



A land surface model combined with a crop growth model for paddy rice (MATCRO-Rice Ver. 1) – Part I: Model description

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Abstract. Crop growth and agricultural management can affect climate at various spatial and temporal scales through the exchange of heat, water, and gases between land and atmosphere. Therefore, accurate simulation of fluxes for heat, water, and gases from agricultural land is important for climate simulations. A land surface model (LSM) combined with a crop growth model (CGM), called LSM-CGM combined model, is a useful tool for simulating these fluxes from agricultural land.

5 Therefore, we developed a new LSM-CGM combined model for paddy rice fields, the MATCRO-Rice model. The main objective of this paper is to present the full description of MATCRO-Rice. The most important feature of MATCRO-Rice is that it can consistently simulate latent and sensible heat fluxes, net carbon flux, and crop yield by exchanging variables between the LSM and CGM. This feature enables us to apply the model to a wide range of integrated issues.

1 Introduction

10 In the last 15 years, climate and land surface modelling studies have shown that crop growth and farm management in agricultural land significantly affect climate via the exchange of heat, water, and gases. For example, applying a regional climate model combined with a crop growth model (CGM) to the United States, Tsvetsinskaya et al. (2001) showed that crop growth can change the surface temperature by 2 to 4°C. Maruyama and Kuwagata (2010) showed that crop growing season can affect the amount of evapotranspiration by using a land surface model (LSM) combined with a CGM. Levis et al. (2012) incorporated a CGM into an earth system model, and showed that the timing of crop sowing can change the amount of precipitation. Using a dynamic global vegetation model combined with a CGM, Bondeau et al. (2007) showed that the global carbon cycle, which has a significant effect on global warming, is largely modified by crop growth and farm management. Osborne et al. (2009), using a global climate model coupled with a CGM, demonstrated that the crop–climate interaction can affect annual variability in surface temperature. All these studies indicate that crop growth and farm management are key determinants of climate and that climate simulations need to accurately simulate the fluxes of heat, water, and gases in agricultural land.

A LSM or dynamic vegetation model (DVM) incorporated with a CGM, called LSM-CGM or DVM-CGM combined models, are a useful tool for simulating the fluxes of heat, water, and gases in agricultural land. Hence, several LSMs and DVMs incorporated with a CGM have been developed (BATS-GF: Tsvetsinskaya et al., 2001; Agro-IBIS: Kucharik, 2003;



ORCHIDEE-STICS: Gervois et al., 2004; LPJmL: Bondeau et al., 2007; GLAM-MOSES2: Osborne et al., 2007; SIBcrop: Lokupitiya et al., 2009; MK10: Maruyama and Kuwagata, 2010; CLM4CNcrop: Levis et al., 2012; JULES-crop: Osborne et al., 2015). Lei et al. (2010) divided these incorporated models into three types in terms of integration schemes for the leaf area index (LAI). Among these types, the type of models that consistently simulate crop production, LAI, water-energy flux, and carbon flux by exchanging variables between an LSM and a CGM allows for wide applicability and comprehensive evaluation of the model with observations (Lei et al., 2010). However, this type comprises currently only four models: Agro-IBIS, SIBcrop, CLM4CNcrop, and JULES-crop. Among these, only JULES-crop can simulate the growth of rice, although rice is one of the major crops, accounting for 23% of agricultural land farmed with cereals worldwide (FAO, 2015). Nevertheless, the JULES-crop model does not consider a flooded surface of paddy rice fields, which is an important parameter when simulating heat and water fluxes in paddy rice fields, because heat and water fluxes in a flooded surface are largely different from those in a non-flooded surface.

We developed a new LSM-CGM model, called MATCRO-Rice. The aim of this paper is to describe the MATCRO-Rice model in detail. The most important feature of MATCRO-Rice is that it can consistently simulate latent heat flux (LHF), sensible heat flux (SHF), net carbon flux, and crop yields by exchanging variables between LSM and CGM. Herein, we first provide the overview of MATCRO-Rice in Section 2, and then describe the LSM and CGM of MATCRO-Rice in detail in Sections 3 and 4, respectively. Last, we discuss the applications and limitations of MATCRO-Rice in Section 5. The model validation for MATCRO-Rice is described in the accompanied paper (Masutomi et al., 2016).

2 Model overview: MATCRO-Rice

MATCRO-Rice has two main components: LSM and CGM. The LSM component mainly simulates LHF and SHF. It is based on MATSIRO (Takata et al., 2003), which is embedded in global climate models (MIROC5.0: Watanabe et al., 2010; NICAM: Satoh et al., 2008) and a climate system model (MIROC-ESM: Watanabe et al., 2011). In addition, MATSIRO is used for a range of hydrological applications (e.g., Pokhrel et al., 2012; Hirabayashi et al., 2013).

The CGM of MATCRO-Rice mainly simulates rice yield and biomass for each organ during a growing period. The CGM used in MATCRO-Rice is based on CGMs developed by the School of de Wit (Bouman et al., 1996; e.g., MACROS: Penning de Vries et al., 1989; SUCROS: Goudriaan and van Laar, 1994; ORYZA2000: Bouman et al., 2001).

The meteorological inputs to run MATCRO-Rice are listed in Table 1. The standard outputs of MATCRO-Rice are LHF, SHF, biomass of organs during a growing period, and crop yield. All other variables simulated in MATCRO-Rice can be output if needed. The feature of MATCRO-Rice is to exchange variables between the LSM and CGM. The variables exchanged are listed in Table 2.



3 Land surface model

The main outputs of the LSM of MATCRO-Rice are LHF and SHF. The LSM has five modules, which are "energy balance at the canopy and surface water", "within-canopy shortwave radiation", "bulk transfer coefficient for latent and sensible heat", "canopy water balance", and "soil water and heat transfer". Each module is described in detail in the following sections. Before
5 describing each module, we note the following two major modifications from the original LSM, MATSIRO (Takata et al., 2003).

1. LAI, crop height, and root depth, which are constant in the original MATSIRO, are dynamically calculated in the CGM and are the inputs to the LSM.
 2. Surface water is added above the soil surface to represent a flooded surface in paddy rice fields.
- 10 Other minor modifications are described separately in each of the following sections. We note that the photosynthesis model used in MATCRO is described in the CGM section (Section 4).

3.1 Energy balance at the canopy and surface water

This module calculates LHF and SHF by solving energy balance at two layers above the soil, canopy and surface water. The module is based on the original MATSIRO (Takata et al., 2003), except for the addition of surface water above the soil and
15 other minor modifications. The energy balance at the canopy and surface water are given as follows:

$$R_{nc} = H_c + \lambda E_c + \lambda E_t, \quad (\text{Canopy}) \quad (1)$$

$$R_{nw} = H_w + \lambda E_w + G_{ws} + S_{tw}, \quad (\text{Water surface}) \quad (2)$$

where R_{nc} and R_{nw} are the net radiant flux density at canopy and surface water, H_c and H_w are the SHF from the canopy and surface water, E_c , E_t , and E_w are the evaporation from wet canopy, transpiration from the canopy, and evaporation from the
20 surface water, respectively, G_{ws} is the heat flux from the surface water to soil, and S_{tw} is the heat flux stored into surface water. It is important to note that the downward flux for R_{nc} , R_{nw} , and G_{ws} indicates a positive flux, whereas downward flux for H_c , H_w , E_c , E_t , and E_w indicates a negative flux. All variables in the model are listed in Table 3. λ is the physical constant for the



latent heat of vaporisation (Table 4). Each radiant, heat, and water flux in Eqs. 1 and 2 are given by the following equations.

$$R_{nc} = (R_s^d(0) - R_s^u(0))(1 - \tau_{cs}) + \epsilon R_l^d(0)(1 - \tau_{cl}) - (2\epsilon\sigma T_c^4 - \epsilon\sigma T_w^4)(1 - \tau_{cl}), \quad (3)$$

$$R_{nw} = (R_s^d(0) - R_s^u(0))\tau_{cs} + \epsilon R_l^d(0)\tau_{cl} - \epsilon\sigma T_w^4 + \epsilon\sigma(1 - \tau_{cl})T_c^4, \quad (4)$$

$$H_c = c_{pa}\rho_a C_{Hc}U(T_c - T_a), \quad (5)$$

$$5 \quad H_w = c_{pa}\rho_a C_{Hw}U(T_w - T_a), \quad (6)$$

$$E_c = f_{cw}\rho_a C_{Ec}U(Q_{sat}(T_c, P_a) - Q), \quad (7)$$

$$E_t = (1 - f_{cw})\rho_a C_{Et}U(Q_{sat}(T_c, P_a) - Q), \quad (8)$$

$$E_w = \rho_a C_{Ew}U(Q_{sat}(T_w, P_a) - Q), \quad (9)$$

$$G_{ws} = k_w(T_w - T_s(0))/d_w, \quad (10)$$

$$10 \quad S_{tw} = c_{pw}\rho_w d_w(dT_w/dt), \quad (11)$$

where $R_s^d(0)$, $R_l^d(0)$, and $R_s^u(0)$ are the downward shortwave radiant flux density, downward longwave radiant flux density, and upward shortwave radiant flux density at the canopy top, respectively, τ_{cs} and τ_{cl} are the canopy transmissivity for shortwave and longwave radiation, respectively, C_{Hc} and C_{Hw} are the bulk transfer coefficients (BTCs) for sensible heat between canopy and atmosphere and between surface water and atmosphere, respectively, C_{Ec} and C_{Ew} are the BTCs for latent heat between canopy and atmosphere and between canopy and atmosphere, respectively, T_a , P_a , U , and Q are air temperature, air pressure, wind speed, and specific humidity, respectively, f_{cw} is the fraction of wet canopy, T_c , T_w , and $T_s(0)$ are the canopy, surface water, and soil surface temperature, respectively, c_{pa} and c_{pw} are the specific air and water heat, respectively, k_w is the water thermal conductivity, ρ_w and ρ_a are water and air density, respectively, σ is the Boltzmann constant, Q_{sat} is specific humidity at saturation, d_w is the depth of surface water, ϵ is the longwave emissivity of surface water, and d/dt indicates the time differentiation. The argument of the radiant flux density denotes LAI depth from the canopy top, and the argument of soil temperature denotes soil depth from the soil surface. Therefore, $R_s^d(0)$, $R_l^d(0)$, and $R_s^u(0)$ indicate the radiant flux density at the canopy top, and $T_s(0)$ indicates the soil surface temperature.

T_a , P_a , U , Q , $R_s^d(0)$, and $R_l^d(0)$ are meteorological forcing inputs (Table 1). $R_s^u(0)$, τ_{cs} , τ_{cl} , f_{cw} , C_{Ec} , C_{Ew} , C_{Hc} , C_{Hw} , and $T_s(0)$ are calculated from Eqs. 21, 20, 23, 39, 25, 24, 27, 26, and 45, respectively, which are given in the following sections. The variables ρ_a and Q_{sat} are physically calculated from the air temperature and air pressure (Appendix A), c_{pa} , c_{pw} , k_w , ρ_w , and σ are physical constants (Table 4), d_w is a simulation setting parameter (Table 5), and ϵ is set to 0.96 (Campbell and Norman, 1998). T_c and T_w are numerically determined to satisfy Eqs. 1 to 11. The numerical method is described in Masutomi et al. (2016).

The original MATSIRO uses C_{Hc} instead of C_{Ec} in Eq. 8 when specific humidity of the air is greater than the saturated specific humidity of the canopy (i.e., $Q_{sat} - Q < 0$), because dew condensation occurs at canopy of interest. MATCRO does not consider the effect for simplicity. It should be noted that C_{Hc} is used for calculating the evaporation from wet canopy in Eq. 7.



3.2 Within-canopy shortwave radiation

The main role of this module is to simulate direct downward photosynthesis active radiation (PAR), scattered downward PAR, and scattered upward PAR at a LAI depth of l from the canopy top by calculating the transmission and reflection of shortwave radiation by leaves within canopies. These PARs are used for calculating carbon assimilation in the CGM (Section 4.1). In addition to the simulation of PARs, transmissivities for shortwave and longwave radiation are simulated in this module. The transmissivities are used for calculating LHF and SHF (Section 3.1).

This module is based on the simple model developed by Watanabe and Ohtani (1995). The model determines radiation within canopies by calculating the transmission and reflection of the radiation within the canopy. In this model, radiation within the canopy is divided into three components (downward direct, downward scattered, and upward scattered) and two wavebands (PAR and near infrared [NIR]). In addition, the following three assumptions are considered in the model for simplicity.

1. Leaf orientation is random (i.e., spherical distribution).
2. Leaf reflectivity and transmissivity of the radiation are vertically uniform within a canopy.
3. Scattered radiation income from a zenith angle of 53° .

It should be noted that the assumption 3 is based on the fact that radiant flux uniformly emitted from a horizontal plane is approximately equal to radiant flux density from a zenith angle of 53° . From the three assumptions above, we can express analytically the radiant flux density for downward direct ($D_i^d(l)$), downward scattered ($S_i^d(l)$), and upward scattered ($S_i^u(l)$) within canopy for each waveband ($i = 1$: PAR; $i = 2$: NIR), as follows:

$$D_i^d(l) = D_i^d(0) \exp(-Fl \sec(\theta)), \quad (12)$$

$$S_i^d(l) = C_{1,i} \exp(a_i l) + C_{2,i} \exp(-a_i l) + C_{3,i} D_i^d(l), \quad (13)$$

$$S_i^u(l) = A_{1,i} C_{1,i} \exp(a_i l) + A_{2,i} C_{2,i} \exp(-a_i l) + C_{4,i} D_i^d(l). \quad (14)$$

Here, F is a parameter for the distribution of leaf orientation. If we assume spherical distribution for leaf orientation as mentioned above, we have $F = 0.5$ (Goudriaan and van Laar (1994)). The variable l is a LAI depth from the canopy top. The variable θ is a zenith angle of the sun (Appendix B). The function $\sec()$ indicates the secant function. The coefficients, a_i , $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, $A_{1,i}$, and $A_{2,i}$ are calculated as shown in Appendix C. It should be noted that a_i indicates the extinction coefficient for scattered radiation. $D_i^d(0)$ is obtained by splitting radiant flux density for downward shortwave at the top of the canopy into direct and scattered radiation as follows:

$$D_i^d(0) = 0.5 R_s^d(0) (1 - f_{df}), \quad (15)$$

$$S_i^d(0) = 0.5 R_s^d(0) f_{df}, \quad (16)$$

where $R_s^d(0)$ is the downward shortwave radiant flux density at the canopy top and f_{df} is the fraction of scattered radiation to total radiation. In Eqs. 15 and 16, we assumed that both PAR and NIR are half of $R_s^d(0)$. According to Goudriaan and van Laar



(1994), f_{df} is given as a function of the transmissivity of atmosphere (τ_{atm}) as follows:

$$f_{df} = \begin{cases} 1 & (\tau_{atm} < 0.22) \\ 1 - 6.4(\tau_{atm} - 0.22)^2 & (0.22 \leq \tau_{atm} < 0.35), \\ 1.47 - 1.66\tau_{atm} & (\text{Otherwise}) \end{cases} \quad (17)$$

$$\tau_{atm} = R_s^d(0) \sec(\theta) / R_{ex}, \quad (18)$$

$$R_{ex} = R_{sun}(1 + 0.033) \cos(2\pi(D_{oy}/365)), \quad (19)$$

5 where R_{ex} is the extraterrestrial radiation, R_{sun} is the solar constant, and D_{oy} is the number of days from Jan 1. The equations 15–19 that calculate $D_i^d(0)$ are based on formulations by Goudriaan and van Laar (1994), while the original MATSIRO uses different equations.

The transmissivity of canopies for shortwave radiation (τ_{cs}) is expressed as

$$\tau_{cs} = R_s^d(L) / (R_s^d(0) - R_s^u(0)). \quad (20)$$

10 Here, $R_s^u(0)$ and $R_s^d(L)$ are the radiant flux density for upward shortwave at the canopy top and downward shortwave at the bottom of the canopy, respectively. L denotes the LAI, which is calculated in the CGM (Section 4.4). $R_s^u(0)$ and $R_s^d(L)$ are represented by

$$R_s^u(0) = r_{11}D_1^d(0) + r_{21}D_2^d(0) + r_{12}S_1^d(0) + r_{22}S_2^d(0), \quad (21)$$

$$R_s^d(L) = \tau_{11}D_1^d(0) + \tau_{21}D_2^d(0) + \tau_{12}S_1^d(0) + \tau_{22}S_2^d(0), \quad (22)$$

15 where r_{ij} and τ_{ij} are the canopy reflectivity and transmissivity, respectively, i and j represent wavebands ($i = 1$: PAR; $i = 2$: NIR) and direct ($j = 1$) or scattered radiation ($j = 2$). These are given in Appendix D.

Last, the transmissivity of a canopy for longwave radiation (τ_{cl}) is expressed as

$$\tau_{cl} = \exp(-FLd_f), \quad (23)$$

20 where, d_f is the scattered factor. We set $d_f = \sec(2\pi(53/360))$ from the assumption that scattered radiation income is from a zenith angle of 53° (Watanabe, 1994).

3.3 Bulk transfer coefficient for latent and sensible heat

This module calculates BTCs for latent and sensible heat (C_{Ec} , C_{Ew} , C_{Hc} , and C_{Hw}). The BTCs are used to simulate energy balance (Section 3.1). This module is based on Watanabe (1994), where C_{Ew} , C_{Ec} , C_{Hw} , and C_{Hc} are given by

$$C_{Ew} = \kappa^2 \left[\ln \left(\frac{z_a - d}{z_{Mw}} \right) + \Psi_M(\zeta_w) \right]^{-1} \left[\ln \left(\frac{z_a - d}{z_{Qw}} \right) + \Psi_E(\zeta_w) \right]^{-1}, \quad (24)$$

$$25 \quad C_{Ec} = C_E - C_{Ew}, \quad (25)$$

$$C_{Hw} = \kappa^2 \left[\ln \left(\frac{z_a - d}{z_{Mw}} \right) + \Psi_M(\zeta_w) \right]^{-1} \left[\ln \left(\frac{z_a - d}{z_{Tw}} \right) + \Psi_H(\zeta_w) \right]^{-1}, \quad (26)$$

$$C_{Hc} = C_H - C_{Hw}, \quad (27)$$



where C_E and C_H are the BTCs for latent and sensible heat between the entire surface (canopy + surface water) and atmosphere and are given by

$$C_E = \kappa^2 \left[\ln \left(\frac{z_a - d}{z_M} \right) + \Psi_M(\zeta) \right]^{-1} \left[\ln \left(\frac{z_a - d}{z_Q} \right) + \Psi_E(\zeta) \right]^{-1}, \quad (28)$$

$$C_H = \kappa^2 \left[\ln \left(\frac{z_a - d}{z_M} \right) + \Psi_M(\zeta) \right]^{-1} \left[\ln \left(\frac{z_a - d}{z_T} \right) + \Psi_H(\zeta) \right]^{-1}. \quad (29)$$

- 5 In Eqs. 24 to 29, κ is the Karman constant, d is the zero-plane displacement height, z_a is the reference height at which wind velocity is observed, z_{Mw} , z_{Tw} , z_{Qw} are the roughness lengths that express the effect of surface water on the profiles of momentum, temperature, and specific humidity, respectively, z_M , z_T , and z_Q are the roughness lengths of an entire surface (canopy + surface water) for the profiles of momentum, temperature, and specific humidity, respectively. z_a is a simulation setting parameter (Table 5), and d , z_M , z_T , z_Q , z_{Mw} , z_{Tw} , and z_{Qw} are the functions of crop height and LAI (Appendix E).
- 10 Ψ_M , Ψ_H , and Ψ_E are the diabatic correction factors for momentum, heat, and vapour transport, respectively. The factors are functions of atmospheric stability ζ as follows:

$$\Psi_M(\zeta) = \begin{cases} 6 \ln(1 + \zeta) & (\zeta > 0 : \text{stable}) \\ -1.2 \ln \left[\frac{1 + (1 - 16\zeta)^{1/2}}{2} \right] & (\text{Otherwise: unstable}), \end{cases} \quad (30)$$

$$\Psi_H(\zeta) = \Psi_E(\zeta) = \begin{cases} 6 \ln(1 + \zeta) & (\zeta > 0 : \text{stable}) \\ -2 \ln \left[\frac{1 + (1 - 16\zeta)^{1/2}}{2} \right] & (\text{Otherwise: stable}). \end{cases} \quad (31)$$

- 15 The equations above are adopted from Campbell and Norman (1998), whereas the original MATSRIO model employs different equations. The variable ζ is replaced by either the atmospheric stability between the entire surface and atmosphere (ζ) or the atmospheric stability between surface water and atmosphere (ζ_w). These are given by

$$\zeta = \frac{z_a - d}{L_{MO}}, \quad (32)$$

$$\zeta_w = \frac{z_a - d}{L_{MOw}}, \quad (33)$$

- 20 where L_{MO} and L_{MOw} are the Monin-Obukhov lengths for the exchange between the entire surface and atmosphere and between the surface water and atmosphere, respectively, and are given by

$$L_{MO} = \frac{\Theta_0 C_M^{3/2} U^2}{\kappa g \{ C_{Hw}(T_w - T_a) + C_{Hc}(T_c - T_a) \}}, \quad (34)$$

$$L_{MOw} = \frac{\Theta_0 C_{Mw}^{3/2} U^2}{\kappa g C_{Hw}(T_w - T_a)}, \quad (35)$$

- where g is the gravitational constant, T_w and T_c are the temperatures of the surface water and canopy, Θ_0 is the potential temperature, C_M and C_{Mw} are the BTC for momentum between an entire surface and atmosphere and between water surface and atmosphere, respectively. C_{Mw} in Eq. 35 is introduced according to Maruyama and Kuwagata (2008), while the original



MATSIRO uses C_M . T_w and T_c are calculated in Section 3.1. Θ_0 is given by

$$\Theta_0 = T_a * (1.0 * 10^5 / P_a)^{(R_{dry}/c_{pa})}, \quad (36)$$

where R_{dry} is the gas constant of dry air. Although the original MATSIRO fixes Θ_0 at 300 K, MATCRO calculates the value according to Campbell and Norman (1998). C_M and C_{Mw} are given by

$$5 \quad C_M = k^2 \left[\ln \left(\frac{z_a - d}{z_M} \right) + \Psi_M(\zeta) \right]^{-2}, \quad (37)$$

$$C_{Mw} = k^2 \left[\ln \left(\frac{z_a - d}{z_{Mw}} \right) + \Psi_M(\zeta_w) \right]^{-2}. \quad (38)$$

Now we have six independent equations, Eqs. 24, 25, 26, 27, 37, and 38, for six unknown variables, C_{Ew} , C_{Ec} , C_{Hw} , C_{Hc} , C_M , and C_{Mw} , respectively. Therefore, we can determine the values of these variables by numerically solving Eqs. 24 to 38. The numerical method is described in Masutomi et al. (2016).

10 3.4 Canopy water balance

The main purpose of this module is to calculate the fraction of wet canopy (f_{cw}) which is used for simulating energy balance at canopy (Section 3.1). To calculate f_{cw} , this module calculates water balance at canopy. Although the module is based on the original MATSIRO, the amount of water that canopies can hold was replaced by using the method described in Penning de Vries et al. (1989). The variable f_{cw} is given as

$$15 \quad f_{cw} = w_c / w_{cap}, \quad (39)$$

where w_c is the amount of water stored in canopy and w_{cap} is the water capacity of the canopy. The w_c is calculated by solving the canopy water balance, which is given by

$$\rho_w \frac{dw_c}{dt} = I_c - D_g - E_c, \quad (40)$$

where ρ_w is the density of water, I_c is the amount of precipitation intercepted by canopy, D_g is the amount of water that falls from the canopy onto surface water due to gravity, and E_c is the amount of water that evaporates from the canopy (Eq. 7). I_c depends on the amount of precipitation (P_r) and LAI (L) and is given by

$$I_c = f_{int} P_r, \quad (41)$$

$$f_{int} = \begin{cases} L & (L < 1) \\ 1 & (\text{otherwise}) \end{cases}, \quad (42)$$

where f_{int} indicates the interception efficiency of precipitation by canopy. According to Rutter et al. (1975) and Penning de Vries et al. (1989), D_g and w_{cap} are given as

$$D_g = \rho_w D_1 \exp(D_2 w_c), \quad (43)$$

$$w_{cap} = (W_{sh} * 10^{-4}) / \rho_w, \quad (44)$$



respectively, where D_1 and D_2 are parameters (Rutter et al., 1975), and W_{sh} is the shoot dry weight, which is calculated in the CGM (Eq. 127).

3.5 Soil water and heat transfer

This module calculates heat and water transfer in soil. The main role of this module is to determine the temperature at a soil surface ($T_s(0)$), which is used for simulating energy balance of the surface water (Section 3.1). Although this module is based on the original MATSIRO, the calculations of the surface and base runoffs are simplified because hydrological calculations are not the main purpose of MATCRO-Rice.

Soil temperature at a soil depth of z from the soil surface ($T_s(z)$) is calculated from the gradient of heat flux in the soil as follows:

$$c_{hs}(z) \frac{\partial T_s(z)}{\partial t} = \frac{\partial G_s(z)}{\partial z}, \quad (45)$$

where c_{hs} is the volumetric heat capacity of the soil and $G_s(z)$ is the heat flux at a soil depth of z and is given from the gradient of soil temperature

$$G_s(z) = \begin{cases} k_{ts}(z) \frac{\partial T_s(z)}{\partial z} & (0 \leq z < z_{max}) \\ 0 & (z = z_{max}). \end{cases} \quad (46)$$

Here, k_{ts} is the soil thermal conductivity. In Eq. 46, we assumed that heat flux at the bottom of the soil layer ($z = z_{max}$) is zero. z_{max} is a simulation setting parameter. When solving Eqs. 45 and 46, the heat flux from surface water to soil (G_{ws}), calculated in Eq. 10, is used as a boundary condition. The parameter c_{hs} is calculated from the heat capacities of soil components as follows.

$$c_{hs}(z) = \rho_s c_{pm} + \rho_w c_{pw} w_s(z), \quad (47)$$

where ρ_s is the bulk density of soil, c_{pm} is the specific heat of soil minerals, and $w_s(z)$ is the volumetric concentration of soil water. ρ_s is a soil-type specific parameter determined by soil type at a simulation site, and c_{pm} is given according to Campbell and Norman (1998). We note that the first term of the right hand side in Eq. 47 indicates the heat capacity of dry soil. Although the original MATSIRO model assigns a default value to the heat capacity of dry soil for all soil types, MATCRO-Rice calculates the value of the heat capacity of dry soil using the bulk density of soil and the heat capacity of soil minerals, as shown in the first term of Eq. 47. It should be noted that the effect of soil organic matter on c_{hs} is not considered in MATCRO. The parameter $k_{ts}(z)$ in Eq. 46 is given by

$$k_{ts}(z) = K_e(z)(k_{tss} - k_{ts0}) + k_{ts0}, \quad (48)$$

$$K_e(z) = \begin{cases} \log(w_s(z)/w_{sat}) + 1.0 & (\text{if } w_s(z)/w_{sat} \geq 0), \\ 0 & (\text{otherwise}) \end{cases} \quad (49)$$

where k_{ts0} and k_{tss} are the thermal conductivity of dry and saturated soils, respectively, K_e is the Kersten number, and w_{sat} is the volumetric soil water concentration at saturation. k_{ts0} and k_{tss} are parameters. We set $k_{ts0}=0.25$ (Campbell and Norman,



1998), and $k_{tss} = 1.58$ (Best et al., 2011). The parameter w_{sat} is specific to soil type. Equations 48 and 49 for the calculation of $k_{ts}(z)$ are based on the equations developed by Best et al. (2011), while the original MATSIRO employs a different equation. The variable $w_s(z)$ depends on the gradient of water flux and absorption by roots at a soil depth z and is given by

$$w_s(z) = w_{sat} \quad (0 \leq z \leq z_{sat}), \quad (50)$$

$$5 \quad \frac{\partial w_s(z)}{\partial t} = \frac{\partial F_s(z)}{\partial z} + S_s(z) \quad (z_{sat} < z \leq z_{max}), \quad (51)$$

where $F_s(z)$ and $S_s(z)$ are water flux and absorption by roots at a soil depth of z , respectively. For simplicity, the top soil layer is assumed to be saturated, because the surface above soil is flooded. Given the assumption, we do not need to explicitly simulate water flow from a flooded surface into soil. This assumption is not considered in the original MATSIRO. z_{sat} is a simulation setting parameter. $F_s(z)$ is calculated from the gradient of water potentials as follows.

$$10 \quad F_s(z) = \begin{cases} -K(z) \left(\frac{\partial \psi(z)}{\partial z} + 1 \right) & (0 \leq z \leq z_b) \\ (w_{sat}/\tau_b)(w_s(z)/w_{sat})^2 & (z_b < z \leq z_{max}) \end{cases}, \quad (52)$$

where $K(z)$ is the hydraulic conductivity and $\psi(z)$ is the water potential at a soil depth of z . $F_s(z)$ in the bottommost layer ($z_b < z \leq z_{max}$) represents the base flow, and τ_b is the recession constant for base flow. This model uses a simple model for simulating base flow developed by Hanasaki et al. (2008), although the original MATSIRO utilizes a more complicated model (TOPMODEL: Beven and Kirkby (1979)). z_b is a simulation setting parameter, and τ_b is determined as described in Hanasaki et al. (2008). $K(z)$ and $\psi(z)$ are given by Clapp and Hornberger (1978) as follows.

$$K(z) = K_s \left(\frac{w_s(z)}{w_{sat}} \right)^{2B+3}, \quad (53)$$

$$\psi(z) = \psi_s \left(\frac{w_s(z)}{w_{sat}} \right)^{-B}, \quad (54)$$

where K_s and ψ_s are hydraulic conductivity and water potentials at saturation, respectively, and B is a parameter that determines the relationship of hydraulic conductivity or water potentials between saturated and unsaturated soils. K_s , ψ_s , and B are soil-type specific parameters. $S_s(z)$ in Eq. 51 is calculated from the transpiration

$$S_s(z) = \begin{cases} E_t/(\rho_w z_{rt}) & (0 \leq z \leq z_{rt}) \\ 0 & (z_{rt} < z \leq z_{max}) \end{cases}, \quad (55)$$

where E_t is the transpiration calculated in Eq. 8 and z_{rt} is a root depth calculated by the CGM (Eq. 131). In Eq. 55, we assumed that $S_s(z)$ has no dependency on soil depth.

4 Crop growth model

25 The main purpose of the CGM is to simulate rice yield and biomass growth for each organ during a growing period. The CGM has four modules: "net carbon assimilation", "crop development", "crop growth", and "LAI, height, and root depth". Each module is described in detail in the following sections.



4.1 Net carbon assimilation

The main role of this module is to calculate net carbon assimilation (A_n) in canopy for simulating crop growth. In addition, the stomatal conductance per unit leaf area for both sides of the leave (\bar{g}_s) is calculated for simulating roughness length (Appendix E). Although this module is based on the Big-leaf model (Sellers et al., 1992, 1996a) used in the original MATSIRO, we refined two points in the calculation according to the approach described by de Pury and Farquhar (1997) and Dai et al. (2004). The first refinement is that leaves in a canopy are divided into sunlit and shade leaves. Subsequently, A_n per unit leaf area for each the sunlit and shade leaves are calculated. The second refinement is that A_n for the entire canopy is calculated considering vertical distribution of nitrogen within the canopy.

A_n for the entire canopy is given by

$$10 \quad A_n = \bar{A}_{n,sn}L_{sn} + \bar{A}_{n,sh}L_{sh}, \quad (56)$$

where $\bar{A}_{n,sn}$ and $\bar{A}_{n,sh}$ are net carbon assimilation per unit leaf area for sunlit and shade leaves, respectively, L_{sn} and L_{sh} are LAI for sunlit and shade leaves, respectively, and overbars represent the amounts per unit leaf area. $\bar{A}_{n,sn}$ and $\bar{A}_{n,sh}$ are defined by the difference between gross carbon assimilation and respiration as follows:

$$\bar{A}_{n,x} = \bar{A}_{g,x} - \bar{R}_{d,x}, \quad (57)$$

15 where $\bar{A}_{g,x}$ and $\bar{R}_{d,x}$ are gross carbon assimilation and respiration per unit leaf area, respectively, and the suffix x indicates sn or sh . L_{sn} and L_{sh} are given as follows.

$$L_{sn} = \int_0^L f_{sn}(l)dl, \quad (58)$$

$$L_{sh} = \int_0^L (1 - f_{sn}(l))dl, \quad (59)$$

where $f_{sn}(l)$ is the fraction of sunlit leaves at a LAI depth of l and is defined as follows:

$$20 \quad f_{sn}(l) = \exp(-Fl \sec(\theta)), \quad (60)$$

where F denotes distribution of leaf orientation and θ is a zenith angle of the sun (Appendix B). The effect of photosynthesis down-regulation due to acclimatization to elevated CO_2 is represented as follows:

$$\bar{A}_{g,x} = f_{dwn} * \bar{A}_{g',x}, \quad (61)$$

$$f_{dwn} = \{1 + \gamma_{gd} \ln(C_a/C_0)\} / \{1 + \gamma_g \ln(C_a/C_0)\}, \quad (62)$$

25 where $\bar{A}_{g',x}$ is gross carbon assimilation per unit leaf area for sunlit and shade leaves without photosynthesis down-regulation, f_{dwn} is the factor for photosynthesis down-regulation, γ_{gd} and γ_g are parameters that characterize the response to increased CO_2 , and C_0 is the base concentration of CO_2 . The Eqs. 61 and 62 are based on Arora et al. (2009), although the original MATSIRO does not consider the effect of photosynthesis down-regulation. We set $\gamma_{gd} = 0.42$, $\gamma_g = 0.9$, and $C_0 = 288$ according to



Arora et al. (2009). The calculation for $\bar{A}_{g',x}$ and $\bar{R}_{d,x}$ is based on the leaf photosynthesis model developed by Collatz et al. (1991). In their model, $\bar{A}_{g',x}$ is determined by three limiting factors: Rubisco, light, and sucrose synthesis, as follows:

$$\bar{A}_{g',x} \leq \min(\bar{w}_{c,x}, \bar{w}_{e,x}, \bar{w}_{s,x}), \quad (63)$$

where $\bar{w}_{c,x}$, $\bar{w}_{e,x}$, and $\bar{w}_{s,x}$ are Rubisco-limited, light-limited, and sucrose-limited carbon assimilation per unit leaf area, respectively. To implement smooth transition between each limited state, $\bar{A}_{g',x}$ is determined practically by solving the following two equations (Sellers et al., 1996b):

$$\beta_{ce}\bar{w}_{p,x}^2 - \bar{w}_{p,x}^2(\bar{w}_{c,x}^2 + \bar{w}_{e,x}^2) + \bar{w}_{c,x}^2\bar{w}_{e,x}^2 = 0 \quad (64)$$

$$\beta_{ps}\bar{A}_{g',x}^2 - \bar{A}_{g',x}^2(\bar{w}_{p,x}^2 + \bar{w}_{s,x}^2) + \bar{w}_{p,x}^2\bar{w}_{s,x}^2 = 0, \quad (65)$$

where β_{ce} and β_{pc} are the parameters that determine the smoothness of transition between each limited state. β_{ce} is a crop-specific parameter and β_{pc} is a parameter that does not depend on crop type. The variables $\bar{w}_{c,x}$, $\bar{w}_{e,x}$, and $\bar{w}_{s,x}$ are given by

$$\bar{w}_{c,x} = \bar{V}_{mc,x} \left\{ \frac{c_{i,x} - \Gamma^*}{c_{i,x} + K_c(1 + [O_2]/K_O)} \right\} \quad (66)$$

$$\bar{w}_{e,x} = \epsilon_e \bar{Q}_x \left\{ \frac{c_{i,x} + \Gamma^*}{c_{i,x} + 2\Gamma^*} \right\} \quad (67)$$

$$\bar{w}_{s,x} = \bar{V}_{ms,x}/2. \quad (68)$$

Here, $\bar{V}_{mc,x}$ and $\bar{V}_{ms,x}$ are the maximum Rubisco capacity per unit leaf area for $\bar{w}_{c,x}$ and $\bar{w}_{s,x}$, respectively, $c_{i,x}$ is the partial pressure of intercellular CO₂, [O₂] is the partial pressure of intercellular O₂, \bar{Q}_x is the photon flux density for PAR absorbed per unit leaf area by sunlit and shade leaves, ϵ_e is the quantum efficiency, Γ^* is the light compensation point, and K_c and K_O are the Michaelis constant for CO₂ fixation and oxygen inhibition, respectively. We set [O₂] = 20,900 (Collatz et al., 1991). ϵ_e is a crop specific parameter. $\bar{V}_{mc,x}$ and $\bar{V}_{ms,x}$ are given by

$$\bar{V}_{mc,x} = \bar{V}_{max,x} [2^{Q_t} / \{1 + \exp(s_1(T_c - s_2))\}], \quad (69)$$

$$\bar{V}_{ms,x} = \bar{V}_{max,x} [2^{Q_t} / \{1 + \exp(s_3(s_4 - T_c))\}], \quad (70)$$

where $\bar{V}_{max,x}$ is the reference value for the maximum Rubisco capacity per unit leaf area of sunlit ($\bar{V}_{max,sn}$) and shade ($\bar{V}_{max,sh}$) leaves, s_1 , s_2 , s_3 , and s_4 are parameters that represent temperature dependence of $\bar{V}_{max,x}$ on $\bar{V}_{mc,x}$ or $\bar{V}_{ms,x}$. The variables s_1 and s_2 are parameterised in Masutomi et al. (2016), whereas s_3 is a parameter that does not depend on crop type and s_4 is a crop-specific parameter. Q_t is given by

$$Q_t = (T_c - 298)/10. \quad (71)$$



$\bar{V}_{max,sn}$ and $\bar{V}_{max,sh}$ are defined by

$$\bar{V}_{max,sn} = \left(\int_0^L V_{max}(l) f_{sn}(l) dl \right) / L_{sn}, \quad (72)$$

$$\bar{V}_{max,sh} = \left(\int_0^L V_{max}(l) (1 - f_{sn}(l)) dl \right) / L_{sh}, \quad (73)$$

where $V_{max}(l)$ is the reference value for the maximum Rubisco capacity at a LAI depth of l . The vertical distribution of $V_{max}(l)$ depends on that of leaf nitrogen within canopy and is given by

$$V_{max}(l) = V_{max}(0) \exp(-K_n l), \quad (74)$$

where K_n is a parameter that represents the vertical distribution of leaf nitrogen, and $V_{max}(0)$ is the reference value for the maximum Rubisco capacity at the canopy top. $V_{max}(0)$ as well as s_1 and s_2 are parameterized in Masutomi et al. (2016), and we set $K_n = 0.3$ (Oleson and Lawrence, 2013). Γ^* , K_c , and K_O are given by

$$\Gamma^* = 0.5[O_2]/S, \quad (75)$$

$$K_c = 30 \times 2.1^{Q_t}, \quad (76)$$

$$K_O = 30000 \times 1.2^{Q_t}, \quad (77)$$

$$S = 2600 \times 0.57^{Q_t}, \quad (78)$$

where S is the ratio of the partition of RuBP to the carboxylase or oxygenase reactions of Rubisco.

\bar{Q}_x in Eq. (67) is defined by the following equation:

$$\bar{Q}_x = Q_x / L_x. \quad (79)$$

Here, Q_x is the PAR absorbed by the entire canopy for sunlit (Q_{sn}) and shade (Q_{sh}) leaves. Q_{sn} and Q_{sh} consist of direct and scattered components and are given as

$$Q_{sn} = Q_{sn,d} + Q_{sn,s}, \quad (80)$$

$$Q_{sh} = Q_{sh,s}, \quad (81)$$

where $Q_{sn,d}$, $Q_{sn,s}$, and $Q_{sh,s}$ are the direct PAR absorbed by sunlit leaves, the scattered PAR absorbed by sunlit leaves, and the scattered PAR absorbed by shade leaves, respectively. These are described by

$$Q_{sn,d} = k_q \int_0^L \frac{dD_1^d(l)}{dl} dl, \quad (82)$$

$$Q_{sn,s} = k_q \int_0^L \frac{d(S_1^d(l) - S_1^u(l))}{dl} f_{sn}(l) dl, \quad (83)$$

$$Q_{sh,s} = k_q \int_0^L \frac{d(S_1^d(l) - S_1^u(l))}{dl} (1 - f_{sn}(l)) dl, \quad (84)$$



where $D_1^d(l)$, $S_1^d(l)$, and $S_1^u(l)$ are calculated by the LSM (Eqs. 12 to 14) and k_q is a constant that transfers the radiant flux density to photon flux density.

$\bar{R}_{d,x}$ in Eq. 57 is given by the following equation:

$$\bar{R}_{d,x} = f_d \bar{V}_{max,x} [2^{Q_t} / \{1 + \exp(s_5(T_c - s_6))\}], \quad (85)$$

- 5 where f_d is a respiration factor and crop-specific parameter, whereas s_5 and s_6 are parameters that are not crop-dependent. It should be noted that $\bar{A}_{n,x}$ can be calculated using the equations described in this section (Eqs. 57 to 85) if $c_{i,x}$ is given.

$\bar{A}_{n,x}$ should be equal to the CO₂ flux between the leaf interior and boundary layer and the CO₂ flux between the leaf boundary layer and the atmosphere. If these requirements are fulfilled the following equation can be derived:

$$\bar{A}_{n,x} = (\bar{g}_l / P_a)(c_a - c_{s,x}) / 1.4 = (\bar{g}_{st,x} / P_a)(c_{s,x} - c_{i,x}) / 1.6, \quad (86)$$

- 10 where c_a is the partial pressure of atmospheric CO₂, $c_{s,x}$ is the partial pressure of CO₂ at the leaf boundary layer for sunlit and shade leaves, \bar{g}_l is the leaf boundary conductance for vapour per unit leaf area, and $\bar{g}_{st,x}$ is the stomatal conductance for vapour per unit leaf area for sunlit and shade leaves. From Eq. 86, $c_{i,x}$ and $c_{s,x}$ are defined by

$$c_{i,x} = c_a - (1.4/\bar{g}_l + 1.6/\bar{g}_{st,x})\bar{A}_{n,x}P_a, \quad (87)$$

$$c_{s,x} = c_a - 1.4\bar{A}_{n,x}P_a/\bar{g}_l. \quad (88)$$

- 15 The parameters c_a and \bar{g}_l are given by

$$c_a = (C_a * 10^{-6})P_a, \quad (89)$$

$$\bar{g}_l = (\bar{g}_a/2) * P_a / (T_c R_{vap} \omega_{H_2O}), \quad (90)$$

$$\bar{g}_a = c_h U_c. \quad (91)$$

- where w_{H_2O} is a constant for the molar weight of vapour, \bar{g}_a is the leaf boundary conductance for heat per unit leaf area (for both sides of the leaf), c_h is the leaf transfer coefficient for heat and is a crop specific parameter, U_c is the mean wind speed in the canopy (Appendix F). Note that Eqs. 90 and 91 are based on Maruyama and Kuwagata (2008), whereas the original MATSIRO uses C_h instead of $\bar{g}_a/2$ in Eq. 90.

$\bar{A}_{n,x}$ meets the Ball-Berry relationship (Ball, 1988), which describes the relationship between $\bar{A}_{n,x}$, $\bar{g}_{st,x}$, and other environmental conditions. The Ball-Berry relationship is given by

$$25 \quad \bar{g}_{st,x} = \begin{cases} m \frac{\bar{A}_{n,x} P_a}{c_{s,x}} h_{s,x} + b & (\text{if } \bar{A}_{n,x} > 0), \\ b & (\text{otherwise}) \end{cases} \quad (92)$$

where m and b are the slope and intercept of the Ball-Berry relationship, and $h_{s,x}$ is the relative humidity at leaf boundary. It is noteworthy that b indicates the stomatal conductance when $\bar{A}_{n,x}$ is equal to or less than zero (Baldocchi, 1994) and that the effect of water stress on b is not considered in MATCRO-Rice because the surface is flooded. The variables m and b are crop specific parameters, and $h_{s,x}$ is defined by

$$30 \quad h_{s,x} = e_{s,x} / e_{sat}(T_c, P_a), \quad (93)$$



where $e_{s,x}$ is the vapour pressure at leaf boundary and e_{sat} is the saturated vapour pressure. The variable $e_{s,x}$ is expressed as

$$e_{s,x} = (e_a \bar{g}_l + e_i \bar{g}_{st,x}) / (\bar{g}_l + \bar{g}_{st,x}), \quad (94)$$

where e_a and e_i are the vapour pressure in the air and leaf, respectively. Eq. 94 is derived from the fact that the water vapour flux from the stomata to leaf surface is equal to the water vapour flux from the leaf surface into the atmosphere, which is shown

5 in the following equation:

$$\bar{g}_{st,x}(e_i - e_s) = \bar{g}_l(e_{s,x} - e_a). \quad (95)$$

The parameters e_a , e_i , and e_{sat} are given by

$$e_a = Q(R_{dry}/R_{vap}), \quad (96)$$

$$e_i = e_{sat}(T_c, P_a), \quad (97)$$

$$10 \quad e_{sat}(T_c, P_a) = Q_{sat}(T_c, P_a)(R_{dry}/R_{vap}), \quad (98)$$

where e_i is assumed to be saturated.

Now we have three relationships (Eqs. 57 to 85, Eq. 87, and Eq. 92) in terms of three unknown variables ($\bar{A}_{n,x}$, $c_{i,x}$, and $\bar{g}_{st,x}$). Therefore, we can determine the values for $\bar{A}_{n,x}$, $c_{i,x}$, and $\bar{g}_{st,x}$, by numerically solving the three relationships. The numerical method is described in Masutomi et al. (2016).

15 Last, \bar{g}_s is given by the following equation:

$$\bar{g}_s = \bar{g}_{st} * (T_c R_{vap} w_{H_2O} / P_a), \quad (99)$$

$$\bar{g}_{st} = \{(\bar{g}_{st,sn} * L_{sn} + \bar{g}_{st,sh} * L_{sh}) / L\} * 2, \quad (100)$$

where \bar{g}_{st} is the stomatal conductance for vapour per unit leaf area for both sides of the leaf.

4.2 Crop development

20 The crop development module calculates DVS , which is an index used to quantify developmental stage of crops. DVS is mainly used for determining the timing of transplanting, heading, and harvesting. In addition, DVS is used for partitioning of carbon assimilation into each organ and for estimating LAI and height. This module is based on the formulation by Bouman et al. (2001). DVS is calculated from

$$DVS = GDS/mGDS, \quad (101)$$

$$25 \quad GDS = \int_0^t DVR dt', \quad (102)$$

$$DVR = \begin{cases} 0 & (T_a < T_b | T_h \leq T_a) \\ T_a - T_o & (T_b \leq T_a < T_o) \\ (T_o - T_b)(T_h - T_a) / (T_h - T_o) & (T_o \leq T_a < T_h) \end{cases}, \quad (103)$$



where GDS is the growing degree seconds at t , $mGDS$ is GDS required until maturation, DVR is the development rate at t , T_0 is the melting temperature of water, and T_b , T_h , and T_o are the minimum temperature, maximum temperature, and optimal temperature for development, respectively. The value of $mGDS$ is parameterized in Masutomi et al. (2016), and T_b , T_h , and T_o are crop-specific parameters. T_0 is a physical constant (Table 4). It should be noted that $DVS = 0$ represents sowing and $DVS = 1$ represents maturation. Furthermore, we introduce two parameters that represent the timing of emergence ($eDVS$) and heading ($hDVS$). Both $eDVS$ and $hDVS$ are crop-specific parameters. The values of $eDVS$ and $hDVS$ are parameterized in Masutomi et al. (2016).

During the transplantation of rice seedling, the seedlings enter transplanting shock, which prevents shoot growth (Bouman et al., 2001). In MATCRO-Rice, the transplanting shock period is defined by DVS , where $trDVS$ is DVS at the time when transplanting shock starts and $teDVS$ is DVS at which transplanting shock ends. Both $trDVS$ and $teDVS$ are parameterized in Masutomi et al. (2016).

4.3 Crop growth

This module calculates the growth of organs and reserves. The organs considered in MATCRO-Rice include leaf, stem, panicle, and root. In addition, the model considers glucose reserves in leaves and starch reserves in stem. All carbon assimilated in leaves through photosynthesis is first stored in leaf in the form of glucose. Then, the stored glucose is partitioned to each organ and stored in the stem when the amount of the stored glucose exceeds the critical rate to dry weight of leaf. This module is based on MACROS (Penning de Vries et al., 1989).

The dry weights of each organ and reserve are expressed by

$$W_{lef} = W_{lef,0} + \int_{t_e}^t (G_{R,lef} - L_{S,lef}) dt', \quad (104)$$

$$W_{stm} = W_{stm,0} + \int_{t_e}^t G_{R,stm} dt', \quad (105)$$

$$W_{pnc} = \int_{t_e}^t G_{R,pnc} dt' \quad (106)$$

$$W_{rot} = W_{rot,0} + \int_{t_e}^t G_{R,rot} dt', \quad (107)$$

$$W_{stc} = \int_{t_e}^t (G_{R,stc} - R_{M,stc}) dt', \quad (108)$$

$$W_{glu} = W_{glu,0} + \int_{t_e}^t G_{R,glu} dt', \quad (109)$$



where W_{lef} , W_{stm} , W_{pnc} , W_{rot} , W_{stc} , W_{glu} are the dry weight of leaves, stems, panicles, roots, starch reserves, and glucose reserves at t , respectively, $W_{lef,0}$, $W_{stm,0}$, $W_{rot,0}$, and $W_{glu,0}$ represent the initial dry weight at emergence of each organ and reserve, $G_{R,lef}$, $G_{R,stm}$, $G_{R,pnc}$, $G_{R,rot}$, $G_{R,stc}$, and $G_{R,glu}$ are the growth rates of the corresponding organ and reserve, $L_{S,lef}$ is the loss rate of leaves due to leaf death, $R_{M,stc}$ is the loss rate of starch reserves in stem due to remobilization, t_e is the time at emergence after sowing, and $W_{lef,0}$, $W_{stm,0}$, $W_{rot,0}$, and $W_{glu,0}$ are simulation setting parameters.

The glucose reserve in leaf is supplied through photosynthesis in leaves and remobilization from the stem. Thus, the supply of glucose is given by

$$S_{glu} = A_n C_{CO_2,glu} + R_{M,stc} C_{stc,glu}, \quad (110)$$

where, S_{glu} is the supply of glucose to leaf reserve, A_n is the net carbon assimilation calculated in Eq. 56, and $C_{CO_2,glu}$ and $C_{stc,glu}$ are the conversion factors from CO_2 or starch to glucose, which are chemically determined (Table 4). We assumed that the partition of glucose in leaves to each organ occurs if the following equation is met:

$$W_{glu} + S_{glu} \delta t > k_{glu} W_{lef}, \quad (111)$$

where δt is one simulation time step, k_{glu} is the critical ratio at which the partition of glucose happens, and δt is a simulation setting parameter. We set $k_{glu} = 0.1$ (Penning de Vries et al., 1989). When Eq. 111 is met, the amount of glucose that exceeds the critical ratio is partitioned to each organ and reserve according to the following equation:

$$G_{P,glu} = (W_{glu} + S_{glu} \delta t - k_{glu} W_{lef}) / \delta t, \quad (112)$$

where $G_{P,glu}$ is the amount of glucose partitioned to each organ and reserve. The growth rate of each organ and reserve is expressed as follows:

$$G_{R,lef} = G_{P,glu} P_{R,sh} P_{R,lef} C_{glu,lef}, \quad (113)$$

$$G_{R,stm} = G_{P,glu} P_{R,sh} (1 - P_{R,lef} - P_{R,pnc}) (1 - f_{stc}) C_{glu,stm}, \quad (114)$$

$$G_{R,pnc} = G_{P,glu} P_{R,sh} P_{R,pnc} C_{glu,pnc}, \quad (115)$$

$$G_{R,rot} = G_{P,glu} (1 - P_{R,sh}) C_{glu,rot}, \quad (116)$$

$$G_{R,stc} = G_{P,glu} P_{R,sh} (1 - P_{R,lef} - P_{R,pnc}) f_{stc} C_{glu,stc}, \quad (117)$$

$$G_{R,glu} = (k_{glu} W_{lef} - W_{glu}) / \delta t, \quad (118)$$

where $P_{R,sh}$ is the ratio of glucose partitioned to shoot, $P_{R,lef}$ and $P_{R,pnc}$ are the partition ratios of glucose from shoot to leaf and panicle, f_{stc} is the proportion of glucose allocated to starch reserve in stem, $C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, $C_{glu,pnc}$, and $C_{glu,stc}$ are dry weight of corresponding organs and reserves that are produced from the unit weight of glucose. f_{stc} , $C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, and $C_{glu,pnc}$ are crop-specific parameters. f_{stc} is parameterized in Masutomi et al. (2016). We set the values of $C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, and $C_{glu,pnc}$ according to Penning de Vries et al. (1989). $C_{glu,stc}$ is a chemical constant. If Eq. 111 is not met, glucose is not partitioned into each organ and reserve, except as the glucose reserve in leaf.



Therefore, the growth rate of each organ and reserve are calculated as follows:

$$G_{R,lef} = G_{R,stm} = G_{R,rot} = G_{R,pnc} = G_{R,stc} = 0 \quad (119)$$

$$G_{R,glu} = S_{glu}. \quad (120)$$

The partition ratios to each organ are given as

$$5 \quad P_{R,sh} = \begin{cases} 1 - P_{rot} & (DVS \leq trDVS) \\ 0 & (trDVS < DVS \leq teDVS) \\ 1 - P_{rot} & (teDVS < DVS \leq DVS_{rot1}) \\ \frac{1 - P_{rot}(DVS_{rot1} - DVS)}{(DVS_{rot2} - DVS_{rot1})} & (DVS_{rot1} < DVS \leq DVS_{rot2}) \\ 1 & (\text{Otherwise}) \end{cases} \quad (121)$$

$$P_{R,lef} = \begin{cases} P_{lef} & (DVS \leq DVS_{lef1}) \\ \frac{P_{lef}(DVS_{lef2} - DVS)}{(DVS_{lef2} - DVS_{lef1})} & (DVS_{lef1} < DVS \leq DVS_{lef2}), \\ 0 & (\text{Otherwise}) \end{cases} \quad (122)$$

$$P_{R,pnc} = \begin{cases} 0 & (DVS \leq DVS_{pnc1}) \\ \frac{(DVS - DVS_{pnc1})}{(DVS_{pnc2} - DVS_{pnc1})} & (DVS_{pnc1} < DVS \leq DVS_{pnc2}), \\ 1 & (\text{Otherwise}) \end{cases} \quad (123)$$

10 where DVS_{rot1} , DVS_{rot2} , DVS_{lef1} , DVS_{lef2} , DVS_{pnc1} , and DVS_{pnc2} represent the DVS values at which corresponding partitions change, P_{rot} is the ratio of partitioned glucose to the roots at $DVS < DVS_{rot1}$, and P_{lef} is the ratio of glucose partitioned to the leaf and glucose partitioned to shoot at $DVS < DVS_{lef}$. DVS_{rot1} , DVS_{rot2} , DVS_{lef1} , DVS_{lef2} , DVS_{pnc1} , DVS_{pnc2} , P_{rot} , and P_{lef} are crop-specific parameters and are parameterized in Masutomi et al. (2016). In Eq. 121, we assume that no glucose is partitioned to shoot during transplanting shock ($teDVS < DVS \leq teDVS$). It is important to note that
 15 transplanting shock is considered only when transplanting is conducted.

Loss of leaf dry weight due to leaf death ($L_{S,lef}$) and remobilization from starch reserve in stem ($R_{M,stm}$) occur after heading and they are defined as follows

$$L_{S,lef} = \begin{cases} 0 & (DVS \leq hDVS), \\ r_{dd,lef}(W_{lef} + W_{glu}) & (\text{Otherwise}) \end{cases} \quad (124)$$

$$R_{M,stm} = \begin{cases} 0 & (DVS \leq hDVS), \\ r_{rm,stm}W_{stc} & (\text{Otherwise}) \end{cases} \quad (125)$$



where $r_{dd,lef}$ and $r_{rm,stc}$ represent the ratios of leaf death and remobilization. $r_{dd,lef}$ varies with DVS as follow:

$$r_{dd,lef} = r_{d1,lef}(DVS - hDVS)/(1 - hDVS) \quad (126)$$

where $r_{d1,lef}$ is the ratio of leaf death at harvest ($DVS = 1$) and it is parameterized in Masutomi et al. (2016). We set $r_{rm,stc} = 1.16 * 10^{-6}$, assuming that all starch stored in stem is remobilized in 10 days after heading (Bouman et al., 2001).

5 Last, the dry weight of shoot (W_{sh}), used in Section 3.4, is given by

$$W_{sh} = W_{lef} + W_{stm} + W_{pnc} + W_{stc} + W_{glu}. \quad (127)$$

4.4 LAI, crop height, and root depth

Leaf area index (L), crop height (h_{gt}), and root depth (z_{rt}) are expressed as

$$L = (W_{lef} + W_{glu})/SLW, \quad (128)$$

$$10 \quad SLW = SLW_{mx} + (SLW_{mn} - SLW_{mx}) \exp(-k_{SLW}DVS), \quad (129)$$

$$h_{gt} = \begin{cases} h_{gt,aa}L^{h_{gt,ab}} & (DVS < hDVS), \\ h_{gt,ba}L^{h_{gt,bb}} & (hDVS < DVS) \end{cases} \quad (130)$$

$$z_{rt} = \min\{z_{rt,mx}, r_{rt}(t - t_e)\}, \quad (131)$$

15 where SLW is the specific leaf weight, SLW_{mx} and SLW_{mn} are the maximum and minimum values of specific leaf weight, respectively, k_{SLW} is a parameter that determines the relationship between DVS and specific leaf weight, $h_{gt,aa}$, $h_{gt,ab}$, $h_{gt,ba}$, and $h_{gt,bb}$ are parameters that define the relationship between LAI and crop height, $z_{rt,mx}$ is the maximum root depth, and r_{rt} is the root growth rate. The allometric equations for estimating crop height (Eq. 130) is based on Maruyama and Kuwagata (2010). SLW_{mx} , SLW_{mn} , k_{SLW} , $h_{gt,aa}$, $h_{gt,ab}$, $h_{gt,ba}$, and $h_{gt,bb}$ are crop-specific parameters; they are parameterized in Masutomi et al. (2016). $z_{rt,mx}$ and r_{rt} are also crop-specific parameters, and they are set to $z_{rt,mx} = 0.3$ and $r_{rt} = 1.16 * 10^{-7}$ ($= 0.01$ m day⁻¹) (Penning de Vries et al., 1989).

4.5 Crop yield

Crop yield is calculated from dry weight of the panicle at maturity as follows:

$$Yld = k_{yld}W_{pnc,mt}, \quad (132)$$

25 where Yld is the crop yield, $W_{pnc,mt}$ is the dry weight of the panicle at maturity, k_{yld} is the ratio of the crop yield to $W_{pnc,mt}$. The variable k_{yld} is a crop specific parameter and it is parameterized in Masutomi et al. (2016).



5 Concluding remarks

We developed a new LSM-CGM combined model for paddy rice fields called MATCRO-Rice, which is fully described in the present paper. MATCRO-Rice has two features: (i) The model can consistently simulate LHF, SHF, biomass growth for each organ, and crop yield by exchanging variables listed in Table 2; (ii) The model considers water surface in paddy rice fields.

5 According to our literature survey, MATCRO-Rice is the first LSM-CGM combined model for rice that employs these two features.

The first feature enables us to apply the model to a wide range of integrated issues. For example, by using MATCRO-Rice, we can assess the impacts of paddy rice fields on climate through heat and water fluxes and consistently assess the impacts of climate on rice productivity. Osborne et al. (2009) showed that the interaction between agricultural land and climate can
10 play an important role in the annual variability of both the climate and crop yield. MATCRO-Rice can investigate the impact of the interactions at paddy rice fields on climate and rice productivity. MATCRO-Rice can be a useful tool for addressing the integrated issues of agriculture and hydrology.

MATCRO-Rice can be also applied to simultaneously assess the climate change impacts on rice productivity and hydro-
15 logical cycle in paddy rice fields. Masutomi et al. (2009) showed that climate change will have significant impact on rice productivity across Asia. In addition, agricultural land is one of the key players in global hydrological cycle, and climate change will alter globally the hydrological cycle (Oki and Kanae, 2006).

The first feature also gives us a chance to comprehensively evaluate the model with observations (Lei et al., 2010). Model evaluation is described in the companion paper (Masutomi et al., 2016).

The current version (Ver. 1) of MATCRO-Rice has a couple of major limitations. First, nitrogen dynamics is not included in
20 MATCRO-Rice, although it is well known that nitrogen stress significantly affects crop growth, and hence LHF and SHF. This indicates that MATCRO-Rice simulates LHF, SHF, biomass growth, and crop yield with no nitrogen stress. To apply the model to the site with nitrogen stress, it is necessary to include nitrogen dynamics. This feature is an important future challenge.

Second, the impact of water stress on crop growth is not considered in MATCRO. This limitation is not considered a problem in irrigated land but in rain-fed land. If the model is applied in rain-fed lands, the model needs to be improved.

25 6 Code availability

The source code of MATCRO will be distributed at request to the corresponding author (Yuji Masutomi: yuji.masutomi@gmail.com). The website for MATCRO-Rice will be developed in the near future.



Appendix A: ρ_a and Q_{sat}

The air density (ρ_a) and the specific humidity at saturation (Q_{sat}) are calculated physically according to the equation for the state of dry air and the Clausius-Clapeyron equation, respectively, as follow:

$$\rho_a = P_a / (R_{dry} T_a), \quad (A1)$$

$$5 \quad Q_{sat}(T_x, P_a) = (R_{dry} / R_{vap}) \{ e_{sat}(T_0) \exp((\lambda / R_{vap})(1/T_0 - 1/T_x)) \} / P_a, \quad (A2)$$

where T_a is air temperature, P_a is air pressure, T_x is temperature of the canopy (T_c) or surface water (T_w), T_0 is the melting temperature of the water, R_{dry} and R_{vap} are the gas constants of the dry air and vapour, respectively, $e_{sat}(T_0)$ is the vapour pressure at melting temperature of the water, and λ is the latent heat of vaporisation. T_a and P_a are meteorological inputs (Table 1). T_x (T_c or T_w) is calculated in Section 3.1. The other parameters are physical constants (Table 4).

10 Appendix B: Zenith angle θ

According to Goudriaan and van Laar (1994), zenith angle of the sun (θ) is calculated as follows.

$$\cos(\theta) = \sin(2\pi L_t / 360) \sin(\delta_s) + \cos(2\pi L_t / 360) \cos(\delta_s) \cos(h_{arg}), \quad (B1)$$

$$\delta_s = -\arcsin(\sin(23.45(2\pi/360)) \cos(2\pi(D_{oy} + 10)/365)), \quad (B2)$$

$$h_{arg} = 2\pi(h_r - 12)/24, \quad (B3)$$

15 where L_t is the latitude in radians at the simulation site, δ_s is the declination of the sun, h_{arg} is the hour angle from noon ($h_r = 12$), D_{oy} is the number of days from Jan 1 at the simulation site, and h_r is the local time at the simulation site.



Appendix C: Coefficients for radiation equations

The coefficients for radiation equations (Eqs. 12–14) are calculated as follows:

$$a_i = F d_f \{(1 - t_i)^2 - r_i^2\}^{1/2}, \quad (C1)$$

$$C_{1,i} = \{-(A_{2,i} - r_g)(S_i^d(0) - C_{3,i}D_i^d(0)) \exp(-a_i L) + (C_{3,i}r_g + r_g - C_{4,i})D_i^d(0) \exp(-FL \sec(\theta))\} / A_{3,i}, \quad (C2)$$

$$C_{2,i} = \{(A_{1,i} - r_g)(S_i^d(0) - C_{3,i}D_i^d(0)) \exp(a_i L) - (C_{3,i}r_g + r_g - C_{4,i})D_i^d(0) \exp(-FL \sec(\theta))\} / A_{3,i}, \quad (C3)$$

$$C_{3,i} = \sec(\theta) \{t_i \sec(\theta) + d_f t_i (1 - t_i) + d_f r_i^2\} / \{d_f^2 ((1 - t_i)^2 - r_i^2) - \sec^2(\theta)\}, \quad (C4)$$

$$C_{4,i} = \{r_i (d_f - \sec(\theta)) \sec(\theta)\} / \{d_f^2 ((1 - t_i)^2 - r_i^2) - \sec^2(\theta)\}, \quad (C5)$$

$$A_{1,i} = (1 - t_i + \{(1 - t_i)^2 - r_i^2\}^{1/2}) / r_i, \quad (C6)$$

$$A_{2,i} = (1 - t_i - \{(1 - t_i)^2 - r_i^2\}^{1/2}) / r_i, \quad (C7)$$

$$A_{3,i} = (A_{1,i} - r_g) \exp(a_i L) - (A_{2,i} - r_g) \exp(-a_i L), \quad (C8)$$

where i indicates the wavebands of radiation ($i = 1$: PAR; $i = 2$: NIR), r_i and t_i are the leaf reflectivity and transmissivity, respectively, F is the distribution of leaf orientation, d_f is a scattering factor, $A_{3,i}$ is a new variable introduced in Eqs. C2 and C3, L is the LAI, r_g is the surface albedo for shortwave radiation, $D_i^d(0)$ and $S_i^d(0)$ are direct and scattered downward radiant flux density at the canopy top, respectively, and θ is the zenith angle of the sun. r_i and t_i are crop-specific parameters determined by Sellers et al. (1996b). F is set to 0.5 from the assumption of random leaf orientation (Goudriaan and van Laar, 1994), and d_f is $\sec(2\pi(53/360))$ (Watanabe and Ohtani, 1995). $A_{3,i}$ is defined in Eq. C8, L is calculated in the CGM (Eq. 128), and r_g for surface water is given in Maruyama and Kuwagata (2010). $D_i^d(0)$ and $S_i^d(0)$ are given in Eqs. 15 and 16, respectively, and θ is calculated in B1.

It should be noted that a_i , $A_{1,i}$, and $A_{2,i}$ are not variables determined by constant parameters, while $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, and $A_{3,i}$ are variables.

Appendix D: Reflectivity and transmissivity of canopies

Reflectivity (r_{ij}) and transmissivity (τ_{ij}) of canopy for each waveband ($i = 1$: PAR, $i = 2$: NIR) and for each direction ($j = 1$: direct, $j = 2$: scattered) are given as follows.

$$r_{i1} = C_{4,i} - C_{3,i}r_{i2}, \quad (D1)$$

$$r_{i2} = (A_{1,i}C_{1,i} + A_{2,i}C_{2,i}) / (C_{1,i} + C_{2,i}), \quad (D2)$$

$$\tau_{i1} = (1 + C_{3,i} - C_{4,i} \exp(-FL \sec(\theta))) - C_{3,i}\tau_{i2}, \quad (D3)$$

$$\tau_{i2} = \{(C_{1,i}(1 - A_{1,i}) \exp(a_i L)) + C_{2,i}(1 - A_{2,i} \exp(-a_i L))\} / (C_{1,i} + C_{2,i}), \quad (D4)$$



where a_i , $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, $A_{1,i}$, and $A_{2,i}$, the coefficients of radiation equations (Eqs. 12–14), are calculated as shown in Appendix C, F is a parameter that defines the distribution of leaf orientation, L is the LAI, which is calculated in the CGM (Eq. 128), and θ is the zenith angle of the sun (Appendix B).

Appendix E: d , z_M , z_T , z_Q , z_{Mw} , z_{Tw} , and z_{Qw}

- 5 Zero-plane displacement height (d), roughness lengths of an entire surface for the profiles of momentum, temperature, and specific humidity (z_M , z_T , and z_Q), and roughness lengths that express the effect of surface water on the profiles of momentum, temperature, and specific humidity (z_{Mw} , z_{Tw} , and z_{Qw}) are calculated according to Watanabe (1994) as follows.

$$d = h_{gt} \left[1 - \frac{1}{A^+} \{1 - \exp(-A^+)\} \right], \quad (\text{E1})$$

$$\left(\ln \frac{h_{gt} - d}{z_M} \right)^{-1} = \left\{ 1 - \exp(-A^+) + \left(-\ln \frac{z_{Ms}}{h_{gt}} \right)^{-1/0.45} \exp(-2A^+) \right\}^{0.45}, \quad (\text{E2})$$

$$10 \left(\ln \frac{h_{gt} - d}{z_M} \right)^{-1} \left(\ln \frac{h_{gt} - d}{z_X} \right)^{-1} = C_X^\infty \left\{ 1 - \exp(-P_{3X}A^+) + \left(\frac{C_X^0}{C_X^\infty} \right)^{1/0.9} \exp(-P_{4X}A^+) \right\}^{0.9}, \quad (\text{E3})$$

$$\left(\ln \frac{h_{gt} - d}{z_{Mw}} \right)^2 = \left(\ln \frac{h_{gt} - d}{z_M} \right) \left(\ln \frac{h_{gt} - d}{z_M^+} \right), \quad (\text{E4})$$

$$\left(\ln \frac{h_{gt} - d}{z_{Mw}} \right) \left(\ln \frac{h_{gt} - d}{z_{Xw}} \right) = \left(\ln \frac{h_{gt} - d}{z_M} \right) \left(\ln \frac{h_{gt} - d}{z_X^+} \right), \quad (\text{E5})$$

$$A^+ = \frac{c_m L}{2k^2}, \quad (\text{E6})$$

$$C_X^0 = \left(\ln \frac{h_{gt} - d}{z_M} \right)^{-1} \left(\ln \frac{h_{gt} - d}{z_X^+} \right)^{-1}, \quad (\text{E7})$$

$$15 C_X^\infty = \frac{-1 + (1 + 8F_X)^{0.5}}{2}, \quad (\text{E8})$$

$$F_X = \frac{c_X}{c_m}, \quad (\text{E9})$$

$$\left(\ln \frac{h_{gt} - d}{z_*^+} \right)^{-1} = \frac{1}{-\ln \left(\frac{z_{*s}}{h_{gt}} \right)} \left(\frac{P_{1*}}{P_{1*} + A^+ \exp(A^+)} \right)^{P_{2*}}, \quad (\text{E10})$$

$$P_{1*} = 0.00115 \left(\frac{z_{*s}}{h_{gt}} \right)^{0.1} \exp \left\{ 5 \left(\frac{z_{*s}}{h_{gt}} \right) \right\}, \quad (\text{E11})$$

$$P_{2*} = 0.55 \exp \left\{ -0.58 \left(\frac{z_{*s}}{h_{gt}} \right)^{0.35} \right\}, \quad (\text{E12})$$

$$20 P_{3X} = \{F_X + 0.084 \exp(-15F_X)\}^{0.15}, \quad (\text{E13})$$

$$P_{4X} = 2F_X^{1.1}, \quad (\text{E14})$$

$$c_e = c_h / (1 + c_h (U_c / \bar{g}_s)). \quad (\text{E15})$$



Here, z_{Ms} , z_{Ts} , and z_{Qs} are the roughness lengths of surface water for momentum, temperature, and specific humidity, respectively. In this model, we assume z_{Ms} , z_{Ts} , and $z_{Qs} = 0.001$ m (Kimura and Kondo, 1998). c_m , c_h , and c_e are the leaf transfer coefficients for momentum, temperature, and specific humidity, respectively. c_m and c_h are crop-specific parameters, while c_e is calculated in Eq. E15. h_{gt} and L are crop height and LAI, respectively, and are calculated in the CGM (Eqs. 130 and 128). \bar{g}_s is the stomatal conductance per unit leaf area for both sides of the leaf (Eq. 99). U_c is the mean wind speed in the canopy and is calculated in Appendix F. A^+ , C_X^0 , C_X^∞ , z_M^+ , z_X^+ , z_*^+ , P_{1*} , P_{2*} , P_{3X} , P_{4X} , F_X are the intermediate variables, and κ is the Karman constant. The symbol "*" indicates "M", "T", or "Q", and the symbol "X" indicates "T" or "Q".

Appendix F: Mean wind speed in the canopy

Mean wind speed in the canopy (U_c) is expressed as

$$10 \quad U_c = (U_h / \gamma_m h_{gt}) * \{1 - \exp(-\gamma_m h_{gt})\}, \quad (F1)$$

$$U_h = U / (1 + \ln((z_a - h_{gt}) + 1)), \quad (F2)$$

$$\gamma_m = c_m (L / h_{gt}) / (2k^2), \quad (F3)$$

where U_h is the reference wind speed, and γ_m is the coefficient of exponential decrease for wind speed in the canopy.

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Table 1. Meteorological inputs

Variable	Unit	Description
P_a	Pa	Air pressure
P_r	$\text{kg m}^{-2} \text{s}^{-1}$	Precipitation
Q	kg kg^{-1}	Specific humidity
$R_s^d(0)$	W m^{-2}	Downward shortwave radiant flux density at the canopy top
$R_l^d(0)$	W m^{-2}	Downward longwave radiant flux density at the canopy top
T_a	K	Air temperature
U	m s^{-1}	Wind speed

Table 2. Variables exchanged between the land surface model (LSM) and crop growth model (CGM)

Variable	Unit	Description
LSM to CGM		
$R_1^d(l)$	W m^{-2}	direct downward radiant flux density for photosynthesis active radiation (PAR) at a leaf area index (LAI) depth of l
$S_1^d(l)$	W m^{-2}	scattered downward radiant flux density for PAR at a LAI depth of l
$S_1^u(l)$	W m^{-2}	scattered upward radiant flux density for PAR at a LAI depth of l
T_c	K	canopy temperature
CGM to LSM		
\bar{g}_s	m s^{-1}	stomatal conductance per unit leaf area for both sides of the leaf
h_{gt}	m	canopy height
L	$\text{m}^2 \text{m}^{-2}$	LAI
W_{sh}	kg ha^{-1}	dry matter weight of shoot
z_{rt}	m	root depth



Table 3: Variables

Symbol	Units	Eq.	Description
$\bar{A}_{g,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	61	gross primary production per unit leaf area of sunlit ($\bar{A}_{g,sn}$) and shade ($\bar{A}_{g,sh}$) leaves
$\bar{A}'_{g',x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	65	gross primary production without photosynthesis down-regulation per unit leaf area of sunlit ($\bar{A}'_{g',sn}$) and shade ($\bar{A}'_{g',sh}$) leaves
A_n	$\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$	56	net carbon assimilation
$\bar{A}_{n,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	57	net carbon assimilation per unit leaf area of sunlit ($\bar{A}_{n,sn}$) and shade ($\bar{A}_{n,sh}$) leaves
$A_{\beta,i}$	-	C8	variable for the calculation of coefficients of radiation equations (Eqs. C2 and C3)
A^+	-	E6	intermediate variable for the calculation of roughness
C_E	-	28	BTC for latent heat between the entire surface and atmosphere
C_{Ec}	-	25	bulk transfer coefficients (BTC) for latent heat between canopy and atmosphere
C_{Ew}	-	24	BTC for latent heat between surface water and atmosphere
C_{Hc}	-	27	BTC for sensible heat between canopy and atmosphere
C_{Hw}	-	26	BTC for sensible heat between surface water and atmosphere
C_M	-	37	BTC for momentum between the entire surface and atmosphere
C_{Mw}	-	38	BTC for momentum between surface water and atmosphere
$C_{x,i}$	-	C2 to C5	coefficients of radiation equations (Eqs. 12–14; $x = 1, 2, 3, 4$)
C_X^0	-	E7	intermediate variable for the calculation of roughness (X denotes "T" or "Q")
C_X^∞	-	E8	intermediate parameter for the calculation of roughness (X denotes "T" or "Q")
c_a	Pa	89	partial pressure of atmospheric CO_2
c_e	-	E15	leaf transfer coefficient for specific humidity
$c_{hs}(z)$	$\text{J m}^{-3} \text{ K}^{-1}$	47	volumetric heat capacity of soil at a depth of z
$c_{i,x}$	Pa	57 to 98	partial pressure of intercellular CO_2
$c_{s,x}$	Pa	88	partial pressure of CO_2 at leaf boundary
$D_i^d(l)$	W m^{-2}	12	radiant flux density for downward direct radiation for photosynthesis active radiation (PAR) ($i = 1$) or near infrared radiation (NIR) ($i = 2$) at a leaf area index (LAI) depth of l
D_g	$\text{kg m}^{-2} \text{ s}^{-1}$	43	amount of water that falls from canopy onto surface water due to gravity
D_{oy}	day	-	the number of days from Jan 1
DVR	K	103	development rate at t
DVS	-	101	development stage at t
d	m	E1	zero-plane displacement height
E_c	$\text{kg m}^{-2} \text{ s}^{-1}$	7	evaporation from canopy
E_t	$\text{kg m}^{-2} \text{ s}^{-1}$	8	transpiration from canopy
E_w	$\text{kg m}^{-2} \text{ s}^{-1}$	9	evaporation from surface water
e_a	Pa	96	atmospheric vapour pressure
e_i	Pa	97	vapour pressure in leaf
e_{sat}	Pa	98	saturated vapour pressure
$e_{s,x}$	Pa	94	vapour pressure at leaf boundary in sunlit ($e_{s,sn}$) and shade ($e_{s,sh}$) leaves
$F_s(z)$	$\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}$	52	water flux at a soil depth of z
F_X	-	E9	intermediate parameter for the calculation of roughness (X denotes "T" or "Q")
f_{cw}	-	39	fraction of canopy that is wet
f_{df}	-	17	fraction of scattered radiation
f_{dwn}	-	62	factor of photosynthesis down-regulation
f_{int}	-	42	interception efficiency of precipitation by canopy
GDS	$\text{K} \cdot \text{s}$	102	growing degree seconds at t_s
$G_{P,glu}$	$\text{kg ha}^{-1} \text{ s}^{-1}$	118 and 120	glucose partitioned to each organ
$G_{R,glu}$	$\text{kg ha}^{-1} \text{ s}^{-1}$	118 and 120	growth rate of glucose reserves in leaves
$G_{R,pnc}$	$\text{kg ha}^{-1} \text{ s}^{-1}$	115 and 119	growth rate of dry weight for panicles



continued

Symbol	Units	Eq.	Description
$G_{R,rot}$	$\text{kg ha}^{-1} \text{s}^{-1}$	116 and 119	growth rate of dry weight for roots
$G_{R,leaf}$	$\text{kg ha}^{-1} \text{s}^{-1}$	113 and 119	growth rate of dry weight for leaves
$G_{R,stc}$	$\text{kg ha}^{-1} \text{s}^{-1}$	117 and 119	growth rate of dry weight for starch reserves in stems
$G_{R,stm}$	$\text{kg ha}^{-1} \text{s}^{-1}$	114 and 119	growth rate of dry weight for stems
$G_s(z)$	W m^{-2}	46	heat flux at soil depth of z
G_{ws}	W m^{-2}	10	heat flux from surface water to soil
\bar{g}_a	m s^{-1}	91	leaf boundary conductance per unit leaf area for both sides of the leaf
\bar{g}_l	$\text{mol m}^{-2}(\text{l}) \text{s}^{-1}$	90	leaf boundary conductance for vapour per unit leaf area
\bar{g}_s	m s^{-1}	99	stomatal conductance per unit leaf area for both sides of the leaf
\bar{g}_{st}	$\text{mol m}^{-2}(\text{l}) \text{s}^{-1}$	100	stomatal conductance for vapour per unit leaf area for both sides of the leaf
$\bar{g}_{st,x}$	$\text{mol m}^{-2}(\text{l}) \text{s}^{-1}$	92	stomatal conductance for vapour per unit leaf area in sunlit ($\bar{g}_{st,sn}$) and shade ($\bar{g}_{st,sh}$) leaves
H_c	W m^{-2}	5	sensible heat flux from canopy
H_w	W m^{-2}	6	sensible heat flux from surface water
h_{gt}	m	130	canopy height
h_{arg}	rad	B3	hour angle from noon ($h_r = 12$)
h_r	hour	-	local time at the simulation site
$h_{s,x}$	Pa Pa^{-1}	93	relative humidity at leaf boundary in sunlit ($h_{s,sn}$) and shade ($h_{s,sh}$) leaves
I_c	$\text{kg m}^{-2} \text{s}^{-1}$	41	amount of precipitation intercepted by canopy
$K(z)$	kg s m^{-3}	53	hydraulic conductivity at a soil depth of z
K_c	Pa	76	Michaelis constant for CO_2 fixation
$K_e(z)$	-	49	the Kersten number
K_O	Pa	77	Michaelis constant for O_2 inhibition
$k_{ts}(z)$	$\text{W m}^{-1} \text{K}^{-1}$	48	thermal conductivity at a soil depth of z
L	$\text{m}^2 \text{m}^{-2}$	128	LAI
L_{MO}	m	34	Monin-Obukhov length of the entire surface
L_{MOw}	m	35	Monin-Obukhov length of surface water
$L_{S,leaf}$	$\text{kg ha}^{-1} \text{s}^{-1}$	124	loss rate of dry weight for leaves
L_{sn}	$\text{m}^2(\text{l}) \text{m}^{-2}$	58	LAI for sunlit leaves
L_{sh}	$\text{m}^2(\text{l}) \text{m}^{-2}$	59	LAI for shade leaves
l	$\text{m}^2(\text{l}) \text{m}^{-2}$	-	LAI depth from the top of canopy
$P_{R,sh}$	-	121	ratio of glucose partitioned to shoot
$P_{R,pnc}$	-	123	ratio of glucose partitioned to panicle from the glucose partitioned to shoot
$P_{R,leaf}$	-	122	ratio of glucose partitioned to leaf from the glucose partitioned to shoot
P_{1*}	-	E11	intermediate variable for the calculation of roughness (* denotes "M", "T", or "Q")
P_{2*}	-	E12	intermediate variable for the calculation of roughness (* denotes "M", "T", or "Q")
P_{3X}	-	E13	intermediate parameter for the calculation of roughness (X denotes "T" or "Q")
P_{4X}	-	E13	intermediate parameter for the calculation of roughness (X denotes "T" or "Q")
Q_{sat}	Kg Kg^{-1}	A2	specific humidity at saturation
Q_{sn}	$\text{mol m}^{-2} \text{s}^{-1}$	80	photon flux density for PAR absorbed by canopy in sunlit leaves
$Q_{sn,d}$	$\text{mol m}^{-2} \text{s}^{-1}$	82	direct PAR absorbed in sunlit leaves
$Q_{sn,s}$	$\text{mol m}^{-2} \text{s}^{-1}$	83	scattered PAR absorbed in shade leaves
Q_{sh}	$\text{mol m}^{-2} \text{s}^{-1}$	81	photon flux density for PAR absorbed by canopy in shade leaves
$Q_{sh,s}$	$\text{mol m}^{-2} \text{s}^{-1}$	84	scattered PAR absorbed in shade leaves
\bar{Q}_x	$\text{mol m}^{-2}(\text{l}) \text{s}^{-1}$	79	photon flux density for PAR absorbed by leaves in sunlit (\bar{Q}_{sn}) and shade (\bar{Q}_{sh}) leaves
$\bar{R}_{d,x}$	$\text{mol}(\text{CO}_2) \text{m}^{-2}(\text{l}) \text{s}^{-1}$	85	respiration in sunlit ($\bar{R}_{d,sn}$) and shade ($\bar{R}_{d,sh}$) leaves
R_{ex}	W m^{-2}	19	extraterrestrial radiation
$R_{M,stc}$	$\text{kg ha}^{-1} \text{s}^{-1}$	125	remobilization rate of dry weight from starch reserves
R_{nc}	W m^{-2}	3	net radiant flux density at canopy



continued

Symbol	Units	Eq.	Description
R_{nw}	W m^{-2}	4	net radiant flux density at surface water
$R_l^d(l)$	W m^{-2}	21	radiant flux density for downward longwave at a LAI depth of l
$R_s^d(l)$	W m^{-2}	21	radiant flux density for downward shortwave at a LAI depth of l
$R_s^u(l)$	W m^{-2}	21	radiant flux density for upward shortwave at a LAI depth of l
$r_{dd,lef}$	s^{-1}	126	ratio of dead leaf
r_{ij}	-	D1 and D2	reflectivity of canopies ($i = 1$:PAR; $i = 2$:NIR; $j = 1$:direct; $j = 2$:scattered)
S	-	78	Ratio of RuBP partitioned to carboxylase or oxygenase
$S_i^d(l)$	W m^{-2}	13	radiant flux density for downward scattered radiation for PAR ($i = 1$) or NIR ($i = 2$) at a LAI depth of l
$S_i^u(l)$	W m^{-2}	14	radiant flux density for upward scattered radiation for PAR ($i = 1$) or NIR ($i = 2$) at a LAI depth of l
S_{glu}	$\text{kg ha}^{-1} \text{s}^{-1}$	110	supply of glucose to the reserves in leaf
SLW	$\text{kg m}^{-2}(l)$	129	specific leaf area
$S_s(z)$	$\text{m}^3 \text{m}^{-3} \text{s}^{-1}$	55	absorption for transpiration by root at soil depth of z
S_{tw}	W m^{-2}	11	heat flux stored in surface water
T_c	K	3 to 11	canopy temperature
$T_s(z)$	K	45	soil temperature at z of soil depth
T_x	K	A2	temperature of canopy (T_c) or surface water (T_w)
T_w	K	3 to 11	surface water temperature
t	s	-	time
t_e	s	-	time at emergence after sowing
U_c	m s^{-1}	F1	wind speed in the canopy
U_h	m s^{-1}	F2	reference wind speed
$V_{max}(l)$	$\text{mol}(\text{CO}_2) \text{m}^{-2}(l) \text{s}^{-1}$	74	reference value for maximum Rubisco capacity at a LAI depth of l
$\bar{V}_{max,x}$	$\text{mol}(\text{CO}_2) \text{m}^{-2}(l) \text{s}^{-1}$	72 and 73	reference value for maximum Rubisco capacity per unit leaf area of sunlit and shade leaves
$\bar{V}_{mc,x}$	$\text{mol}(\text{CO}_2) \text{m}^{-2}(l) \text{s}^{-1}$	69	maximum Rubisco capacity per unit leaf area of sunlit ($\bar{V}_{mc,sn}$) and shade ($\bar{V}_{mc,sh}$) leaves for $\bar{w}_{c,x}$
$\bar{V}_{ms,x}$	$\text{mol}(\text{CO}_2) \text{m}^{-2}(l) \text{s}^{-1}$	70	maximum Rubisco capacity per unit leaf area of sunlit ($\bar{V}_{ms,sn}$) and shade ($\bar{V}_{ms,sh}$) leaves for $\bar{w}_{s,x}$
W_{glu}	kg ha^{-1}	109	dry weight of glucose reserves in leaves
W_{pnc}	kg ha^{-1}	106	dry weight of panicles
$W_{pnc,mt}$	kg ha^{-1}	-	dry weight of panicles at maturity
W_{rot}	kg ha^{-1}	107	dry weight of roots
W_{sh}	kg ha^{-1}	127	dry weight of shoot
W_{stc}	kg ha^{-1}	108	dry weight of starch reserves in stems
W_{stm}	kg ha^{-1}	105	dry weight of stems
w_c	m	40	amount of water stored in canopy
w_{cap}	m	44	canopy water capacity
$w_s(z)$	$\text{m}^3 \text{m}^{-3}$	50 and 51	volumetric concentration of soil water at a soil depth of z
Yld	kg ha^{-1}	132	crop yield
z	m	-	soil depth
z_M	m	E2	roughness length of the entire surface for momentum profile
z_{Mw}	m	E4	roughness length that express the effect of water surface on the profile of momentum
z_M^+	m	E10	intermediate variable for the calculation of roughness
z_Q	m	E3	roughness length of the entire surface for specific humidity profile
z_{Qw}	m	E5	roughness length that express the effect of water surface on the profile of specific humidity
z_{rt}	m	131	root depth

*continued*

Symbol	Units	Eq.	Description
z_T	m	E3	roughness length of the entire surface for temperature profile
z_{Tw}	m	E5	roughness length that express the effect of water surface on the profile of temperature
z_X^+	m	E10	intermediate variable for the calculation of roughness (X denotes "T" or "Q")
z_*^+	m	E10	intermediate variable for the calculation of roughness (* denotes "M", "T", or "Q")
δ_s	rad	B2	declination of the sun
Γ^*	Pa	75	light compensation point
γ_m	-	F3	coefficient of exponential decrease for wind speed in the canopy
$\bar{\omega}_{c,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	66	Rubisco limited assimilation in sunlit ($\bar{\omega}_{c,sn}$) and shade ($\bar{\omega}_{c,sh}$) leaves
$\bar{\omega}_{e,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	67	light-limited assimilation in sunlit ($\bar{\omega}_{e,sn}$) and shade ($\bar{\omega}_{e,sh}$) leaves
$\bar{\omega}_{p,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	64	Rubisco and light-limited assimilation in sunlit ($\bar{\omega}_{p,sn}$) and shade ($\bar{\omega}_{p,sh}$) leaves
$\bar{\omega}_{s,x}$	$\text{mol}(\text{CO}_2) \text{ m}^{-2} (\text{l}) \text{ s}^{-1}$	68	sucrose limited assimilation for sunlit ($\bar{\omega}_{s,sn}$) and shade ($\bar{\omega}_{s,sh}$) leaves
Ψ_E	-	31	adiabatic correction factor for vapour
Ψ_H	-	31	adiabatic correction factor for heat
Ψ_M	-	30	adiabatic correction factor for momentum
$\psi(z)$	J kg^{-1}	54	water potential at a soil depth of z
ρ_a	kg m^{-3}	A1	air density
τ_{atm}	-	18	transmissivity of atmosphere
τ_{cs}	-	20	transmissivity of canopy for shortwave radiation
τ_{cl}	-	23	transmissivity of canopy for longwave radiation
τ_{ij}	-	D3 and D4	transmissivity of canopy ($i = 1:\text{PAR}$; $i = 2:\text{NIR}$; $j = 1:\text{direct}$; $j = 2:\text{scattered}$)
Θ_0	K	36	potential temperature
θ	rad	B1	zenith angle of the sun
ζ	-	32	atmospheric stability between the entire canopy and atmosphere
ζ_w	-	33	atmospheric stability between surface water and atmosphere

**Table 4.** Physical and chemical constants

Variable	Value	Units	Description
$C_{CO_2,glu}$	$1.08 \cdot 10^6$	$\text{kg ha}^{-1} \text{h}^{-1} / (\text{mol m}^{-2} \text{s}^{-1})$	conversion factor from CO_2 to glucose
$C_{glu,stc}$	0.9	$\text{kg ha}^{-1} / (\text{kg ha}^{-1})$	conversion factor of dry weight from glucose to starch
$C_{stc,glu}$	1.11	$\text{kg ha}^{-1} / (\text{kg ha}^{-1})$	conversion factor of dry weight from starch to glucose
c_{pa}	1004.6	$\text{J K}^{-1} \text{Kg}^{-1}$	specific heat of air
c_{pw}	4200	$\text{J K}^{-1} \text{Kg}^{-1}$	specific heat of water
g	9.8	m s^{-1}	gravitational constant
$e_{sat}(T_0)$	611	Pa	vapour pressure at melting temperature of water
k_q	$4.6 \cdot 10^{-6}$	$(\text{mol m}^{-2} \text{s}^{-1}) / (\text{W m}^{-2})$	transfer constant from radiant flux density to photon flux density
k_w	0.6	$\text{W m}^{-1} \text{K}^{-1}$	thermal conductivity of water
R_{dry}	287.04	$\text{J kg}^{-1} \text{K}^{-1}$	gas constant of dry air
R_{sun}	1370	W m^{-2}	solar constant
R_{vap}	461	$\text{J kg}^{-1} \text{K}^{-1}$	gas constant of vapour
T_0	273.15	K	melting temperature of water
w_{H_2O}	0.018	kg/mol	molar weight of vapour
κ	0.4	-	Karman constant
λ	$2.5 \cdot 10^6$	J kg^{-1}	latent heat of vaporisation
ρ_w	1000	kg m^{-3}	water density
σ	$5.67 \cdot 10^{-8}$	$\text{W m}^{-2} \text{K}^{-4}$	Boltzmann constant



Table 5: Parameters

Variable	Value	Units	Description	Source
Simulation setting				
C_a	-	ppm	atmospheric CO ₂ concentration	Masutomi et al. (2016)
d_w	-	m	depth of surface water	Masutomi et al. (2016)
L_t	-	degree	latitude of the simulation site	Masutomi et al. (2016)
SW_{DOY}	-	DOY	DOY of sowing day	Masutomi et al. (2016)
$W_{glu,0}$	-	kg/ha	dry weight of glucose reserve at emergence	Masutomi et al. (2016)
$W_{lef,0}$	-	kg/ha	dry weight of leaf at emergence	Masutomi et al. (2016)
$W_{rot,0}$	-	kg/ha	dry weight of root at emergence	Masutomi et al. (2016)
$W_{stm,0}$	-	kg/ha	dry weight of stem at emergence	Masutomi et al. (2016)
z_a	-	m	reference height at which wind speed is observed	Masutomi et al. (2016)
z_{max}	-	m	depth of soil layer	Masutomi et al. (2016)
z_{sat}	-	m	depth to which soil is saturated	Masutomi et al. (2016)
z_b	-	m	depth from the soil surface to the upper bound of the bottommost layer of soil	Masutomi et al. (2016)
δt	-	s	time resolution	Masutomi et al. (2016)
Soil-type specific				
B	-	-	factor for hydraulic conductivity and water potential	Masutomi et al. (2016)
K_s	-	kg s m ⁻³	hydraulic conductivity at saturation	Masutomi et al. (2016)
w_{sat}	-	m ³ m ⁻³	volumetric concentration of soil water at saturation	Masutomi et al. (2016)
ψ_s	-	J kg ⁻¹	water potential at saturation	Masutomi et al. (2016)
ρ_s	-	kg m ⁻³	soil bulk density	Masutomi et al. (2016)
Crop-specific (paddy rice)				
b	0.01	mol m ⁻² s ⁻¹	intercept of the Ball-Berry model	Sellers et al. (1996b)
$C_{glu,lef}$	0.955	kg ha ⁻¹ /(kg ha ⁻¹)	conversion factor of dry weight from glucose to leaf	Penning de Vries et al. (1989)
$C_{glu,pnc}$	0.821	kg ha ⁻¹ /(kg ha ⁻¹)	conversion factor of dry weight from glucose to panicle	Penning de Vries et al. (1989)
$C_{glu,rot}$	0.928	kg ha ⁻¹ /(kg ha ⁻¹)	conversion factor of dry weight from glucose to root	Penning de Vries et al. (1989)
$C_{glu,stm}$	0.928	kg ha ⁻¹ /(kg ha ⁻¹)	conversion factor of dry weight from glucose to stem	Penning de Vries et al. (1989)
c_h	0.06	-	leaf transfer coefficient for heat	Kimura and Kondo (1998)
c_m	0.2	-	leaf transfer coefficient for momentum	Kimura and Kondo (1998)
$DV S_{rot1}$	Parameterized	-	1st point of DVS at which the partition to root changes	Masutomi et al. (2016)
$DV S_{rot2}$	Parameterized	-	2nd point of DVS at which the partition to root changes	Masutomi et al. (2016)
$DV S_{lef1}$	Parameterized	-	1st point of DVS at which the partition to leaf changes	Masutomi et al. (2016)
$DV S_{lef2}$	Parameterized	-	2nd point of DVS at which the partition to leaf changes	Masutomi et al. (2016)
$DV S_{pnc1}$	Parameterized	-	1st point of DVS at which the partition to panicle changes	Masutomi et al. (2016)
$DV S_{pnc2}$	Parameterized	-	2nd point of DVS at which the partition to panicle changes	Masutomi et al. (2016)
$eDVS$	Parameterized	-	DVS at emergence	Masutomi et al. (2016)
f_d	0.015	-	respiration factor	Sellers et al. (1996b)
f_{stc}	Parameterized	-	fraction of glucose allocated to starch reserves	Masutomi et al. (2016)
$h_{gt,aa}$	Parameterized	-	parameter for relation between leaf area index (LAI) and height before heading	Masutomi et al. (2016)
$h_{gt,ab}$	Parameterized	-	parameter for relation between LAI and height before heading	Masutomi et al. (2016)
$h_{gt,ba}$	Parameterized	-	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
$h_{gt,bb}$	Parameterized	-	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
$hDVS$	Parameterized	-	DVS at heading	Masutomi et al. (2016)
k_{yld}	Parameterized	-	ratio of crop yield to dry weight of panicle at maturity	Masutomi et al. (2016)
k_{SLW}	Parameterized	-	parameter for the relation between SLW and DVS	Masutomi et al. (2016)
m	9	-	the slope of the Ball-Berry model	Sellers et al. (1996b)
$mGDS$	Parameterized	K·s	growing degree second at maturity	Masutomi et al. (2016)
P_{rot}	Parameterized	-	ratio of glucose partitioned to root	Masutomi et al. (2016)
P_{lef}	Parameterized	-	ratio of glucose partitioned to leaf from glucose partitioned to shoot	Masutomi et al. (2016)
$r_{d1,lef}$	Parameterized	s ⁻¹	ratio of dead leaf at harvest	Masutomi et al. (2016)



continued (Table 5)

Variable	Value	Units	Description	Source
$r_{rm, stc}$	$1.16 \cdot 10^{-6}$	s^{-1}	ratio of remobilization	Bouman et al. (2001)
r_{rt}	$1.16 \cdot 10^{-7}$	$m s^{-1}$	growth ratio of root	Penning de Vries et al. (1989)
r_1	0.105	-	leaf reflectivity for photosynthesis active radiation (PAR)	Sellers et al. (1996b)
r_2	0.58	-	leaf reflectivity for near infrared radiation (NIR)	Sellers et al. (1996b)
SLW_{mx}	Parameterized	$kg m^{-2}$	maximum specific leaf area	Masutomi et al. (2016)
SLW_{mn}	Parameterized	$kg m^{-2}$	minimum specific leaf area	Masutomi et al. (2016)
s_1	Parameterized	K^{-1}	temperature dependence of $\bar{V}_{max,x}$ on $\bar{V}_{mc,x}$	Masutomi et al. (2016)
s_2	Parameterized	K	temperature dependence of $\bar{V}_{max,x}$ on $\bar{V}_{m,c,x}$	Masutomi et al. (2016)
s_4	281	K	temperature dependence of $\bar{V}_{max,x}$ on $\bar{V}_{m,s,x}$	Sellers et al. (1996b)
T_b	281.15	K	minimum temperature for development	Bouman et al. (2001)
T_o	303.15	K	optimal temperature for development	Bouman et al. (2001)
T_h	313.15	K	maximum temperature for development	Bouman et al. (2001)
$trDVS$	Parameterized	-	DVS at transplanting and at which transplanting shock starts	Masutomi et al. (2016)
$teDVS$	Parameterized	-	DVS at which transplanting shock ends	Masutomi et al. (2016)
t_1	0.07	-	leaf transmissivity for PAR	Sellers et al. (1996b)
t_2	0.25	-	leaf transmissivity for NIR	Sellers et al. (1996b)
$V_{max}(0)$	Parameterized	$\mu mol m^{-2} s^{-1}$	maximum Rubisco capacity at the canopy top	Masutomi et al. (2016)
$z_{rt,mx}$	0.3	m	maximum root depth	Penning de Vries et al. (1989)
β_{ce}	0.98	-	GPP transition factor	Sellers et al. (1996b)
ϵ_e	0.08	$mol mol^{-1}$	quantum efficiency	Sellers et al. (1996b)
Others				
$A_{x,i}$	C6–C7	-	coefficients of radiation equations (Eqs. 12–14; $x=1,2$)	Watanabe and Ohtani (1995)
a_i	C1	-	extinction coefficient for scattered radiation	Watanabe and Ohtani (1995)
C_0	288	ppm	base concentration of CO ₂ for photosynthesis down-regulation	Arora et al. (2009)
c_{pm}	870	$J kg^{-1} K^{-1}$	specific heat of soil minerals	Campbell and Norman (1998)
D_1	$1.14 \cdot 10^{-11}$	-	coefficient related to gravitational fall of canopy water	Rutter et al. (1975)
D_2	$3.7 \cdot 10^3$	-	coefficient related to gravitational fall of canopy water	Rutter et al. (1975)
d_f	$sec(2\pi(53/360))$	-	scattered factor	Watanabe and Ohtani (1995)
F	0.5	-	distribution of leaf orientation	Goudriaan and van Laar (1994)
K_n	0.3	-	vertical distribution of nitrogen	Oleson and Lawrence (2013)
k_{ts0}	0.25	$W m^{-1} K^{-1}$	thermal conductivity of dry soil	Campbell and Norman (1998)
k_{tss}	1.58	$W m^{-1} K^{-1}$	thermal conductivity of saturated soil	Best et al. (2011)
[O ₂]	20900	Pa	partial pressure of intercellular O ₂	Collatz et al. (1991)
r_g	0.1	-	albedo of surface water for shortwave radiation	Maruyama and Kuwagata (2010)
s_3	0.2	K^{-1}	temperature dependence of $\bar{V}_{max,x}$ on $\bar{V}_{m,s,x}$	Masutomi et al. (2016)
s_5	1.3	K^{-1}	temperature dependence on $\bar{R}_{d,x}$	Sellers et al. (1996b)
s_6	328	K	temperature dependence on $\bar{R}_{d,x}$	Sellers et al. (1996b)
z_{Ms}	0.001	m	roughness length of surface water for momentum	Kimura and Kondo (1998)
z_{Qs}	0.001	m	roughness length of surface water for specific humidity	Kimura and Kondo (1998)
z_{Ts}	0.001	m	roughness length of surface water for heat	Kimura and Kondo (1998)
β_{pc}	0.95	-	GPP transition factor	Sellers et al. (1996b)
ϵ	0.96	-	longwave emissivity of surface water	Campbell and Norman (1998)
γ_d	0.9	-	response parameter to elevated CO ₂	Arora et al. (2009)
γ_{gd}	0.42	-	response parameter to elevated CO ₂	Arora et al. (2009)
τ_b	$8.64 \cdot 10^6$	s	recession constant for base water flow (100day)	Hanasaki et al. (2008)