}.day^{-1}$
RGR_{ti}	RGR	relative growth rate of the i-th leaf per unit time	$cm.cm^{-2}.day^{-1}$
RH	RH	relative humidity of inside air	%
RWC_{c}		relative water content of the crop	-
RWC_{m}		relative water content of the root medium	-

r_{ao}	rao	advective mass transfer resistance between inside and outside of the greenhouse	$s.m^{-1}$
r_m	rm	mesophyll resistance	$s.m^{-1}$
r_{Vca}	rVca	boundary layer resistance of the crop for water vapour transfer	$s.m^{-1}$
r_{Vci}	rVci	internal leaf resistance for water vapour transfer	$s.m^{-1}$
r_{Vga}	rVga	boundary layer resistance of the glazing for water vapour transfer	$s.m^{-1}$
r_{Vma}	rVma	boundary layer resistance of the root medium for water vapour transfer	$s.m^{-1}$
S_c	Sc	circumsolar component of global solar radiation	$W.m^{-2}$
S_{df}	Sdf	diffuse component of global solar radiation	$W.m^{-2}$
S_{dr}	Sdr	direct component of global solar radiation	$W.m^{-2}$
S_{df}'	Sdf	diffuse component of global solar radiation corrected for circumsolar radiation	$W.m^{-2}$
S_{dr}'	Sdr	direct component of global solar radiation corrected for circumsolar radiation	$W.m^{-2}$
S_g	Sg	global solar radiation on the horizontal at the ground	$W.m^{-2}$
S_n	Sn	near infra-red solar radiation	$W.m^{-2}$
S_{ndf}	Sndf	diffuse component of near infra-red solar radiation	$W.m^{-2}$
S_{ndr}	Sndr	direct component of near infra-red solar radiation	$W.m^{-2}$
S_o	So	extra-terrestrial radiation on a horizontal surface	$W.m^{-2}$
S_p	Sp	photosynthetically active solar radiation	$W.m^{-2}$
$\overline{S}_p$	Light	average daily photosynthetically active radiation at the top of the crop	$J.m^{-2}.d^{-1}$
S_{pdf}	Spdf	diffuse component of photosynthetically active solar radiation	$W.m^{-2}$
S_{pdr}	Spdr	direct component of photosynthetically active solar radiation	$W.m^{-2}$
S_{sc}	Ssc	solar constant	$W.m^{-2}$
SAI	SAI	greenhouse structure area index	-
SLA	SLA	specific leaf area of the crop	$m^2.kgDM^{-1}$
s		slope of the saturation vapour pressure curve	$Pa.^{\circ}C^{-1}$
T_a	Ta	temperature of the inside air	$^{\circ}C$

$\overline{T}_c$	Temp	average daily crop temperature	°C
T_{ad}	Tad	dew-point temperature of the inside air	°C
T_{aw}	Taw	wet-bulb temperature of the inside air	°C
T_c	Tc	temperature of the crop canopy	°C
T_{cloud}		temperature of the cloud base	°C
T_d	Td	temperature of the deep ground	°C
T_f	Tf	temperature of the floor layer	°C
T_g	Tg	temperature of the greenhouse glazing	°C
T_h	Th	logarithmic mean temperature of the heating system	°C
T_m	Tm	temperature of the root medium	°C
T_o	To	temperature of the outside air	°C
T_{od}	Tod	dew point temperature of the outside air	°C
T_{ow}	Tow	wet bulb temperature of the outside air	°C
T_s	Ts	temperature of the greenhouse structure	°C
T_{sky}	Tsky	apparent radiant temperature of the sky	°C
T_1	T1	temperature of the 1st soil layer	°C
T_2	T2	temperature of the 2nd soil layer	°C
T_3	T3	temperature of the 3rd soil layer	°C
T_4	T4	temperature of the 4th soil layer	°C
T_5	T5	temperature of the 5th soil layer	°C
t	T	time	s
u_a	Ua	inside air velocity	$m.s^{-1}$
$\overline{u}_o$	Uo	outside wind speed at 10m above ground	$m.s^{-1}$
V_{gb}	Vgb	volume of glazing bars	m^3
V_m		volume of root medium	m^3
V_s	Vs	volume of structure	m^3
W		width of a leaf	cm
WHC_c	WHCc	water holding capacity of the crop	$gH_2O.gDM^{-1}$
WHC_m	WHCm	water holding capacity of the root medium	$gH_2O.gDM^{-1}$
w		humidity ratio	$gH_2O.gDA^{-1}$

X	X	eccentricity of the leaf angle distribution	-
X_{circ}		circumsolar radiation correction factor	-
x_b	Fbark	fraction of bark in the root medium	$m^2.mDM^{-3}$
x_{omm}	xomm	fraction of organic matter in the root medium	$m^2.mDM^{-3}$
x_{qm}	xqm	fraction of quartz minerals in the root medium	$m^2.mDM^{-3}$
Y	Y	parameter of the leaf angle distribution function	-
α	SAzi	azimuth of the solar beam	°
α_{cndf}	Acndf	absorptivity of the crop for diffuse near infra-red radiation	-
α_{cndr}	Acndr	absorptivity of the crop for direct hear infra-red radiation	-
α_{cpdf}	Acpdf	absorptivity of the crop for diffuse photosynthetically active radiation	-
α_{cpdr}	Acpdr	absorptivity of the crop for direct photosynthetically active radiation	-
α_{fn}	Afn	absorptivity of the floor for near infra-red radiation	-
α_{fp}	Afp	absorptivity of the floor for photosynthetically active radiation	-
α_{gdf}	Agdf	absorptivity of the glazing for diffuse radiation	-
α_{gdr}	Agdr	absorptivity of the glazing for direct radiation	-
α_{mn}	Afn	absorptivity of the root medium for near infra-red radiation	-
α_{mp}	Afp	absorptivity of the root medium for photosynthetically active radiation	-
α_{sdf}	Asdf	absorptivity of the structure for diffuse radiation	-
α_{sdr}	Asdr	absorptivity of the structure for direct radiation	-
α_{struc}	StrucAF	light absorption factor of structure	-
β	SAlt	solar altitude	°
Γ	Compoint	compensation point carbon dioxide concentration	$\mu l.l^{-1}$
Γ_{25}	Comp25	compensation point carbon dioxide concentration at 25°C	$\mu l.l^{-1}$
γ	Gamma	the psychrometric constant	$Pa.°C^{-1}$
Δ_a	da	average depth (height) of the greenhouse inside airspace	m

Δ_f	df	thickness of the floor layer	m
Δ_{gl}	dgl	thickness of the glazing	m
Δ_m	BagH	depth of the root medium bags	m
ΔT_h	delT	temperature difference between inlet and outlet of heater	°C
Δ_1	dl	thickness of the 1st soil layer	m
Δ_2	d2	thickness of the 2nd soil layer	m
Δ_3	d3	thickness of the 3rd soil layer	m
Δ_4	d4	thickness of the 4th soil layer	m
Δ_5	d5	thickness of the 5th soil layer	m
δ		solar declination angle	°
ϵ_c	ec	emissivity of the crop	-
ϵ_f	ef	emissivity of the floor	-
ϵ_g	eg	emissivity of the glazing	-
ϵ_h	eh	emissivity of the heating system	-
ϵ_m	em	emissivity of the root medium	-
ϵ_s	es	emissivity of the structure	-
$\epsilon_{sky}(0)$		emissivity of a clear sky	-
$\epsilon_{sky}(C)$	esky	emissivity of a cloudy sky	-
ζ_h	HBlock	radiation interception coefficient of the heating system	-
ζ_s	SBlock	radiation interception coefficient of the greenhouse structure	-
η	Eff	actual light use efficiency factor	$mgCO_2.J^{-1}$
η_{pot}	Eff0	potential light use efficiency factor	$mgCO_2.J^{-1}$
θ_a	La	exponential decay constant for the parameter a during primordial phase of leaf development	plast
θ_b	Lb	exponential decay constant for the parameter b during expanding phase of leaf development	plast
θ_c	Lc	exponential decay constant for the parameter c used to determine the unfolding leaf	-
θ_p	Lp	plastochron constant of adaptation	plast
ι		angle of incidence between a leaf and the solar beam	°
K_c	Kmc	hydraulic conductivity of the crop	$gH_2O.m^{-1}.s^{-1}.bar^{-1}$
κ_a	K	thermal diffusivity of air	$m^2.s^{-1}$
Λ		latitude of the greenhouse	°

λ_o	Lamb	latent heat of vapourization of water at reference temperature of 0°C	$J.g^{-1}$
ν_a	v	kinematic viscosity of air	$m^2.s^{-1}$
Ξ_a	XCO2a	carbon dioxide content of inside air per unit floor area	$mgCO_2.m^{-2}$
ξ_a	XiCO2a	carbon dioxide concentration of inside air	$mgCO_2.m^{-3}$
ξ_o	XiCO2o	carbon dioxide concentration of outside air	$mgCO_2.m^{-3}$
ρ_a	rhoa	density of dry air inside the greenhouse	$gDA.m^{-3}$
ρ_c		density of carbon dioxide in the greenhouse	$gCO_2.m^{-3}$
ρ_{cndf}	Rhocndf	reflectivity of a canopy of non-horizontal leaves and underlying floor for diffuse NIR radiation	-
ρ_{cndr}	Rhocndr	reflectivity of a canopy of non-horizontal leaves and underlying floor for direct NIR radiation	-
ρ_{cpdf}	Rhocpdf	reflectivity of a canopy of non-horizontal leaves and underlying floor for diffuse PAR radiation	-
ρ_{cpdr}	Rhocpdr	reflectivity of a canopy of non-horizontal leaves and underlying floor for direct PAR radiation	-
ρ_{dr}		reflectivity of a canopy of non-horizontal leaves for direct radiation	-
ρ_f		reflectivity of the floor	-
ρ_{hor}		reflectivity of a canopy of horizontal leaves for direct radiation	-
ρ_{ndr}	Rhondr	reflectivity of a canopy of non-horizontal leaves for direct NIR radiation	-
ρ_{nhor}	Rhonhor	reflectivity of a canopy of horizontal leaves for direct NIR radiation	-
ρ_{pdr}	Rhopdr	reflectivity of a canopy of non-horizontal leaves for direct PAR radiation	-
ρ_{phor}	Rhophor	reflectivity of a canopy of horizontal leaves for direct PAR radiation	-
σ	Sigma	the Stephan-Boltzmann constant	$W.m^{-2}.K^{-4}$
σ_n	Sign	scattering coefficient for NIR radiation	-
σ_p	Sigp	scattering coefficient for PAR radiation	-

τ_{cb}	Taucb	transmissivity of a canopy of "black" leaves for far infra-red radiation	-
τ_{cndf}	Taucndf	transmissivity of the crop for diffuse near infra-red radiation	-
τ_{cndr}	Taucndr	transmissivity of the crop for direct near infra-red radiation	-
τ_{cpdf}	Taucpdf	transmissivity of the crop for diffuse photosynthetically active radiation	-
τ_{cpdr}	Taucpdr	transmissivity of the crop for direct photosynthetically active radiation	-
τ_{gdf}	Taugdf	transmissivity of the glazing for diffuse radiation	-
τ_{gdr}	Taugdr	transmissivity of the glazing for direct radiation	-
τ_{R}	TauRF	greenhouse light transmission correction factor	-
Φ_{a}	Phia	thermal capacity of the dry air fraction of the inside air per unit floor area	$J.m^{-2}$
Φ_{c}	Phic	thermal capacity of the dry fraction of the crop per unit floor area	$J.m^{-2}$
Φ_{f}	Phif	thermal capacity of the dry fraction of the floor layer per unit floor area	$J.m^{-2}$
Φ_{g}	Phig	thermal capacity of the glazing per unit floor area	$J.m^{-2}$
Φ_{m}	Phim	thermal capacity of the dry fraction of the root medium per unit floor area	$J.m^{-2}$
Φ_{s}	Phis	thermal capacity of the dry fraction of the greenhouse structure per unit floor area	$J.m^{-2}$
Φ_{1}	Phi1	thermal capacity of the dry fraction of the 1st soil layer per unit floor area	$J.m^{-2}$
Φ_{2}	Phi2	thermal capacity of the dry fraction of the 2nd soil layer per unit floor area	$J.m^{-2}$
Φ_{3}	Phi3	thermal capacity of the dry fraction of the 3rd soil layer per unit floor area	$J.m^{-2}$
Φ_{4}	Phi4	thermal capacity of the dry fraction of the 4th soil layer per unit floor area	$J.m^{-2}$
Φ_{5}	Phi5	thermal capacity of the dry fraction of the 5th soil layer per unit floor area	$J.m^{-2}$
X_{a}	Xa	moisture concentration of the inside air per unit floor area	$g.m^{-2}$
X_{c}	Xc	moisture concentration of the crop per unit floor area	$g.m^{-2}$

X_c'	Xc	maximum moisture concentration of the crop per unit floor area	$g.m^{-2}$
X_f	Xf	moisture concentration of the floor layer per unit floor area	$g.m^{-2}$
X_g	Xg	concentration of moisture on the underside of the glazing per unit floor area	$g.m^{-2}$
X_m	Xm	moisture concentration of the root medium per unit floor area	$g.m^{-2}$
X_m'	Xm	maximum moisture concentration of the root medium per unit floor area	$g.m^{-2}$
X_1	Chil	moisture concentration of the 1st soil layer per unit floor area	$g.m^{-2}$
X_2	Chi2	moisture concentration of the 2nd soil layer per unit floor area	$g.m^{-2}$
X_3	Chi3	moisture concentration of the 3rd soil layer per unit floor area	$g.m^{-2}$
X_4	Chi4	moisture concentration of the 4th soil layer per unit floor area	$g.m^{-2}$
X_5	Chi5	moisture concentration of the 5th soil layer per unit floor area	$g.m^{-2}$
χ_a	Chia	absolute humidity of the inside air	$g.m^{-3}$
χ_o	Chio	absolute humidity of the outside air	$g.m^{-3}$
ψ_c	Psic	water potential of the crop	bar
ψ_m	Psim	water potential of the root medium	bars
Ω_c	Capc	hydraulic capacitance of the crop	$bars^{-1}$
Ω_m	Capm	hydraulic capacitance of the root medium	$bars^{-1}$
ω		hour angle of the sun	°