1 MEC for Crop Growth

$$A = \begin{cases} A_{\max}\left(\frac{t}{t_A}\right)^a & t < t_A \\ A_{\max} & t \geq t_A \end{cases}$$

$$Y_{\mathrm{Q}} = \begin{cases} Y_{\mathrm{Q,max}} & t \leq t_{\mathrm{Q}} \\ Y_{\mathrm{Q,max}} - (Y_{\mathrm{Q,max}} - Y_{\mathrm{Q,min}})\frac{t - t_{\mathrm{Q}}}{t_{\mathrm{M}} - t_{\mathrm{Q}}} & t_{\mathrm{Q}} \leq t \leq t_{\mathrm{M}} \end{cases}$$

$$Y_{\mathrm{Q,max}} = C_1 \frac{1}{\Phi_\gamma c_{\mathrm{CO2}}} + C_2 \frac{1}{\Phi_\gamma} + C_3 \frac{c_{\mathrm{CO2}}}{\Phi_\gamma} + C_4 \frac{c_{\mathrm{CO2}}^2}{\Phi_\gamma} + C_5 \frac{c_{\mathrm{CO2}}^3}{\Phi_\gamma} + C_6 \frac{1}{c_{\mathrm{CO2}}} + C_7 + C_8 c_{\mathrm{CO2}} + C_9 c_{\mathrm{CO2}}^2 + C_{10} c_{\mathrm{CO2}}^3 + C_{11} \frac{\Phi_\gamma}{c_{\mathrm{CO2}}} + C_{12}\Phi_\gamma + C_{13}\Phi_\gamma c_{\mathrm{CO2}} + C_{14}\Phi_\gamma c_{\mathrm{CO2}}^2 + C_{15}\Phi_\gamma c_{\mathrm{CO2}}^3 + C_{16}\frac{\Phi_\gamma^2}{c_{\mathrm{CO2}}} + C_{17}\Phi_\gamma^2 + C_{18}\Phi_\gamma^2 c_{\mathrm{CO2}} + C_{19}\Phi_\gamma^2 c_{\mathrm{CO2}}^2 + C_{20}\Phi_\gamma^2 c_{\mathrm{CO2}}^3 + C_{21}\frac{\Phi_\gamma^3}{c_{\mathrm{CO2}}} + C_{22}\Phi_\gamma^3 + C_{23}\Phi_\gamma^3 c_{\mathrm{CO2}} + C_{24}\Phi_\gamma^3 c_{\mathrm{CO2}}^2 + C_{25}\Phi_\gamma^3 c_{\mathrm{CO2}}^3$$

$$\Longrightarrow Y_{\mathrm{Q,max}} = \sum_{u \in [-1,3]} \sum_{v \in [-1,3]} C_{uv} \cdot \Phi_\gamma^v \cdot c_{\mathrm{CO2}}^u$$

$$\eta_{\mathrm{C}} = \begin{cases} \eta_{\mathrm{C,max}} & t \leq t_{\mathrm{Q}} \\ \eta_{\mathrm{C,max}} - (\eta_{\mathrm{C,max}} - \eta_{\mathrm{C,min}})\frac{t - t_{\mathrm{Q}}}{t_{\mathrm{M}} - t_{\mathrm{Q}}} & t_{\mathrm{Q}} \leq t \leq t_{\mathrm{M}} \end{cases}$$

$$\hat{\dot{n}}_{\mathrm{C}} = 0.0036 \cdot H \cdot \eta_{\mathrm{C}} \cdot A \cdot Y_{\mathrm{Q}} \cdot \Phi_\gamma$$

$$\hat{\dot{n}}_{\mathrm{O2}} = Y_{\mathrm{O2}} \hat{\dot{n}}_{\mathrm{C}}$$

$$\hat{\dot{m}}_B = \frac{\check{m}_{\mathrm{C}}}{w_{\mathrm{C}}} \hat{\dot{n}}_{\mathrm{C}}$$

$$\hat{m}_{\mathrm{T}} = \int_0^{t_{\mathrm{M}}} \hat{\dot{m}}_B \, dt$$

$$\hat{m}_{\mathrm{E}} = f_{\mathrm{E}} \int_{t_{\mathrm{E}}}^{t_{\mathrm{M}}} \hat{\dot{m}}_B \, dt$$

1.1 Variables

Variable	Description	Unit	Former Variable
A	Absorbtance, directional	-	A
a	Empirical exponent	-	n
C	Regression coefficient	-	C
c_{CO2}	Concentration of CO_2, molar	$\mu\mathrm{mol}_{\mathrm{CO2}}\,\mathrm{mol}_{\mathrm{air}}^{-1}$	[CO_2]
f_{E}	Fraction of edible biomass after t_{E}	-	XFRT
H	Photoperiod	$\mathrm{h\,d^{-1}}$	H
$\hat{\dot{m}}_B$	Biomass, per time, areal	$\mathrm{g\,d^{-1}\,m^{-2}}$	CGR
$\hat{m}_{\mathrm{E}}$	Biomass, areal, edible	$\mathrm{g\,m^{-2}}$	TEB
$\hat{m}_{\mathrm{T}}$	Biomass, areal, total	$\mathrm{g\,m^{-2}}$	TCB
$\check{m}$	Mass, molar	$\mathrm{g\,mol^{-1}}$	MW
$\hat{\dot{n}}$	Moles per time, areal	$\mathrm{mol\,d^{-1}\,m^{-2}}$	DCG, DOP
t	Time	d	t
t_A	Time of canopy closure	$\mathrm{d_{AE}}$	t_A
t_{M}	Time of harvest/maturity	$\mathrm{d_{AE}}$	t_M
t_{E}	Time of onset of organ formation	$\mathrm{d_{AE}}$	t_E
t_{Q}	Time of canopy senescence onset	$\mathrm{d_{AE}}$	t_Q
w_{C}	Biomass carbon fraction	-	BCF
Y_{O2}	Oxygen production factor	$\mathrm{mol_{O2}\,mol_{C}^{-1}}$	OPF
Y_{Q}	Canopy quantum yield	$\frac{\mathrm{mol_{C,fixed}}}{\mathrm{mol_{\gamma,absorbed}}}$	CQY
η_{C}	Carbon use efficiency, 24 hr	$\frac{\mathrm{mol_{C,biomass}}}{\mathrm{mol_{C,fixed}}}$	$\mathrm{CUE_{24}}$
σ	Density, areal	$\mathrm{kg\,m^{-2}}$	-
σ_N	Density, areal, numeric	$\mathrm{m^{-2}}$	-
Φ_γ	Photosynthetic photon flux	$\mu\mathrm{mol}_\gamma\,\mathrm{m^{-2}\,s^{-1}}$	PPF

AE is "after emergence". Areal (per area) should not be confused with aerial (above ground). Areal density is not used in the MEC formulae, but it is used in downstream calculations.

1.2 Values for lettuce

A_{max}	0.93
a	2.5
C_{uv}	See BVAD Table 4-108
c_{CO2}	$[330, 1300]\ \mu\text{mol}_{\text{CO2}}\,\text{mol}_{\text{air}}^{-1}$
f_{E}	0.95
t_{E}	$1\,\text{d}_{\text{AE}}$
t_{M}	$30\,\text{d}_{\text{AE}}$
t_{Q}	n/a
w_{C}	0.4
Y_{O2}	1.08
$Y_{\text{Q,min}}$	n/a
$\eta_{\text{C,max}}$	0.625
$\eta_{\text{C,min}}$	n/a
σ_N	$19.2\,\text{m}^{-2}$
Φ_γ	$[200, 500]\ \mu\text{mol}_\gamma\,\text{m}^{-2}\,\text{s}^{-1}$

2 MEC for Crop Transpiration

$$p_{\text{S}}^\star = 0.611 e^{\left(\frac{17.4 T_{\text{L}}}{T_{\text{L}}+239}\right)}$$
$$\Delta p^\star = p_{\text{S}}^\star (1 - \underset{\cdot}{H}_{\text{R}})$$
$$\hat{\dot{n}}_{\text{ps,gross}} = A \cdot Y_{\text{Q}} \cdot \Phi_\gamma$$
$$\hat{\dot{n}}_{\text{ps,net}} = \left(\frac{t_{\text{sol}} - H}{t_{\text{sol}}} + \frac{\eta_{\text{C}} \cdot H}{t_{\text{sol}}}\right) \hat{\dot{n}}_{\text{ps,gross}}$$

$$g_{\text{sfc}} = \frac{g_{\text{atm}} g_{\text{sto}}}{g_{\text{atm}} + g_{\text{sto}}}$$
$$g_{\text{sto}} = \begin{cases} (1.717 T_{\text{L}} - 19.96 - 10.54 \Delta p^\star) \frac{\hat{\dot{n}}_{\text{ps,net}}}{c_{\text{CO2}}} & \text{planophile} \\ 0.1389 + 15.32 \underset{\cdot}{H}_{\text{R}} \frac{\hat{\dot{n}}_{\text{ps,net}}}{c_{\text{CO2}}} & \text{erectophile} \end{cases}$$
$$g_{\text{atm}} = \begin{cases} 2.5 & \text{planophile} \\ 5.5 & \text{erectophile} \end{cases}$$
$$\hat{\dot{V}}_{\text{trs}} = 3600 H \frac{\breve{m}_{\text{water}}}{\rho_{\text{water}}} g_{\text{sfc}} \frac{\Delta p^\star}{P_{\text{atm}}}$$

2.1 Variables

Variable	Description	Unit	Former Variable
g_{atm}	Atmospheric aerodynamic conductance	$\text{mol}_{\text{water}}\,\text{s}^{-1}\,\text{m}^{-2}$	g_A
g_{sfc}	Canopy surface conductance	$\text{mol}_{\text{water}}\,\text{s}^{-1}\,\text{m}^{-2}$	g_C
g_{sto}	Canopy stomatal conductance	$\text{mol}_{\text{water}}\,\text{s}^{-1}\,\text{m}^{-2}$	g_S
$\underset{\cdot}{H}_{\text{R}}$	Relative humidity	-	RH
$\hat{\dot{n}}_{\text{ps,gross}}$	Gross canopy photosynthesis	$\mu\text{mol}_\text{C}\,\text{s}^{-1}\,\text{m}^{-2}$	P_{GROSS}
$\hat{\dot{n}}_{\text{ps,net}}$	Net canopy photosynthesis	$\mu\text{mol}_\text{C}\,\text{s}^{-1}\,\text{m}^{-2}$	P_{NET}
P_{atm}	Total atmospheric pressure	kPa	P_{ATM}
$p_{\text{S}}^\star$	Saturated vapour pressure	kPa	VP_{SAT}
T_{D}	Temperature, dark cycle	$^\circ\text{C}$	T_{DARK}
T_{L}	Temperature, light cycle	$^\circ\text{C}$	T_{LIGHT}
t_{sol}	Length of local sol	$\text{h}\,\text{d}^{-1}$	D_{PG}
$\hat{\dot{V}}_{\text{trs}}$	Daily transpiration rate	$\text{L}\,\text{d}^{-1}\,\text{m}^{-2}$	DTR
$\Delta p^\star$	Vapour pressure deficit	kPa	VPD
ρ	Density	$\text{g}\,\text{L}^{-1}$	ρ

2.2 Values for Lettuce

g_{atm}	$2.5\,\text{mol}_{\text{water}}\,\text{m}^{-2}\,\text{s}^{-1}$
T_{D}	$23\,^\circ\text{C}$
T_{L}	$23\,^\circ\text{C}$
t_{sol}	$24\,\text{h}\,\text{d}^{-1}$

3 MEC for Nominal Temperature Regimes and Photoperiods

$$\Phi'_\gamma = \Phi_\gamma \frac{H}{H_0}$$
$$t_A = D_1 \frac{1}{\Phi'_\gamma c_{\text{CO2}}} + D_2 \frac{1}{\Phi_\gamma} + D_3 \frac{c_{\text{CO2}}}{\Phi'_\gamma} + D_4 \frac{c_{\text{CO2}}^2}{\Phi'_\gamma} + D_5 \frac{c_{\text{CO2}}^3}{\Phi'_\gamma} + D_6 \frac{1}{c_{\text{CO2}}} + D_7 + D_8 c_{\text{CO2}} + D_9 c_{\text{CO2}}^2 + D_{10} c_{\text{CO2}}^3 + D_{11} \frac{\Phi'_\gamma}{c_{\text{CO2}}} + D_{12} \Phi'_\gamma + D_{13} \Phi'_\gamma c_{\text{CO2}} + D_{14} \Phi'_\gamma c_{\text{CO2}}^2 + D_{15} \Phi'_\gamma c_{\text{CO2}}^3 + D_{16} \frac{{\Phi'_\gamma}^2}{c_{\text{CO2}}} + D_{17} {\Phi'_\gamma}^2 + D_{18} {\Phi'_\gamma}^2 c_{\text{CO2}} + D_{19} {\Phi'_\gamma}^2 c_{\text{CO2}}^2 + D_{20} {\Phi'_\gamma}^2 c_{\text{CO2}}^3 + D_{21} \frac{{\Phi'_\gamma}^3}{c_{\text{CO2}}} + D_{22} {\Phi'_\gamma}^3 + D_{23} {\Phi'_\gamma}^3 c_{\text{CO2}} + D_{24} {\Phi'_\gamma}^3 c_{\text{CO2}}^2 + D_{25} {\Phi'_\gamma}^3 c_{\text{CO2}}^3$$

$$\implies t_A = \sum_{u\in[-1,3]} \sum_{v\in[-1,3]} D_{uv} \cdot {\Phi'_\gamma}^{v} \cdot c^u_{\mathrm{CO2}}$$

3.1 Variables

Variable	Description	Unit	Former Variable
D_{uv}	Regression coefficient	-	C
H_0	Photoperiod, nominal	$\mathrm{h\,d^{-1}}$	$\mathrm{H_0}$
Φ'_γ	Photosynthetic photon flux, effective	$\mathrm{\mu mol\,m^{-2}\,s^{-1}}$	$\mathrm{PPF_E}$

3.2 Values for Lettuce

D	See BVAD Table 4-121
H_0	$16\,\mathrm{h\,d^{-1}}$

4 Nitrogen Modelling

Agren: $\frac{\mathrm{d}m_B}{\mathrm{d}t} = \dot{Y}_\mathrm{N}(m_B, m_\mathrm{N})m_\mathrm{N}$

Agren: $\dot{Y}_\mathrm{N} = \alpha - \beta\frac{m_B}{m_\mathrm{N}}$

Agren: $\frac{1}{m_B}\frac{\mathrm{d}m_B}{\mathrm{d}t} = \alpha\frac{m_\mathrm{N}}{m_B} - \beta$

VW: $\alpha = k_B \cdot k_f \qquad \beta = k_d$

KY: $\frac{\mathrm{d}m_B}{\mathrm{d}t} = \dot{Y}_\mathrm{N} \cdot m_\mathrm{N} \qquad \dot{Y}_\mathrm{N} = \eta_\mathrm{u} \cdot \mu_\mathrm{N} \cdot \eta_\mathrm{N} \qquad \eta_\mathrm{u} = \frac{\text{N uptake rate}}{\text{max N uptake rate}} \qquad \mu_\mathrm{N} = \frac{\ln m_\mathrm{N2} - \ln m_\mathrm{N1}}{t_2 - t_1} \qquad \eta_\mathrm{N} = \frac{\Delta m_B(t_2, t_1)}{\langle m_\mathrm{N}\rangle(t_2, t_1)}$

4.1 Variables

Variable	Description	Unit
m_B	Biomass	$\mathrm{g_{DW}}$
m_N	Mass of total nitrogen in plant	g
t	Time	d
$\dot{Y}_\mathrm{N}$	Nitrogen productivity	$\mathrm{g_{DW}\,g_N^{-1}\,d^{-1}}$
α	Leading term in nitrogen productivity	$\mathrm{g_{DW}\,g_N^{-1}\,d^{-1}}$
β	Corrective term in nitrogen productivity	$\mathrm{d^{-1}}$
k_B	Efficiency of biomass formation from PhN	$\mathrm{g_{DW}\,g_N^{-1}\,d^{-1}}$
k_d	Degradation rate of PhN	$\mathrm{d^{-1}}$
k_e	Proportionality of PhN to LfN	-
k_f	Efficiency of formation of PhN from PtN	-
η_N	Nitrogen use efficiency	$\mathrm{g_{DW}\,g_N^{-1}}$
η_u	Nitrogen uptake efficiency	-
μ_N	Relative uptake rate	$\mathrm{d^{-1}}$

5 ESM

$$\mathrm{ESM} = \sum_{i=1}^{n} \left[(m_{0,i} \cdot f_{m_0,i}) + (V_{0,i} \cdot f_{V_0,i}) + (P_i \cdot f_{P,i}) + (Q_i \cdot f_{Q,i}) + (t_i \cdot f_{t,i} \cdot \chi) + (m_i \cdot f_{m,i} \cdot \chi) + (V_i \cdot f_{V_0,i} \cdot \chi)\right]$$

5.1 Variables

Variable	Description	Unit
ESM	Equivalent system mass	kg
$m_{0,i}$	Initial mass of subsystem i	kg
$f_{m_0,i}$	Initial mass stowage factor for subsystem i	$\mathrm{kg\,kg^{-1}}$
$V_{0,i}$	Initial volume of subsystem i	$\mathrm{m^3}$
$f_{V_0,i}$	Mass equivalency factor for the pressurized volume support infrastructure of subsystem i	$\mathrm{kg\,m^{-3}}$
P_i	Power requirement of subsystem i	$\mathrm{kW_e}$
$f_{P,i}$	Mass equivalency factor for the power generation support infrastructure of subsystem i	$\mathrm{kW_e\,kg^{-1}}$
Q_i	Cooling requirement of subsystem i	$\mathrm{kW_{th}}$
$f_{Q,i}$	Mass equivalency factor for the cooling infrastructure of subsystem i	$\mathrm{kW_{th}\,kg^{-1}}$
t_i	Crewtime requirement of subsystem i	$\mathrm{CM\,h\,yr^{-1}}$
$f_{t,i}$	Mass equivalency factor for the crewtime of subsystem i	$\mathrm{kg\,CM^{-1}\,h^{-1}}$
χ	Duration of the mission segment of interest	yr
m_i	Time- or event-dependent mass of subsystem i	$\mathrm{kg\,yr^{-1}}$
$f_{m,i}$	Time- or event-dependent mass stowage factor for subsystem i	$\mathrm{kg\,kg^{-1}}$
V_i	Time- or event-dependent volume of subsystem i	$\mathrm{m^3}$