Appendix 4.2

The Sun-Shade-Open Canopy (SSOC) Soil-Vegetation-Atmosphere Transfer (SVAT) model

Contents

1 Introduction 2
1.1 Links to other model components 2
2 The soil-vegetation-atmosphere transfer (SVAT) model 3
2.1 The overall energy balances 3
2.2 Sensible heat fluxes 4
2.3 Latent heat fluxes 5
3 Calculation of the required parameters and variables 6
3.1 Radiation types and calculations 6
3.1.1 Equations for shortwave radiation 7
3.1.2 Equations for long-wave radiation 9
3.1.3 The radiation balance 9
3.2 Aerodynamic conductance 10
3.3 Boundary layer conductance of sunlit and shaded leaves 12
3.4 Soil aerodynamic conductance 14
4 Determination of state variables and numerical solution (E) 16
5 Parameter overview 18
6 References 21

1 Introduction

This appendix described the Sun-Shade-Open-Canopy (SSOC) Soil-Vegetation-Atmosphere-Transfer (SVAT)-model that calculates the energy balance at leaf level for both sunlit and shaded leaves. The model is typically used in combination with the Farquar photosynthesis models (*FC-C3* and *FC-C4*), described in Appendix 10.3.

The text is written based on Plauborg et al. (2010). Modifications have been made to accommodate text written in other chapters or appendices of the documentation and to link to the reference manual. Also, any changes that may have taken place since 2010 have been included.

1.1 Links to other model components

Soil water dynamics

Soil water dynamics are simulated in 1D or 2D as described in Chapter 4. The model for water uptake in plants uses the functionality in the 1D Daisy. As described in Chapter 4, this model is based on the single root concept, hence the water uptake model requires information on the root length density distribution and the driving force is the crown potential (see Hansen et al. (1991) or Hansen and Abrahamsen, (2009)).

Stomatal conductance model

Stomatal conductance (g_s^w) is an important factor for both transpiration and photosynthesis. As described in Appendix 10.3, Daisy allows the choice between several models for calculating g_s^w. Appendix 10.3 also includes information about the possibilities of including ABA-production in the simulations and its influence on stomatal conductance. The unit of stomatal conductance, i.e. g'^w [mol m^{-2} s^{-1}], can be converted to g^w[m s^{-1}] as follows:

$$g^w_{(f,i)} = \frac{R \cdot T^K}{P} \cdot g'^w_{(f,i)} \tag{2.4.1}$$

where R is the gas constant (8.314 [J mol^{-1} K^{-1}]), T^K is temperature [K] and P is atmospheric pressure [Pa] (calculated in eq. (2.6), Chapter 2). *(f,i)* refers to the sunlit or shaded fraction of the i'th calculation layer of the canopy (see Appendix 10.3).

Stomatal conductance for water vapour.

Up-scaling from leaf to canopy yields the stomatal conductance for water vapour:

$$g^w_{s(f)} = \begin{cases} \sum_i^{n_{LAI}} L_{(sun,i)} \cdot g^w_{s(sun,i)} \\ \sum_i^{n_{LAI}} L_{(sh,i)} \cdot g^w_{s(sh,i)} \end{cases} \tag{2.4.2}$$

where n_{LAI} is the number of leaf layers (typically 30) and $L_{(sun,i)}$ and $L_{(sh,i)}$ are the sunlit and shaded leaf area index in the i'th layer of the canopy (see Appendix 10.3, eq. (10.3.12) and (10.3.13).

2 The soil-vegetation-atmosphere transfer (SVAT) model

2.1 The overall energy balances

A SVAT model simulates the exchange of gases and energy between the canopy-soil-system and the atmosphere. This SVAT model is based on the resistance/conductance concept and considers the following three sources: soil, sunlit and shaded leaves. The SVAT model comprises the following surface fluxes assuming that there is no storage of heat or water vapour in the canopy air space:

$$H_{atm} = H_{soil\to c} + H_{snl\to c} + H_{shl\to c} \tag{2.4.3}$$

$$E_{atm} = E_{soil\to c} + E_{snl\to c} + E_{shl\to c} \tag{2.4.4}$$

where H and E denote ecosystem fluxes of sensible heat [W m^{-2}] and water vapour [kg m^{-2} s^{-1}], respectively. The subscripts describe the pathway of the fluxes: atm, $soil\to c$, $snl\to c$ and $shl\to c$, are the flux into the atmosphere, the flux from the soil to the canopy air space, the flux from the sunlit leaves to the canopy air space and the flux from the shaded leaves to the canopy air space. The conceptualization for the exchange of latent heat or water vapour is shown in Figure 1.

Latent heat fluxes [W m^{-2}] are obtained by multiplying the corresponding water vapour flux by the latent heat of vaporization, λ [J kg^{-1}]:

$$\lambda = 3{,}149{,}000 - 2370 \cdot T_a^K \tag{2.4.5}$$

where T_a^K is the air temperature [K]. The equation differs from Eq. (2.4) in Chapter 2 because the temperature here is in [°K], while it is in [°C] in Chapter 2.

The principles of conservation of energy and matter yields:

$$R_{abs-soil} - L_{o-soil} = G_{soil} + H_{soil\to c} + \lambda \cdot E_{soil\to c} \tag{2.4.6}$$

$$R_{abs-snl} - L_{o-snl} = H_{snl\to c} + \lambda \cdot E_{snl\to c} \tag{2.4.7}$$

$$R_{abs-shl} - L_{o-shl} = H_{shl\to c} + \lambda \cdot E_{shl\to c} \tag{2.4.8}$$

where Eqs. (2.4.6 - 8) are energy balances of the soil, sunlit leaves and shaded leaves, respectively. The terms on the left side of the equations represent the absorbed radiation (R_{abs}) of the considered part of the system minus the outgoing long-wave radiation (L_o), and G_{soil} is the ground heat flux at the surface.

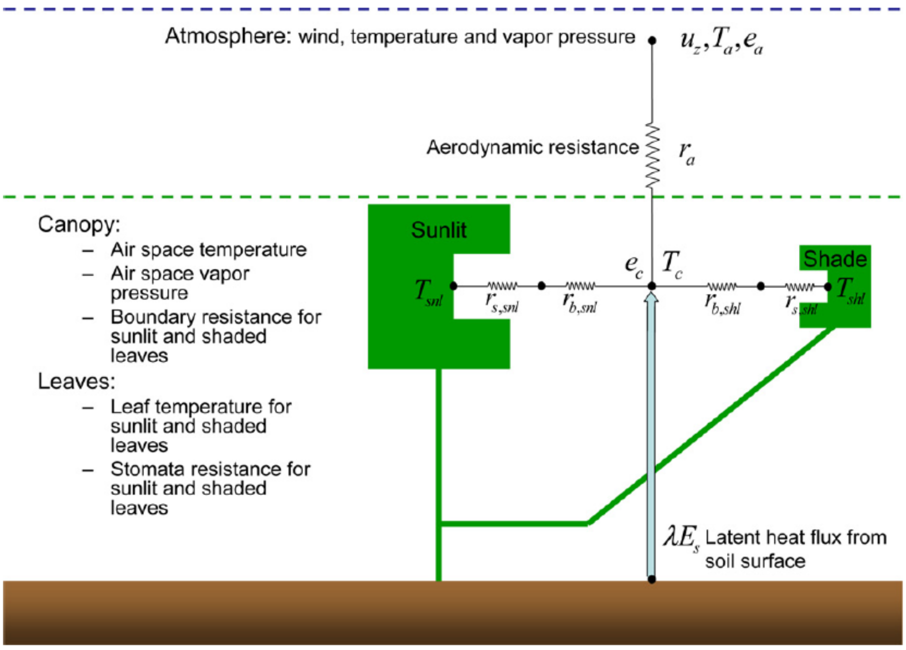

Figure 1. Conceptual model of the exchange of latent heat (water vapour) (Plauborg et al., 2010).

The model considers the absorption of photosynthetically active radiation (PAR), near infrared radiation (NIR), and long-wave thermal radiation separately. Adding the three radiation components in Eqs. (2.4.6 -8) and subtracting the emission of long-wave radiation from each fraction ($L_{o\text{-}soil}$, $L_{o\text{-}snl}$, and $L_{o\text{-}shl}$) yields the net radiation received in the canopy system.

The estimation of the net radiation is explained in section 3.1 of this appendix, and the equations for absorption of PAR are shown in detail in Appendix 10.3.

G_{soil} [W m^{-2}] is estimated by:

$$G_{soil} = \frac{k_h}{z_1}(T_s^K - T_{z1}^K) \quad (2.4.9)$$

where T^K_s and T^K_{z1} are the soil surface temperature [K] and the soil temperature at the depth z_1 [m], respectively, and k_h is the thermal conductivity of the soil [W m^{-1}]. T^K_{z1}, z_1, and k_h are obtained from the soil temperature model (Chapter 5). For simplicity, the values from the beginning of the considered time-step are used.

$E_{soil\rightarrow c}$ in eq. (2.4.6) is estimated by the soil water dynamics model and surface model (Chapter 3 and 4). $E_{soil\rightarrow c}$ represents the combined evaporation through the soil surface and from water stored at the soil surface. Again, the value from the beginning of the considered time-step is used.

2.2 Sensible heat fluxes

The sensible heat fluxes (H_{atm}, $H_{soil\rightarrow c}$, $H_{snl\rightarrow c}$, and $H_{shl\rightarrow c}$) are estimated as:

$$H_{atm} = c_p \rho_a g_a (T_c^K - T_a^K) \quad (2.4.10)$$

$$H_{soil\to c} = c_p \rho_a g^H_{soil\to c}(T^K_s - T^K_c) \quad (2.4.11)$$

$$H_{snl\to c} = c_p \rho_a g^H_{snl\to c}\left(T^K_{snl} - T^K_c\right) \quad (2.4.12)$$

$$H_{shl\to c} = c_p \rho_a g^H_{shl\to c}\left(T^K_{shl} - T^K_c\right) \quad (2.4.13)$$

where

c_p = the specific heat of air (1005 [J kg^{-1} K^{-1}]),

ρ_a = the density of air [kg m^{-3}], calculated as $(m_a \cdot P \cdot 10^{-3})(R \cdot T^K_a)$, where m_a is the molecular weight of air, 29 [g mol^{-1}],

g_a = aerodynamic conductance of heat [m s^{-1}]. $g_a = 1/r_a$, where r_a is calculated in eq. (2.4.39),

$g^H{}_{soil\to c}$ = conductance of heat from soil surface to canopy air (m s^{-1}), (eq. (2.4.55)),

$g^H{}_{snl\to c}$ = conductance of heat from sunlit leaves to canopy air (corresponds to $g^H{}_{b\text{-}snl}$ in eq. (2.4.51) and

$g^H{}_{shl\text{-}\to c}$ = conductance of heat from shaded leaves to canopy air [m s^{-1}] (corresponds to $g^H{}_{b\text{-}shl}$ in eq. (2.4.52)),

T^K_c, T^K_{snl}, and T^K_{shl} = canopy air temperature, and temperature of sunlit and shaded leaves, respectively, in [K].

2.3 Latent heat fluxes

The latent heat fluxes (λE_{atm}, $\lambda E_{snl\to c}$, and $\lambda E_{shl\to c}$) are estimated as:

$$\lambda E_{atm} = \frac{c_p \rho_a g_a}{\gamma}(e_c - e_a) \quad (2.4.14)$$

$$\lambda E_{snl\to c} = \frac{c_p \rho_a g^w_{snl\to c}}{\gamma}\left(e^*(T^K_{snl}) - e_c\right) \quad (2.4.15)$$

$$\lambda E_{shl\to c} = \frac{c_p \rho_a g^w_{shl\to c}}{\gamma}\left(e^*(T^K_{shl}) - e_c\right) \quad (2.4.16)$$

where

λ = latent heat of vaporization [J kg^{-1}], calculated in eq. (2.4.5),

γ = the psychrometer constant [Pa K^{-1}], calculated in Chapter 2, eq. (2.5),

$g^w_{snl\to c}$ = conductance corresponding to water vapour flux from sunlit leaves to the canopy [m s^{-1}], eq. (2.4.53),

$g^w_{shl\to c}$ = conductance corresponding to water vapour flux from shaded leaves to the canopy [m s^{-1}], eq. (2.4.54),

e_a = air vapour pressure [Pa]

e_c = canopy air vapour pressure [Pa]

$e^*(T)$ = saturation vapour pressure at the temperature T.

It is noted that $g^{w}_{snl\to c}$ and $g^{w}_{shl\to c}$ depends on the boundary layer conductance as well as the stomatal conductance.

3 Calculation of the required parameters and variables

3.1 Radiation types and calculations

In this section, the radiation calculations that are required to generate the state variables for eq. (2.4.6), (2.4.7) and (2.4.8) are shown.

Shortwave radiation comprises photosynthetically active radiation (PAR) and near infrared radiation (NIR). PAR contributes 50 % and NIR contributes 47% of the global radiation (Ross, 1975). Only PAR contributes to photosynthesis, while both types are relevant for energy calculations. PAR and NIR are treated in the same way, but differ with respect to optical properties, see Table 1.

Table 1. Optical properties of leaves and soil surface, modified from Plauborg et al. (2010).

		PAR	NIR	Long-wave
Leaf absorptance	α	0.85*	0.17	
Soil surface reflectance	ρ_s	0.1	0.18	
Leaf emissivity	ε_l			0.98
Soil emissivity	ε_s			0.95

*This value is given as 0.8 by Plauborg et al. (2010), the change is described below.

Leaf absorptance and soil surface reflectance values are specified in the sub-model *sun-shade* under *raddist*. α is calculated as $(1\text{-}\sigma)$, where σ is the leaf scattering coefficient. The default value of σ for PAR (*sigma_PAR* [ ]) is 0.15 , originally measured for wheat by de Pury and Farquhar (1997). Thus, $\alpha = 1\text{-}\sigma =$ 0.85. The default value of σ for NIR (*sigma_NIR* [ ]) is 0.83. *sigma_PAR* and *sigma_NIR* may be changed by the user. ρ_s for both PAR and NIR can be modified due to soil water, as functions of pF (*Ps_PAR_SWE* and *Ps_NIR_SWE*). The emissivity factors are specified under the *SVAT* submodel *SSOC*.

The absorbance of PAR in the canopy is described in detail in Appendix 10.3, section 3 and 4, so only a summary of those equations is included below (eq. (2.4.17 - 23).

Division of short-wave radiation

Shortwave radiation, PAR or NIR, (I_t, W m^{-2}) is divided into a direct beam (I_b, W m^{-2}) and a diffuse (I_d, W m^{-2}) component, i.e.:

$$I_b = (1 - f_d) \cdot I_t \qquad (2.4.17)$$

$$I_d = f_d \cdot I_t \qquad (2.4.18)$$

where f_d is the diffuse fraction of the global radiation. f_d may be based on measurements or it may be calculated, see Appendix 10.3, section 3.

The canopy cover fraction

The canopy cover fraction as function of the leaf area index (L_{ai}) is estimated as:

$$f_{can} = 1 - \exp\left(-K_I \cdot L_{ai}\right) \tag{2.4.19}$$

where K_I is an empirical distribution coefficient, ($EpExt$), by default 0.5 [ ], see Chapter 3, eq. 3.16.

The sunlit leaf area fraction

The sunlit fraction of the leaf area index, L_{ai}, is estimated as:

$$f_{snl} = \frac{1 - exp(-k_b L_{ai})}{k_b L_{ai}} \tag{2.4.20}$$

where k_b = Extinction coefficient of beam radiation [].

This equation is obtained by integration of eq. (10.3.10) from Appendix (10.3) to obtain the sunlit area and divided by L_{ai} to obtain the fraction.

3.1.1 Equations for shortwave radiation

Total shortwave radiation absorbed by canopy

Shortwave radiation absorbed by a canopy with the leaf area index L_{ai}, and a spherical leaf distribution is estimated as:

$$I_{abs-can} = I_d\left(1 - \rho_{d,c-s}\right)(1 - \exp\left(-k'_d L_{ai}\right) + I_b\left(1 - \rho_{b,c-s}\right) \cdot (1 - \exp\left(-k'_b L_{ai}\right) \tag{2.4.21}$$

where parameters are obtained from Table 1 and Table 2. The equation is equal to eq. (10.3.27), where $I_{abs\text{-}can}$ is equal to $I_{(total,i)}$ for the largest value of i.

Shortwave radiation absorbed by sunlit fraction

Shortwave radiation absorbed by the sunlit fraction of the canopy is:

$$I_{abs-snl} = I_d\left(1 - \rho_{d,c-s}\right)k'_d \cdot F(k'_d + k_b) + I_b\left(1 - \rho_{b,c-s}\right)k'_b \cdot F(k'_b + k_b) + I_b(1 - \sigma)k_b\left(F(k_b) - F(2k_b)\right) \tag{2.4.22}$$

where

$$F(x) = \left(1 - \exp\left(-x \cdot L_{ai}\right)\right)/x$$

This can be derived from eq. (10.3.14) (10.3.19), (10.3.20) and (10.3.26).

Shortwave radiation absorbed by shaded fraction

Shortwave radiation absorbed by the shaded fraction of the canopy is

$$I_{abs-shl} = I_{abs-can} - I_{abs-snl} \tag{2.4.23}$$

The equation is identical to eq. (10.3.28).

Shortwave radiation absorbed by soil

Shortwave radiation absorbed by the soil is calculated as the incoming beam and diffuse radiation, minus the reflected and absorbed light:

$$I_{abs-soil} = I_d\left(1 - \rho_{d,c-s}\right) + I_b\left(1 - \rho_{b,c-s}\right) - I_{abs-can} \tag{2.4.24}$$

Table 2. Canopy and canopy-soil parameters, assuming spherical leaf distribution. Lai is the leaf area index of the canopy, see also Plauborg et al. (2010) and Appendix 10.3.

Parameter	
Direct-beam extinction coefficient for black leaves, β= sun elevation angle (eq. (10.3.11)).	$k_b = \begin{cases} \dfrac{0.5}{sin(\beta)} & sin(\beta) > 0.0625 \\ 8.0 & sin(\beta) \le 0.0625 \end{cases}$
Direct-beam extinction coefficient (eq. (10.3.16)).	$k'_b = k_b\sqrt{(1-\sigma)}$
Direct beam canopy reflectance (eq. (10.3.17)).	$\rho_{b,c} = 1 - exp\left(-2\dfrac{k_b}{(1+k_b)}\dfrac{\left(1-\sqrt{(1-\sigma)}\right)}{\left(1+\sqrt{(1-\sigma)}\right)}\right)$
Direct-beam canopy-soil reflectance (eq. (10.3.18)).	$\rho_{b,c-s} = \dfrac{\rho_{b,c} + \dfrac{\rho_{b,c}-\rho_s}{\rho_{b,c}\cdot\rho_s - 1} exp(-2k'_b L_{ai})}{1 + \rho_{b,c}\dfrac{\rho_{b,c}-\rho_s}{\rho_{b,c}\cdot\rho_s - 1} exp(-2k'_b L_{ai})}$
Diffuse radiation extinction coefficient for black leaves (eq. (10.3.22-23)).	$k_d = \dfrac{-ln(\tau_d)}{L_{ai}}$ $\tau_d = 2\int_0^{\pi/2} exp(-k_b L_{ai}) sin(\psi)\, cos(\psi)\, d\psi$
Diffuse radiation extinction coefficient (eq. (10.3.21)).	$k'_d = k_d\sqrt{(1-\sigma)}$
Diffuse radiation canopy-soil reflectance (eq. (10.3.24)).	$\rho_{d,c-s} = \dfrac{\rho_{b,c} + \dfrac{\rho_{b,c}-\rho_s}{\rho_{b,c}\cdot\rho_s - 1} exp(-2k'_d L_{ai})}{1 + \rho_{b,c}\dfrac{\rho_{b,c}-\rho_s}{\rho_{b,c}\cdot\rho_s - 1} exp(-2k'_d L_{ai})}$

3.1.2 Equations for long-wave radiation

Absorbed long-wave radiation

The absorbed long-wave radiation can be calculated as:

$$L_{abs-soil} = (1 - f_{can}) \cdot L_{in} \tag{2.4.25}$$

$$L_{abs-ssnl} = f_{can} \cdot f_{snl} \cdot L_{in} \tag{2.4.26}$$

$$L_{abs-shl} = f_{can} \cdot (1 - f_{snl}) \cdot L_{in} \tag{2.4.27}$$

where L_{in} is the incoming long-wave radiation from the atmosphere.

3.1.3 The radiation balance

Total absorbed radiation

The total (PAR, NIR and long-wave) absorbed radiation by soil, sunlit and shaded leaves can now be estimated as

$$R_{abs-soil} = I_{abs-soil}^{PAR} + I_{abs-soil}^{NIR} + L_{abs-soil} \tag{2.4.28}$$

$$R_{abs-snl} = I_{abs-snl}^{PAR} + I_{abs-snl}^{NIR} + L_{abs-snl} \tag{2.4.29}$$

$$R_{abs-shl} = I_{abs-shl}^{PAR} + I_{abs-shl}^{NIR} + L_{abs-shl} \tag{2.4.30}$$

Absorbed net radiation for the soil

The absorbed net-radiation for the soil is estimated as:

$$\begin{aligned} R_{n-soil} &= R_{abs-soil} - L_{o-soil} \\ &= R_{abs-soil} - (1 - f_{can})\varepsilon_s \sigma_{SB} (T_s^K)^4 \\ &= R_{abs-soil} - (1 - f_{can})\varepsilon_s \sigma_{SB} \left(T_a^K + (T_s^K - T_a^K)\right)^4 \\ &\approx R_{abs-soil} - (1 - f_{can})\varepsilon_s \sigma_{SB} (T_a^K)^4 - (1 - f_{can}) 4 \varepsilon_s \sigma_{SB} \\ &\qquad \cdot (T_a^K)^3 (T_s^K - T_a^K) \\ &= R_{abs-soil}^{Eq} - G_{soil}^R (T_s^K - T_a^K) \end{aligned} \tag{2.4.31}$$

where

σ_{SB} = Stefan-Boltzmann constant (5.67·10^{-8} [W m^{-2} K^{-4}]),

ε_s = soil emissivity for long-wave radiation (Table 1, by default 0.95 [ ]). The value can be modified by the plf *epsilon_soil_SWE*, allowing a modifying factor [ ] as function of pF (by default 1),

$R_{abs-soil}^{Eq}$ = $(R_{abs-soil} - (1 - f_{can})\varepsilon_s \sigma_{SB} (T_a^K)^4)$ is absorbed equilibrium net radiation for the soil [W m^{-2}], and

G_{soil}^R = $\left((1 - f_{can}) 4 \varepsilon_s \sigma_{SB} (T_a^K)^3\right)$ is soil radiative conductance [W m^{-2} K^{-1}].

Absorbed net radiation for leaves

Correspondingly, the absorbed net radiation for sunlit and shaded leaves can be written as:

$$R_{n-snl} \approx R^{Eq}_{abs-snl} - G^R_{snl}\left(T^K_{snl} - T^K_a\right) \quad (2.4.32)$$

$$R_{n-shl} \approx R^{Eq}_{abs-shl} - G^R_{shl}\left(T^K_{shl} - T^K_a\right) \quad (2.4.33)$$

where

$R^{Eq}_{abs-snl}$ = $(R_{abs-snl} - f_{can} f_{snl} \varepsilon_s \sigma_{SB} (T^K_a)^4)$ is absorbed equilibrium net radiation for the sunlit leaves [W m^{-2}],

$R^{Eq}_{abs-shl}$ = $(R_{abs-shl} - f_{can}(1 - f_{snl}) \varepsilon_s \sigma_{SB} (T^K_a)^4)$ is absorbed equilibrium net radiation for the shaded leaves [W m^{-2}],

G^R_{snl} = $(f_{can} f_{snl} 4 \varepsilon_s \sigma_{SB} (T^K_a)^3)$ is soil radiative conductance [W m^{-2} K^{-1}] for sunlit leaves, and

G^R_{snl} = $(f_{can}(1 - f_{snl}) 4 \varepsilon_s \sigma_{SB} (T^K_a)^3)$ is soil radiative conductance [W m^{-2} K^{-1}] for shaded leaves, respectively.

3.2 Aerodynamic conductance

The aerodynamic conductance, g_a, is a state variable in eq. (2.4.10 and 2.4.14). It is the reciprocal of r_a ($g_a = 1/r_a$), which is derived below. It describes the ease of transport from the canopy airspace to the atmosphere.

Displacement height and roughness length for momentum

Displacement height (d [m]) and roughness length for momentum (z_0 [m]) is, according to Shuttleworth and Gurney (1990), estimated as:

$$d = 1.1 \cdot h_{veg} \cdot ln\left(1 + \sqrt[4]{c_d L_{ai}}\right) \quad (2.4.34)$$

$$z_0 = \begin{cases} z_0' + 0.3 \cdot h_{veg}\sqrt{c_d L_{ai}} & 0.0 \le c_d L_{ai} < 0.2 \\ 0.3 \cdot \left(h_{veg} - d\right) & 0.2 \le c_d L_{ai} < 1.5 \end{cases} \quad (2.4.35)$$

where

h_{veg} = vegetation height [m], calculated by the crop module (Chapter 10),

L_{ai} = leaf area index, calculated by the crop module (Chapter 10),

c_d = effective drag coefficient (c_d ≈ 0.07 [ ]) and

z'_0 = the roughness length for momentum for bare soil. This parameter is user defined in *SVAT-SSOC*, by default = 0.0006 [m].

Roughness length for heat

The roughness length for heat is

$$z_{0h} = \frac{z_0}{7} \quad (2.4.36)$$

Aerodynamic stability indicator, η

The aerodynamic stability indicator (η) is according to Choudhury et al. (1986) estimated as:

$$\eta = \frac{5(z_r - d)g(T_0^K - T_a^K)}{T_a^K \cdot u_z^2} \quad (2.4.37)$$

where

z_r = the screen-height [m], equal to the measurement height for wind, specified in the weather file,

g = acceleration of gravity (9.82 [m s^{-2}]),

$T^K{}_a$ = air temperature [K],

u_z = wind speed [m s^{-1}] at screen height,

$T^K{}_0$ = the land surface temperature [K], see eq. (2.4.38).

The equation for land surface temperature is based on Norman et al. (1995) and cited by Houborg (2006):

$$\mathrm{T}_0^{\mathrm{K}} = \sqrt[4]{f_{veg} \cdot (T_c^K)^4 + (1 - f_{veg}) \cdot (T_s^K)^4} \quad (2.4.38)$$

where

T_c and T_s are in [°K], and $f_{veg} = (1 - e^{-k_b \cdot LAI})$.

$\eta < 0$ corresponds to a stable atmosphere while $\eta > 0$ corresponds to an unstable atmosphere.

Aerodynamic resistance, r_a

Aerodynamic resistance, r_a [s m^{-1}] between canopy source height (canopy point) and reference (screen) height above the canopy is estimated as:

$$r_a = \begin{cases} \frac{1}{\kappa^2 u_z}\left[ln\left(\left(\frac{z_r - d}{z_0}\right) - \psi *\right)\right]\left[ln\left(\left(\frac{z_r - d}{z_{0h}}\right) - \psi *\right)\right], \eta \leq 0 \\ \frac{\ln\left(z_r - \frac{d}{z_0}\right)\ln\left(z_r - \frac{d}{z_{0h}}\right)}{\kappa^2 u_z (1+\eta)^{3/4}}, \quad \eta > 0 \end{cases} \quad (2.4.39)$$

where κ is von Karman's constant (0.41 [ ]) and ψ^* is given by:

$$\psi * = \frac{\psi_a - \sqrt{\psi_a^2 - 4(1+\eta) \cdot \eta \cdot \left(ln(z_r - d/z_0)\right)^2}}{2 \cdot (1-\eta)}$$

$$\psi_a = ln\left(\frac{z_r - d}{z_{0h}}\right) + 2\eta \cdot ln\left(\frac{z_r - d}{z_0}\right) \quad (2.4.40)$$

When $\psi^* < -5$, then ψ^* is set to -5 (Choudhury et al., 1986).

Aerodynamic conductance, g_a

Hence, the aerodynamic conductance, $g_a = 1/r_a$, depends on the state variables vegetation height (h_{veg}), leaf area index (L_{ai}), wind speed (u_z), air temperature (T_a), and land surface temperature (T_0).

3.3 Boundary layer conductance of sunlit and shaded leaves

The boundary layer conductances of sunlit and shaded leaves describe the ease with which heat and water vapour is transported from the leaf surface to the canopy air space. The conductances calculated here are used in eq. (2.4.12), (2.4.13), (2.4.15) and (2.4.16). Furthermore, the diffusion coefficients for heat, water and CO_2 (eq. (2.4.41-43) are used to convert the stomatal conductance for heat to stomatal conductance for water and CO_2.

Diffusion coefficients for heat and water vapour

Diffusion coefficients [m^2 s^{-1}] of heat, D_h, water vapour, D_w, and CO_2, D_{CO2}, can be expressed as:

$$D_h = 1.869 \cdot 10^{-5} \left(\frac{P_0}{P}\right)\left(\frac{T_a^K}{273.16\,[K]}\right)^{1.81} \tag{2.4.41}$$

$$D_w = 2.178 \cdot 10^{-5} \left(\frac{P_0}{P}\right)\left(\frac{T_a^K}{273.16\,[K]}\right)^{1.81} \tag{2.4.42}$$

$$D_{CO_2} = 1.381 \cdot 10^{-5} \left(\frac{P_0}{P}\right)\left(\frac{T_a^K}{273.16\,[K]}\right)^{1.81} \tag{2.4.43}$$

where

P_0 = air pressure at sea level, 101,300 [Pa].

P =air pressure at the surface, calculated in eq. (2.6), Chapter 2.

$T^K{}_a$ = air temperature (at screen-height) [K].

Leaf boundary layer conductance due to free convection

Leaf boundary layer conductance for heat (eq. (2.4.44)), water vapour (eq. (2.4.45)), and CO_2 (eq. 2.4.46) due to free convection are calculated according to Houborg (2006):

$$g_{lbf}^H = D_h \left(\frac{\sqrt[4]{g \cdot w_l^3 v^{-2}(T_l^K - T_a^K)(T_a^K)^{-1}}}{w_l}\right) \tag{2.4.44}$$

$$g_{lbf}^w = \begin{cases} 0.5 \cdot g_{lbf}^H (D_w/D_h) & \text{hypostomotous leaves} \\ g_{lbf}^H (D_w/D_h) & \text{amphistomatous leaves} \end{cases} \tag{2.4.45}$$

$$g_{lbf}^{CO_2} = g_{lbf}^w \left(D_{CO_2}/D_w\right) \tag{2.4.46}$$

where

g =acceleration due to gravity (9.82 [m s^{-1}]),

w_l = leaf width, by default 0.03 [m] *in Canopystandard* and *Canopysimple* (unless otherwise specified),

$T^K{}_l$ = leaf temperature [K] (sunlit or shaded leaves) and

v = molecular viscosity, [m^2 s^{-1}] calculated as:

$$v = 1.327 \cdot 10^{-5} \left(\frac{P_0}{P}\right)\left(\frac{T_a^K}{273.16\ [K]}\right)^{1.81} \quad (2.4.47)$$

Leaf boundary layer conductance due to forced convection

Leaf boundary layer conductance for heat, eq. (2.4.48), for water vapour, eq. (2.4.49), and for CO_2, eq. (2.4.50), due to forced convection are also calculated according to Houborg (2006) as:

$$g_{lbu}^{H} = 0.006\sqrt{\frac{u_z \cdot exp(-k_u L_{ai})}{w_l}} \quad (2.4.48)$$

$$g_{lbu}^{w} = \begin{cases} 0.5 \cdot g_{lbu}^{H}(D_w/D_h) & \text{hypostomotous leaves} \\ g_{lbu}^{H}(D_w/D_h) & \text{amphistomatous leaves} \end{cases} \quad (2.4.49)$$

$$g_{lbu}^{CO_2} = g_{lbf}^{w}\left(D_{CO_2}/D_w\right) \quad (2.4.50)$$

where

u_z = wind speed (m s^{-1}) at screen-height (measured values, input),

k_u = parameter describing the vertical variation of wind speed within the canopy (k_u = 0.5 (Houborg, 2006)) and

L_{ai} = leaf area index.

Hypostomotous leaves have stomata on one side of the leaf only, while amphistomotous leaves have stomata on both sides of the leaf.

Total leaf boundary layer conductance, heat

Applying the "big leaf" approach, leaf boundary layer conductance is up-scaled to canopy level according to Wang and Leuning (1998). The total boundary conductance at canopy level for heat for sunlit leaves, eq. (2.4.51), and shaded leaves, eq. (2.4.52), due to the combined effect of free and forced convection is:

$$g_{b-snl}^{H} = L_{ai}^{snl} g_{lbf-snl}^{H} + \frac{1 - exp(-(0.5k_u + k_b)L_{ai})}{0.5k_u + k_b} g_{lbu}^{H} \quad (2.4.51)$$

$$g_{b-shl}^{H} = L_{ai}^{shl} g_{lbf-shl}^{H} + \left[\frac{1 - exp(-0.5k_u L_{ai})}{0.5k_u} - \frac{1 - exp(-(0.5k_u + k_b)L_{ai})}{0.5k_u + k_b}\right] g_{lbu}^{H} \quad (2.4.52)$$

where

L_{ai}^{snl} and L_{ai}^{shl} = the leaf area indices of sunlit and shaded leaves, respectively.

$g_{lbf-snl}^{H}$ and $g_{lbf-shl}^{H}$ = leaf boundary layer conductance for heat of sunlit and shaded leaves, respectively (Eq. 2.4.44), and

k_b = extinction coefficient for black leaves in direct-beam irradiance (see Table 2 or eq. (10.3.11) in Appendix 10.3).

Total leaf boundary layer conductance, water vapour

g^{w}_{b-snl}, g^{w}_{b-shl}, $g^{CO_2}_{b-snl}$ and $g^{CO_2}_{b-shl}$ are estimated by eqs. (2.4.51) and (2.4.52), respectively, by substituting the appropriate leaf boundary layer conductances. The boundary layer conductances depends on the following state variables: total leaf area index, (L_{ai}), sunlit leaf area index, (L^{snl}_{ai}), shaded leaf area index, (L^{shl}_{ai}), wind speed (u_z), air temperature ($T^K{}_a$) and leaf temperature of sunlit ($T^K{}_{snl}$) and shaded leaves ($T^K{}_{shl}$).

Conductance for latent heat from stomata to canopy air

The conductance for latent heat from the stomata of sunlit and shaded leaf surface into the canopy air is given by eqs. (2.4.53) and (2.4.54), respectively:

$$g^{w}_{snl\rightarrow c} = \frac{g^{w}_{b-snl} \cdot g^{w}_{s-snl}}{g^{w}_{b-snl} + g^{w}_{s-snl}} \tag{2.4.53}$$

$$g^{w}_{shl\rightarrow c} = \frac{g^{w}_{b-shl} \cdot g^{w}_{s-shl}}{g^{w}_{b-shl} + g^{w}_{s-shl}} \tag{2.4.54}$$

where

g^{w}_{s-snl} and g^{w}_{s-shl} is the bulk stomatal conductance for sunlit and shaded leaves, respectively [m s^{-1}].

The stomatal conductances for water are derived as described in Appendix 10.3.

3.4 Soil aerodynamic conductance

The soil aerodynamic conductance describes the ease with which heat is transported from the soil surface to the canopy air space. The state variable is used in eq. (2.4.11).

Soil aerodynamic conductance depends on local wind speed

The conductance for transport of heat between the soil surface and a height of the canopy point ($g^{H}_{soil\rightarrow c}$, [m s^{-1}]) can, according to Norman et al. (1995), be estimated as:

$$g^{H}_{soil\rightarrow c} = 0.004 + 0.12 \cdot u_s \tag{2.4.55}$$

where

u_s =a wind speed characterizing the conditions in the canopy air space just above the soil surface [m s^{-1}]. u_s is estimated as:

$$u_s = u_c \cdot exp\left(-a\left(1 - \frac{0.05}{h_{veg}}\right)\right) \tag{2.4.56}$$

$$a = 0.28 \cdot L_{ai}^{2/3} \cdot h_{veg}^{1/3} \cdot l_m^{1/3}$$

where

u_c = a wind speed at the top of the canopy [m s^{-1}],

L_{ai} = leaf area index,

h_{veg} = vegetation height [m], and

l_m = mean leaf size [m], given by four times the leaf area divided by the perimeter. If we assume elliptical leaves and that the major axis equals the leaf width, w_l [m] and the minor axis equals ½ w_l, then we get $l_m \approx 1.26 \cdot w_l$, as calculated below:

$$l_m = \frac{4\pi \cdot w_i \cdot (0.5 \cdot w_i)}{2\pi \cdot \sqrt{0.5 \cdot \left(w_i^2 + (0.5 \cdot w_i)^2\right)}} = \frac{w_i}{\sqrt{0.5} \cdot \sqrt{(1 + 0.5^2)}} \quad (2.4.57)$$

The Monin-Obukhov length

The stability characterized by the Monin-Obukhov length (L_{mo} [m]) is calculated as:

$$L_{mo} = \frac{r_a u_*^3 T_a^K}{\kappa g (T_0^K - T_a^K)} \quad (2.4.58)$$

where

r_a = aerodynamic resistance [s m^{-1}],

u_* = friction velocity [m s^{-1}],

T_a^K = air temperature at screen height) [K],

κ = von Karman's constant (κ = 0.41 [ ]),

g = acceleration due to gravity (9.82 [m s^{-2}]) and

T_0^K = land surface temperature [K], eq. (2.4.38).

L_{mo} is positive in stable conditions and negative in unstable conditions.

The friction velocity

The friction velocity is calculated as:

$$u_* = \frac{\kappa \cdot u_z}{ln[(z_r - d)/z_0]} \quad (2.4.59)$$

where

u_z = wind speed [m s^{-1}] at screen-height (measured data, input),

z_r = screen-height [m], specified in weather file,

d = displacement height [m], calculated in eq. (2.4.34) and

z_0 = roughness length for momentum [m], calculated in eq. (2.4.35)

Estimation of the wind speed at the top of the canopy, u_c [m s^{-1}] depends on the temperature difference between the land surface temperature (T_0) and the air temperature (T_a). If $(T_0 - T_a) \geq 0.1)$, u_z is estimated as:

$$u_c = \begin{cases} u_z \left[\dfrac{ln\left[\left(h_{veg} - d\right)/z_0\right]}{ln[(z_r - d)/z_0] + 4.7(z_r - d)/L_{mo}}\right] & for\ L_{mo} \geq 0 \\ u_z \left[\dfrac{ln\left[\left(h_{veg} - d\right)/z_0\right]}{ln[(z_r - d)/z_0] - \psi}\right] & for\ L_{mo} < 0 \end{cases} \quad (2.4.60)$$

where

$$\psi = ln\left[\left(\frac{1+y}{2}\right)^2\left(\frac{1+y^2}{2}\right)\right] - 2\arctan(y) + \frac{\pi}{2}$$

$$y = \left(1 - 16\left(\frac{z_r - d}{L_{mo}}\right)\right)^{-0.25}$$

and h_{veg} is vegetation height [m].

If $(T_0 - T_a) < 0.1)$, a test value (q) is calculated:

$$q = \frac{ln[(h_{veg} - d)/z_0]}{ln[(z_r - d)/z_0]} \qquad (2.4.61)$$

If $q<0$, $u_c = u_z$, while if $q \geq 0$, $u_c = u_z \cdot q$.

The soil aerodynamic conductance depends on the following state variables: vegetation height (h_{veg}), leaf area index (L_{ai}), wind speed (u_z), air temperature (T_a^K), and soil surface temperature (T_s^K).

4 Determination of state variables and numerical solution (E).

When the boundary conditions, $E_{soil \to c}$ and all conductances are known, the state variables T_s^K, T_c^K, T_{snl}^K, T_{shl}^K, and e_c can be calculated, and subsequently all the fluxes can be estimated. The boundary conditions comprise air temperature, vapour pressure and wind speed at screen height, as well as soil temperature at the depth z_1. The conductances depend on the canopy, which is characterised by vegetation height and leaf area index. Furthermore, conductances depend on state variables. A consequence of this is that the solution to the problem requires iteration.

The basic SVAT equations based on mass and energy conservation (eqs. (2.4.3), (2.4.4) and (2.4.6) through (2.4.8) can now be formulated. Introducing eq. (2.4.10) - (2.4.13) in Eq. (2.4.3) yields:

$$\begin{aligned} c_p\rho_a g_a(T_c^K - T_a^K) &= c_p\rho_a g_{soil \to c}^H(T_s^K - T_c^K) \\ &+ c_p\rho_a g_{snl \to c}^H(T_{snl}^K - T_c^K) \\ &+ c_p\rho_a g_{shl \to c}^H(T_{shl}^K - T_c^K) \end{aligned} \qquad (2.4.62)$$

and introducing the Penman approximation and Eq. (2.4.14 - .16), in eq. (2.4.4) yields:

$$\frac{c_p \rho_a}{\gamma} g_a (e_c - e_a) = \frac{c_p \rho_a}{\gamma} g^{w}_{snl \to c} \left(e^*(T^K_a) + \Delta \left(T^K_{snl} - T^K_a \right) - e_c \right) + \frac{c_p \rho_a}{\gamma} g^{w}_{shl \to c} \left(e^*(T_a) + \Delta \left(T^K_{shl} - T^K_a \right) - e_c \right) + \gamma E_{soil \to c} \quad (2.4.63)$$

where Δ is the slope of the saturation vapour pressure vs. temperature curve at the temperature T_a. This parameter is calculated in eq. (2.3), Chapter 2.

Furthermore, introducing Eq. (2.4.31), Eq. (2.4.9), and Eq. (2.4.11), in Eq. (2.4.6); Eq. (2.4.32), Eq. (2.4.12) and Eq. (2.4.15), in Eq. (2.4.7); and eq. (2.4.33), Eq. (2.4.13), and eq. (2.4.16), in Eq. (2.4.8) yields:

$$R^{Eq}_{abs-soil} - G^{R}_{soil} (T^K_s - T^K_a) = \frac{k_h}{z_1} (T^K_s - T^K_{z1}) + c_p \rho_a g^{H}_{soil \to c} (T^K_s - T^K_c) + \gamma E_{soil \to c} \quad (2.4.64)$$

$$R^{Eq}_{abs-snl} - G^{R}_{snl} \left(T^K_{snl} - T^K_a \right) = c_p \rho_a g^{H}_{snl \to c} \left(T^K_{snl} - T^K_c \right) + \frac{c_p \rho_a}{\gamma} g^{w}_{snl \to c} \left(e^*(T^K_a) + s \left(T^K_{snl} - T^K_a \right) - e_c \right) \quad (2.4.65)$$

$$R^{Eq}_{abs-shl} - G^{R}_{shl} \left(T^K_{shl} - T^K_a \right) = c_p \rho_a g^{H}_{shl \to c} \left(T^K_{shl} - T^K_c \right) + \frac{c_p \rho_a}{\gamma} g^{w}_{snl \to c} \left(e^*(T^K_a) + s \left(T^K_{shl} - T^K_a \right) - e_c \right) \quad (2.4.66)$$

Assuming that the state variables $T^K_s, T^K_c, T^K_{snl}, T^K_{shl}$, and e_c are the only unknown variables, they can be found by solving Eq. (2.4.62) through (2.4.66). When $T^K_s, T^K_c, T^K_{snl}, T^K_{shl}$, and e_c are known, the system is determined and the appropriate sensible heat, latent heat, and radiative fluxes can be calculated. However, several of the conductances depend on the above state variables. Furthermore, the stomatal conductance depends on the photosynthesis, which depends on the stomatal conductance. Hence, the equations must be solved in an iterative manner.

Daisy components

Daisy is structured with a number of components, and each component represents real world identifiable concepts of the system being modeled, for example “crop” or “photosynthesis”. The components most relevant to this article are listed below, together with selected inputs and outputs.

- *raddist*: Distributes radiation between layers of sunlit and shaded leaves.
- *photosynthesis*: Finds assimilate production for sunlit and shaded leaves based on radiation, temperature, nitrogen content, atmospheric CO_2 concentration, and stomatal conductance.

- *stomatacon*: Finds stomatal conductance based on assimilate production, humidity, ABA concentration in the xylem sap, and crown water potential.
- *RootSystem*: Finds crown water potential and water uptake as a function of soil pressure potential (head) and potential transpiration.
- *ABAproduction*: Find the ABA concentration in the xylem as a function of water uptake and soil pressure potential.
- *SVAT*, *SSOC*: Find temperatures, humidity and actual transpiration based on radiation and stomatal conductance.

Loops

There are several cyclic dependencies between these components. Three levels of iteration loops are used for finding a solution. The innermost loop is internal to the photosynthesis component and used for finding matching values for surface CO_2 and assimilate production, keeping all other factors constant. This loop resides inside a loop that tries to find matching values for assimilate production and stomatal conductance.

The outermost loop is the most complex one. The actual transpiration calculated by the *SVAT* component is used as potential transpiration, the resulting crown water potential and root ABA production is used for the already coupled stomatal conductance and assimilate production (together with the temperatures and humidity from the *SVAT* component), and the stomatal conductance is then used by the *SVAT* component. When a solution is found, the value for the water uptake calculated by the *RootSystem* component should be identical to the value for the transpiration from the *SVAT* component.

The innermost loop is solved using Newton-Raphson iteration as the functions are fixed and simple enough to derive, the middle loop is solved by using the result of the last guess to find the next and assuming convergence, and the outmost loop is solved by using a binary search algorithm.

5 Parameter overview

Table 3. Related Parameter names in Daisy.

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
$\sigma(PAR)$	Leaf scattering coefficient of PAR	raddist, sun-shade	*Sigma_PAR*	0.15	[ ]
$\sigma(NIR)$	Leaf scattering coefficient of NIR	raddist, sun-shade	*Sigma_NIR*	0.83	[ ]
$\rho_s(PAR)$	Soil reflection coefficient of PAR	raddist, sun-shade	*Ps_PAR*	0.1	[ ]
$\rho_s(NIR)$	Soil reflection coefficient of NIR	raddist, sun-shade	*Ps_NIR*	0.18	
	Effect of soil water (pF) on $\rho_s(PAR)$.	raddist, sun-shade	*Ps_PAR_SWE*	plf, default is a constant value of 1	[pF -><none>]
	Effect of soil water (pF) on $\rho_s(NIR)$.	raddist, sun-shade	*Ps_NIR_SWE*	plf, default is a constant value of 1	[pF -><none>]
hyposto-matous	Defines whether the leaves have stomata on one side (true), or on both sides (false)	svat, SSOC	*hypostomatous*	true	
z'_0	Bare soil roughness height for momentum	svat, SSOC	*z_0b*	0.0006	[m]
ε_i	Leaf emmisivity for long wave radiation	svat, SSOC	*epsilon_leaf*	0.98	[fraction]
ε_s	Soil emmisivity for long wave radiation	svat, SSOC	*epsilon-soil*	0.95	[fraction]
	Effect of soil water (pF) on *epsilon-soil*.	svat, SSOC	*epsilon-soil_SWE*	plf, default is a constant value of 1	[pF -><none>]

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
	Model (solver component) used for solving the energy balance equation system	svat, SSOC	*solver*	exsparse	
	Largest number of interations before giving up on convergence.	svat, SSOC	*max_iteration*	1500	
K_l	Extinction coefficient used for transpiration, eq. (3.35)	CanopySimple, CanopyStandard	*EPext*	0.5	[ ]
w_l	Used by the SSOC-model for calculation of boundary layer conductance of sunlit and shaded leaves, as well as for calculation of soil aerodynamic conductance.	CanopySimple, CanopyStandard	*leaf_width*	User defined plf, default = constant value of 3	[DS-> cm]
h_{veg}	Crop height as function of DS	CanopyStandard	*HvsDS*	User specified	[DS->cm]

Original text from	Plauborg et al. (2010)	
Updated by	date	For Daisy version
Styczen, M	2025-03-18	6.47

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