

Supplementary Material (S1)

S1: Detailed model design, structure and equations in CoupModel

1. Soil surface energy balance

Energy balance is important to land surface exchanges in CoupModel. In computing the energy fluxes, total net radiation ($R_{n,tot}$) was calculated from net longwave radiation and shortwave incoming radiation R_{is} . LW_{in} was estimated from meteorological measurements using Konzelmann et al. (1994) function, while R_{is} is one of the driving variables of the model. The fluxes were partitioned in CoupModel according to the surface energy balance (eq.A1),

$$\underbrace{\underbrace{\sigma(\varepsilon_s(T_s + 273.15)^4)}_{LW_{out}} - \underbrace{\varepsilon_a(T_a + 273.15)^4}_d}_{R_{n,tot}} + (1 - a_r)R_{is} = H + LE + q_h + \frac{dF}{dt} \quad (eq. A1)$$

where LW_{out} is the longwave radiation emitted from the ground calculated by using simulated temperature of soil surface, T_s with consideration of snow surface temperatures in winter. LW_{in} represents the incoming longwave radiation from the atmosphere which is based on measured air temperature, T_a (forcing variable). σ is the Stefan-Boltzmann constant and is the ε_s emissivity of the ground. Atmospheric emissivity ε_a is estimated from Konzelmann et al (1994) function. The surface albedo of ground a_r was simulated by considering the dynamic area cover of peat soil and snow. Peat soil albedo was set to 7% as measured by Munro et al. (2010). The snow approach used in the study follows Gustafsson et al. (2001) where snow albedo was assumed to be a function of snow age with 90% for newly formed snow which decreased to 40% c.a. 1 month time. CoupModel partitioned $R_{n,tot}$ into latent (LE), sensible (H) and soil heat flux (q_h) fluxes respectively. Change energy storage (dF/dt) within the measured reference height ($Z_{ref}= 1.5m$) and soil surface was assumed to be zero in the study.

The model calculated H and LE between the soil surface and reference level of meteorological inputs from gradients of temperature and vapour pressure respectively

$$H_s = \rho_a c_p \frac{T_s - T_a}{r_{as}} \quad (eq. A2)$$

$$LE = \frac{\rho_a c_p}{\gamma} \frac{(e_{surf} - e_a)}{r_{as}} \quad (eq. A3)$$

$$q_h = k_h \frac{T_s - T_l}{\frac{\Delta z_l}{2}} \quad (eq. A4)$$

Where ρ_a is the soil density, c_p is the air heat capacity, γ is the psychrometric constant, e_{surf} is the vapour pressure of the soil surface, e_a is the actual vapour pressure of the atmosphere (forcing variable), aerodynamic resistance above the soil surface r_{as} which was assumed to be the same for sensible and latent heat flux. Under neutral conditions, r_{as} (eqs. 2 & 3) was calculated as a function of wind speed and temperature gradients,

$$r_{as} = \frac{1}{k^2 u} \ln \left(\frac{z_{ref}-d}{z_{OM}} \right) \ln \left(\frac{z_{ref}-d}{z_{OH}} \right) \quad (\text{eq. A5})$$

Where measured wind speed, u (forcing variable) was given at the reference height, k (=0.4) is von Karman's constant, d is the displacement height ($d=0$), z_{OM} and z_{OH} are the roughness length for momentum and heat respectively. Under non-neutral conditions, eq. (A5) was further corrected with the Monin-Obukhov stability function (Beljaars and Holtslag 1991). This involves a dimensionless factor kB^{-1} . In this study, $kB^{-1} = 2.3$ was obtained from the synthesized value from available measured peatland data (Humphreys et al., 2006)

Alvenas and Jansson (1997) scheme was used to account for the non-equilibrium effects of rapid moisture fluctuations close to the soil surface. This was done by modifying e_{surf} by an available factor that is driven by soil moisture availability (eq. A7) calculated by water balance at the first soil layer (eq. A8)

$$e_{surf} = e(T_s) * \exp \left(\frac{\psi M_w g e_c}{R(T_s + 273.15)} \right) \quad (\text{eq. A6})$$

$$e_c = 10^{(-\delta \psi_g)} \quad (\text{eq. A7})$$

$$\delta_s(t) = \max(-2, \min(1, \delta_s(t-1) + (P - E)\Delta t)) \quad (\text{eq. A8})$$

Where $e(T_s)^*$ is the saturated vapor pressure at the surface temperature T_s , ψ is the mean soil water potential in the topsoil layer, g is the gravity constant, and R is the gas constant, e_c is an empirical correction factor that compensates for the differences between the mean soil moisture potential in the top-soil layer and the soil moisture potential at the surface, defined as eq. (A7), eq. (A8) calculates the water balance and was assumed to vary from a deficit of -2mm to a surplus of +1mm at one timestep t , where δ_s and ψ_g are parameters.

2. Soil temperature

Soil heat flux q_h in eq. (A1) was further used to calculate the soil temperature profile by considering heat conduction and convection flow (eqs. A9-A11),

$$q_h = -k_h \frac{\partial T_s}{\partial z} + C_w T_s q_w \quad (\text{eq. A9})$$

$$k_h = h_1 + h_2 \Theta \quad (\text{eq. A10})$$

$$\frac{\partial(CT)}{\partial t} - L_f \rho \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} (-q_h) \quad (\text{eq. A11})$$

Where dT/dz is the gradient of soil temperature with depth, k_h is the thermal conductivity of peat soil calculated by an empirical approach of de Vries (1975), assuming proportional to the soil water content, Θ and h_1 and h_2 are parameters (eq. 10). The subscript h in eq. (A9) is heat, w is liquid water, i and f in eq. (A11) refer to ice and freezing respectively, t is time, C is heat capacity, L_f is latent heat of melting. In this study model default values were used for the snow and soil frost modules.

3. Soil water flow

The soil water process (eqs. A12-A13) was described based on the matrix flow and bypass flow,

$$q_w = -k_w \left(\frac{\partial \psi}{\partial z} - 1 \right) + q_{\text{bypass}} \quad (\text{eq. A12})$$

$$\frac{\partial \theta}{\partial t} = - \frac{\partial q_w}{\partial z} \quad (\text{eq. A13})$$

Where q_w is the water flow flux, k_w is the unsaturated hydraulic conductivity, ψ is the water tension/potential and q_{bypass} is the bypass flow.

The soil water retention curve was based on the van Genuchten (1980) approach

$$S_e = \frac{1}{(1 + (\alpha \psi)^n)^m} = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (\text{eq. A14})$$

Where S_e is the effective saturated water content, α , n , m are van Genuchten parameters ($m=1-1/n$), θ_r is the residual water content, θ_s is the saturated water content.

The (un)saturated hydraulic conductivity was calculated by Mualem (1976) and modified to consider macropores (pp 63-68 in Jansson and Karlberg, 2011)

$$k_w^* = k_{\text{mat}} S_e^{(n+2+\frac{2}{\lambda})} \quad (\text{eq. A15})$$

$$k_{\text{mat}} = 10^{((\log k_{\text{sat}} - \log h_{\text{com}}) h_{\text{sens}} + \log k_{\text{sat}})} \quad (\text{eq. A16})$$

$$k_w^{**} = 10^{\left(\log(k_w^* (\theta_s - \theta_m)) + \frac{\theta - \theta_s + \theta_m}{\theta_m} \log\left(\frac{k_{\text{sat}}}{k_w^* (\theta_s - \theta_m)}\right)\right)} \quad (\text{eq. A17})$$

$$k_w = (r_{\text{AOT}} + r_{\text{AIT}} T_s) \max(k_w^{**}, k_{\text{minus}}) \quad (\text{eq. A18})$$

Where (eqs. A15-A16) accounts for the matric pores, k_w^* is the unsaturated hydraulic conductivity, k_{mat} is the saturated matrix conductivity, h_{com} and h_{sens} are parameters. The (eq. A17) additionally accounts for the conductivity in macropores, θ_m is the water content at which the macropore water flow occurs, k_{sat} is the saturated total hydraulic conductivity and $k_w^* (\theta_s - \theta_m)$ is the unsaturated hydraulic conductivity calculated by eq. (A15), the effects of temperature on hydraulic conductivity were calculated by eq. (A18), r_{AOT} and r_{AIT} are scaled parameters for temperature, k_{minus} is the minimum hydraulic conductivity parameter.

The bypass flow (eqs. A19-A21) was calculated by an empirical approach (Jansson et al., 2005)

$$q_{\text{bypass}} = \begin{cases} 0 & 0 < q_{\text{in}} < S_{\text{mat}} \\ q_{\text{in}} - q_{\text{mat}} & q_{\text{in}} \geq S_{\text{mat}} \end{cases} \quad (\text{eq. A19})$$

$$q_{\text{mat}} = \begin{cases} \max\left(k_w(\theta) \left(\frac{\partial \psi}{\partial z} + 1\right), q_{\text{in}}\right) & 0 < q_{\text{in}} < S_{\text{mat}} \\ S_{\text{mat}} & q_{\text{in}} \geq S_{\text{mat}} \end{cases} \quad (\text{eq. A20})$$

$$S_{\text{mat}} = a_{\text{scale}} a_r k_{\text{mat}} pF \quad (\text{eq. A21})$$

Where q_{in} is the infiltration rate, S_{mat} is the sorption capacity rate, k_{mat} is the maximum conductivity of the matric pores, a_r is the compartment thickness (for each layer), pF is $10^{\log}$ of the water tension ψ and a_{scale} is the sorption scaling coefficient.

The lateral flow across the swamp was calculated by Darcy-type function (He et al., 2021),

$$q_{\text{wp}} = \int_{z_p}^{z_{\text{sat}}} k_{\text{sat}} \frac{(z_{\text{sat}} - z_p)}{d_u d_p} dz \quad (\text{eq. A22})$$

Where q_{wp} is the horizontal flow rate, d_u is the unit length of the horizontal element, z_{sat} is the simulated depth of the groundwater level, k_{sat} is the saturated hydraulic conductivity of each soil layer including macropores, d_p is the distance between drainage pipes, z_p is the level of drainage pipes.

During over-saturated periods (e.g. snowmelt and heavy rainfall), the flow of water in the upper soil layer can be directed upwards and added to the surface runoff to drainage pipes. The model formed a pool of water on the soil surface when precipitation exceeded the infiltration capacity of the first soil layer. Water in the surface pool could either infiltrate with a delay into the soil profile or be lost as surface runoff, as overland flow. The flow was regulated by a first-order runoff coefficient (eq. A21)

4. Plant biotic processes

Canopy photosynthetic rate and C assimilation was estimated by light use efficiency approach,

$$C_{atm \rightarrow a} = \varepsilon_l \eta f(T_l) f(CN_l) f\left(\frac{E_{ta}}{E_{tp}}\right) R_{s,pl} \quad (eq. A23)$$

Where rate of photosynthesis ($\text{g C m}^{-2} \text{ day}^{-1}$), $C_{atm \rightarrow a}$ is a function of global radiation absorbed by the swamp's canopy $R_{s,pl}$ but ultimately this is constrained by unfavorable temperature $f(T_l)$, nitrogen $f(CN_l)$, and water $f\left(\frac{E_{ta}}{E_{tp}}\right)$ conditions. ε_l is the radiation use efficiency and η is the conversion factor from biomass to carbon

where ε_L is the radiation use efficiency and η is the conversion factor from biomass to carbon. $R_{s,pt}$ is the global radiation absorbed by canopy and $f(T_l)$, $f(CN_l)$, and $f(E_{ta}/E_{tp})$ limitations due to unfavourable temperature, nitrogen, and water conditions.

Response function for leaf temperature $f(T_l)$

$$f(T_l) = \begin{cases} 0 & T_l < p_{\max} \\ (T_l - p_{\min})/(p_{o1} - p_{\max}) & p_{\max} \leq T_l \leq p_{o1} \\ 1 & p_{o1} < T_l < p_{o2} \\ 1 - (T_l - p_{o2})/(p_{\max} - p_{o2}) & p_{o2} \leq T_l \leq p_{\max} \\ 0 & T_l > p_{\max} \end{cases} \quad (eq. A24)$$

where $p_{\min}$, p_{o1} , p_{o2} and $p_{\max}$ are parameters and T_l the leaf temperature.

Response function for fixed leaf C:N ratio $f(CN_l)$

$$f(CN_l) = p_{\text{fixedN}} \quad (eq. A25)$$

Where p_{fixedN} is a parameter.

Response function for transpiration $f(E_{ta}/E_{tp})$

$$f(E_{ta}/E_{tp}) = \frac{E_{ta}}{E_{tp}} \quad (eq. A26) \quad \text{where } E_{ta} \text{ and } E_{tp} \text{ are actual and potential transpiration}$$

Allocation of new assimilates to the leaves $C_{a \rightarrow \text{Leaf}}$

$$C_{a \rightarrow \text{Leaf}} = l_{c1} \cdot C_a \quad (\text{eq. A27}) \quad \text{where } l_{c1}, \text{ is a parameter and } C_a \text{ is the new assimilated carbon}$$

Allocation of new assimilates to the roots $C_{a \rightarrow \text{Root}}$

$$C_{a \rightarrow \text{Root}} = (1 - l_{c1}) \cdot C_a \quad (\text{eq. A28}) \quad \text{where } l_{c1}, \text{ is a parameter and } C_a \text{ the new assimilated carbon.}$$

The plant growth and maintenance respiration processes ($\text{g C m}^{-2} \text{ day}^{-1}$) are estimate by

$$C_{\text{respleaf}} = k_{\text{mrespleaf}} \cdot f(T_a) \cdot C_{\text{leaf}} + k_{\text{gresp}} \cdot C_{a \rightarrow \text{Leaf}} \quad (\text{eq. A29})$$

Where $k_{\text{mrespleaf}}$ is the maintenance coefficient for leaves, k_{gresp} is the growth respiration coefficient, $f(T_a)$ is the temperature response, $C_{a \rightarrow \text{Leaf}}$ is the carbon allocation to leaf and C_{leaf} is the carbon content of leaf. Similar methods were used for stem and root respiration estimates. In this case, the equation calculates respiration from stem and roots by substituting $k_{\text{mrespleaf}}$ with $k_{\text{mrespstem}}$, & k_{mrespoot} and using the corresponding storage pools. Respiration from the old carbon pools is estimated with the same maintenance respiration coefficients that is used for respiration from new carbon pools.

Temperature response for maintenance respiration

$$f(T) = t_{Q10}^{(T - t_{Q10}^{\text{lose}})/10} \quad (\text{eq. A30}) \quad \text{where } t_{Q10} \text{ and } t_{Q10 \text{ bas}} \text{ are parameters.}$$

Reallocation of C from leaf pool to stem pool. It is represented here as pool for senescent leaves

$$C_{\text{Leaf} \rightarrow \text{Sem}} = I_{LS} \cdot C_{\text{Leaf}} \text{ where } I_{LS} \text{ is a parameter and } C_{\text{Leaf}} \text{ the carbon in the leaf pool.}$$

Leaf C entering the surface litter pool

$$C_{\text{Leaf} \rightarrow \text{LitterSurface}} = f(T_{\text{Sum}}) \cdot f(A_l) \cdot S_{\text{newleaf}} \cdot C_{\text{Leaf}} \quad (\text{eq. A31})$$

where S_{newleaf} is a scaling factor and stem C is calculated analogously with S_{newstem}

Leaf litter fall dependence of temperature sum

$$f(T_{\text{Sum}}) = l_{Lc1} + (l_{Lc2} - l_{Lc1}) \cdot \min\left(1, \frac{\max(0, T_{\text{Sum}} - t_{L1})}{\max(1, t_{L2} - t_{L1})}\right) \quad (\text{eq. A32})$$

where t_{L1} , t_{L2} , l_{Lc1} and l_{Lc2} are parameters and T_{Sum} is the so called "dorming" temperature sum, $T_{\text{Dormsum}} \cdot T_{\text{Dormsum}}$ is calculated at the end to the growing season when air temperature is below the

threshold temperature $T_{DormTth}$, as the accumulated difference between $T_{DormTth}$ and T_a . $T_{DormTth}$ is a parameter. The stem litter rate is calculated analogously with the parameters t_{Sl} , t_{S2} , I_{Sl} and I_{Sc2} .

Leaf litter fall dependence of LAI

$$f(A_l) = e^{I_{LaiEnh} \cdot A_l} \quad (\text{eq. A33})$$

where I_{LaiEnh} is a parameter and A_l the leaf area index

Root C entering the soil litter pool of the corresponding layer

$$C_{Root \rightarrow Litter} = f(l_{Rc}) \cdot C_{Root} \cdot S_{newroot} \quad (\text{eq. A34})$$

where $S_{newroot}$ is a scaling factor. The root litter rate function, $f(l_{Rc})$, can be calculated with Eq. (A32) by exchanging the parameters t_{L1} , t_{L2} , l_{Lc1} and l_{Lc2} to t_{R1} , t_{R2} , l_{Rc1} and l_{Rc2} .

Litter fall from roots, leaves and stems in “old” biomass are calculated similarly to the “new” biomass but with the important exception that some of the old leaves may be retained

$$C_{OldLeaf \rightarrow LitterSurface} = f(l_{Lc}) \cdot (C_{OldLeaf} - C_{RemainLeaf}) S_{old leaf} \quad (\text{eq. A35})$$

where $S_{oldleaf}$ is a scaling factor. The litter fall for stems and roots is calculated analogously.

Fraction of the whole $C_{OldLeaf}$ pool that will be excluded from the calculation of the litterfall from the old leaves

$$C_{RemainLeaf} = C_{OldLeaf} \left(1 - \frac{1}{l_{life} - 1} \right) \quad \text{where } l_{life} \text{ is a parameter (eq. A36)}$$

Allocation to the mobile C pool for developing new leaves during litter fall

$$C_{Mobile} = (C_{Leaf \rightarrow LitterSurface} + C_{OldLeaf \rightarrow LitterSurface}) \cdot m_{retain} \quad (\text{eq. A37})$$

where m_{retain} is an allocation coefficient

Allocation from mobile C pool at leafing as an additional supply. This process goes on as long there is C left in the mobile pool.

$$C_{Mobile \rightarrow Leaf} = C_{Mobile} \cdot m_{shoot} \quad (\text{eq. A38})$$

where m_{shoot} is an allocation coefficient and C_{Mobile} the carbon in the mobile pool.

5. Plant abiotic process

Plant interception of global radiation (MJ m⁻² day⁻¹)

$$R_{s,pl} = \left(1 - e^{-k_{rn} \frac{A_l}{f_{cc}}}\right) \cdot f_{cc} (1 - a_{pl}) R_{is} \text{ (eq. A39)}$$

where k_{rn} is the light use extinction coefficient given as a single parameter common for all plants, f_{cc} is the surface canopy cover, a_{pl} is the plant albedo and R_{is} , is the global radiation

Surface canopy cover (m²m⁻²)

$$f_{cc} = p_{cmax} (1 - e^{-p_{ck} A_l}) \text{ (eq. A40)}$$

Where p_{cmax} is a parameter that determines the maximum surface cover and p_{ck} is a parameter that governs the speed at which the maximum surface cover is reached. A_l is the leaf area index of the plant.

Leaf Area Index (m²m⁻²)

$$A_l = \frac{B_l}{p_{l,sp}} \text{ (eq. A41)}$$

Where $p_{l,sp}$ is a parameter estimated from specific leaf area and B_l is the total mass of leaf (i.e leaf C content in the leaves, $C_{Leaf} + C_{OldLeaf}$).

Potential transpiration (m²m⁻²)

$$L_v E_{tp} = \frac{\Delta R_n + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \text{ (eq. A42)}$$

where R_n is net radiation available for transpiration, e_s is the vapour pressure at saturation, e_a is the actual vapour pressure, ρ_a is air density, c_p is the specific heat of air at constant pressure, L_v is the latent heat of vaporisation, Δ is the slope of saturated vapour pressure versus temperature curve, γ is the psychrometer 'constant', r_s is 'effective' surface resistance and r_a is the aerodynamic resistance.

$$r_s = \frac{1}{\max(A_l g_l, 0.001)} \text{ (eq. A43)}$$

where g_l is the leaf conductance.

$$g_l = \frac{R_{is}}{R_{is} + g_{ris}} \frac{g_{\max}}{1 + \frac{(e_s - e_a)}{g_{vpd}}} \quad (\text{eq. A43})$$

where g_{ris} , $g_{\max}$ and g_{vpd} are parameter values, $g_{\max\text{win}}$ corresponds to g_{vpd} in winter. R_{is} , is the global radiation and $(e_s - e_a)$ the vapour pressure deficit.

6. Soil respiration process

Decomposition of soil organic matter was simulated by first-order kinetics (eqs. A44-A45),

Decomposition of the fast C pools ($\text{g C m}^{-2} \text{ day}^{-1}$)

$$C_{\text{DecompL}} = k_l \cdot f(T) \cdot f(\theta) \cdot C_{\text{labile}} \quad (\text{eq. A44})$$

where k_l is a parameter that describes the 1st order decomposition rates and $f(T)$ and $f(\theta)$ are response functions for soil temperature and moisture in the certain layer

Decomposition of the slow C pools ($\text{g C m}^{-2} \text{ day}^{-1}$)

$$C_{\text{DecompL}} = k_h \cdot f(T) \cdot f(\theta) \cdot C_{\text{refractory}} \quad (\text{eq. A45})$$

where k_h is a parameter that describes the decomposition rates and $f(T)$ and $f(\theta)$ are response functions for soil temperature and moisture in the certain layer

Response function for soil temperature

$$f(T) = t_{Q10}^{(T - t_{Q10\text{bas}})/10} \quad (\text{eq. A46})$$

Where t_{Q10} and $t_{Q10\text{bas}}$ are parameters and T is the soil temperature in the certain layer.

Response function for soil moisture was calculated by (eq. A47)

$$f(\theta) = \min \left(\begin{array}{l} \left(\frac{\theta_s - \theta}{p_{\theta Upp}} \right)^{p_{\theta p}} (1 - p_{\theta \text{satact}}) + p_{\theta \text{satact}}, \\ \left(\frac{\theta - \theta_{\text{wilt}}}{p_{\theta Low}} \right)^{p_{\theta p}} \end{array} \right) \quad \begin{array}{l} \theta = \theta_s \\ \theta_{\text{wilt}} \leq \theta \leq \theta_s \\ 0 \\ \theta < \theta_{\text{wilt}} \end{array}$$

where $p_{\theta_{\text{Upp}}}$, $p_{\theta_{\text{Low}}}$, $p_{\theta_{\text{Satact}}}$ and $p_{\theta_{\rho}}$ are parameters and the variables, θ_s , θ_{wilt} , and θ , are the soil moisture content at saturation, the soil moisture content at the wilting point, and the actual soil moisture content, respectively. Soil respiration was assumed to be optimal at 60% and decreased linearly with either water content above or below (Or et al., 2007). The produced CO_2 was assumed to emit directly into the atmosphere thus no transpiration of CO_2 gas in the soil profile was simulated.

Litter from inactive surface litter pool entering the fast SOC pool at continuous rate

$$C_{\text{LitterSurface} \rightarrow \text{Litter } l} = l_{l1} \cdot C_{\text{LitterSurface}} \quad (\text{eq. A48})$$

where l_{l1} is a parameter and $C_{\text{LitterSurface}}$ the carbon in the surface litter pool.

Amount of decomposition product from fast SOC pools being released as CO_2

$$C_{\text{Litter} \rightarrow \text{CO}_2} = (1 - f_{e,l}) \cdot C_{\text{DecompL}} \quad (\text{eq. A49})$$

Amount of decomposition products from fast SOC pools entering the slow decomposition pools

$$C_{\text{Litter} \rightarrow \text{refractory}} = f_{e,l} \cdot f_{h,l} \cdot C_{\text{DecompL}} \quad (\text{eq. A50})$$

Amount of decomposition products from the slow SOC pools being returned to the fast decomposition pools

$$C_{\text{Litter} \rightarrow \text{Litter}} = f_{e,l} (1 - f_{h,l}) \cdot C_{\text{DecompL}} \quad (\text{eq. A51})$$

Amount of decomposition products from the slow SOC pools being released as CO_2

$$C_{\text{refractory} \rightarrow \text{CO}_2} = f_{e,l} \cdot C_{\text{DecompL}} \quad (\text{eq. A52})$$

Where C_{DecompL} represents the decomposition rate of litter pool, $f_{e,l}$ is the efficiency of decay of litter and $f_{h,l}$ is the fraction of C and N in the labile pool that will enter the refractory C pool.

S2: Initial Carbon and Nitrogen layers used for Beverly Swamp in Coup

Depth	Init L1C (active) (g/m2)	Init HC (passive) (g/m2)	Init L1N (active) (gN/m2)	Init HN (passive) (gN/m2)
0-5	1067.949	1220.513	30.51282	61.02564
5-10	1719.494	1965.136	49.12839	98.25678
10-15	1747.074	1996.656	49.9164	99.8328
15-20	311.4887	5161.813	8.899677	258.0906
20-25	207.8285	3444.015	5.937956	172.2007
25-30	358.1405	5934.9	10.23259	296.745
30-40	1020.338	5247.451	29.1525	262.3725
40-50	1056.745	5434.69	30.19272	271.7345
50-65	649.2692	3339.099	18.55055	166.9549
65-80	1091.221	5611.992	31.17774	280.5996
80-100	1111.299	18415.81	31.7514	920.7905
100-120	647.3291	10727.17	18.49512	536.3584
120-150	1058.263	17536.93	30.23609	876.8466

S3: List of model parameters used in the model run that differ from the model default for Beverly swamp

Symbol	Parameters	Value	Units	References
Z_o	Surface roughness length	2.7±0.5	m	Munro 1987 & Munro et al 2000
P_{ral}	Air resistance inside canopy	6.7-10	s/m	Munro 1987 & Munro et al 2000
g_{max}	Maximal conductance of fully stomata	0.01-0.02	m/s	Munro 1987 & Munro et al 2000
g_{ris}	Global radiation intensity that represents half-light saturation in light response	5300000	J/m ² /day	Thambipillai, 2000
g_{vpd}	Vapour pressure deficit that corresponds to a 50% reduction of stomata conductance	125	Pa	Munro 1987 & Munro et al 2000
α_{dry}	Soil albedo when tension >104cm H ₂ O	7	%	Munro et al 2000; Thambipillai, 2000
α_{wet}	Soil albedo when tension <10cm H ₂ O	15	%	Munro et al 2000; Thambipillai, 2000
α_{leaf}	Albedo of vegetation canopy	15-16	%	Munro et al 2000; Thambipillai, 2000
kB^{-1}	Difference between the natural logarithm of surface roughness length for momentum and heat	2.5	-	Munro et al 2000; Thambipillai, 2000
θ_{sat}	Total porosity	80-85	Vol %	Czerneda, 1985 & Munro 1982
θ_m	Macroporosity	18-28	Vol %	Word et al., 2022

K_{sat}	Total saturated hydraulic conductivity ¹	125-0.08	mm d-1	Gupta et al. (2023); Czerneda, 1985
α_{surf}	First-order coefficient for surface runoff	0.4	—	assumed
$P_{\theta Low}$	Lower range for moisture response	12	Vol%	assumed
$P_{\theta Low}$	Upper range for moisture response	12	Vol%	assumed
α_{scale}	The first-order coefficient for the surface runoff	0.1	—	Assumed
θ_r	Residual water content	22	Vol %	Dimitrov and Lafleur (2021); Menberu et al. (2021) ; Letts et al. (2000); Liu and Lennartz et al. (2018)
θ_{wilt}	Wilting point	30	Vol %	
W_{pmax}	Maximum amount of water stored on soil surface without causing surface runoff	200	mm	Valverde, 1978; Woo and Valverde (1981)
t_{WA}	Temperature coefficient in the temperature response function	0.59	--	Assumed
t_{WB}	Temperature coefficient in the temperature response function	0.28	--	Assumed
Δz_{humus}	The thickness of peat layer	0.85	m	Munro et al. 2000
k_{rn}	Extinction coefficient	0.52		Thambipillai, 2000

¹ K_{sat} values were used for the simulated 12 layers which is arranged from top to bottom layer above

l_{life}	Max leaf lifetime	2	Years	Welch, 1985
p_{life}	Max plant lifetime	400	years	Kanda et al (1996); Withington et al. (2006)
ε_L	Radiation use efficiency for photosynthesis at optimum temperature, moisture and C-N ratio	2.8 - 4	gDw/MJ	Horn & Schulz, 2010; Wang et al., 2020
k_{gresp}	Growth respiration coefficient	0.17	Day-1	Amthor & Baldochhi (2001); Amthor 1984; Amthor 1986; Cannel & Thornley, 2000
$k_{mresp\ leaf}$	Maintenance respiration coefficient for leaves	0.002	Day-1	
$k_{mresp\ stem}$	Maintenance respiration coefficient for stem	0.0001	Day-1	
$k_{mresp\ root}$	Maintenance respiration coefficient for root	0.015	Day-1	
$k_{mresp\ coarse\ root}$	Maintenance respiration coefficient for coarse root	0.0008	Day-1	
m_{retain}	coefficient for determining allocation to mobile internal storage pool	0.9	Day-1	assumed
m_{shoot}	Coefficient for determining allocation from the mobile pool to the leaf at leafing.	0.5	Day-1	assumed
l_{Lc1}	rate coefficient for the leaf litter fall before the first threshold	0.001	Day-1	Thambipillai, 2000

	temperature sum tL1 is reached			
l_{Le2}	rate coefficient for the leaf litter fall after the second threshold temperature sum tL2 is reached	0.05	Day-1	Thambipillai, 2000
l_{Sc1}	rate coefficient for the litter fall from stems before the first threshold temperature sum tS1 is reached	1.73e-05	Day-1	Thambipillai, 2000
k_l	First-order decomposition coefficient for labile C	0.001	Day	Field measurement (unpublished), (Literature) Kendall et al (2020)
k_h	First-order decomposition coefficient for refractory C	3×10^{-6}	day	Field measurement (unpublished), Middleton et al. (2020)
l_h	Fraction of above ground residues that enter litter 1 pool	0.001	day	Kendall et al (2020)
cn_m	C:N of soil microbes	7	–	Wang et al. (2015)
C_{tot}	Total soil C at 1.5 m profile	98083	gC/m ²	Waddington et al. (unpublished data); Schmidt et al. (2024)
$C_{tot, layer}$	Total soil C for each simulated layer* ²	13623	gC/m ²	
Q_{10}	Q_{10} value for decomposition	2-3	-	Byun et al. (2021)
T_{aamp}	Amplitude of analytical air temperature	12	oC	Weather station data

² This is an average as different values were used for different layers

T_{amean}	Mean value in air temperature function (also for estimating lower boundary condition)	7.64	oC	Weather station data
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S4: Result of initial parameter screening using One-at-a-time

Parameter	Temperature (1)	Temperature (6)	Saturation Level	TotalWater Content(1)	TotalWater Content(6)	Soil respiration	Radiation Net Tot	TotalLatent Flow	TotalSensible Flow	LeafArea Index(1)	Snow Depth	Surface pool
TemQ10												
TempAirMean												
Theta Lower Range												
Theta upper Range												
Reference Height												
AlbedoLeaf												
TemQ10Bas												
Albedo Dry												
Albedo Wet												
CritThresholdDry												
DrainSpacing												
PrecA0Corr												
PrecA1Corr												
MeltCoefAirTemp												
MeltCoefGlobRad												
KBMinusOne												
RaIncreaseWithLAI												
WindLessExchange Canopy												
WithinCanopyRes												
TempDiffPrec_Air												
CN Ratio Microbe												
RateCoefHumus												
RateCoefLitter1												
RateCoefSurf L1												
SaturationActivity												

AScaleSorption												
SPMaxCover												
SurfCoef												
SPCoverTotal												
SurfPoolMax												
GWSourceFlow												
GWSourceLayer												
AirMinContent												
TempCoefA												
TempCoefB												
CFrozenSurfCorr												
Maximal Cover												
Specific LeafArea												
MaxLeafLifetime												
Max Plant Lifetime												
Shoot Coef												
MobileAlloCoef												
RadEfficiency												
Leafc1												
RootWaterc1												
RootCNc1												
RootMassc1												
GrowthCoef												
MCoefLeaf												
MCoefStem												
MCoefRoot												
MCoefCoarseRoot												
LeafRate1												
LeafRate2												
LeafTsum1												

stemRate1												
stemRate2												
StemTsum1												
RootRate1												
Rootrate2												
CoarseRootRate1												
CoarseRootRate2												
LAI enh Coef												
Roughness Min												
AirResisLAI Effect												
Conduct Ris												
Conduct VPD												
Conduct Max												
Roughness max												
n-value (1)												
n-value (6)												
n-value (9)												
n-value (11)												
Alpha(1)												
Alpha(6)												
Alpha (9)												
Alpha(11)												
Wilting point												
Residual water												
Total conductivity(1)												
Total conductivity(6)												
Total conductivity(9)												
Total conductivity(11)												
Total conductivity(12)												

n Tortuosity												
Macropore(1)												
Macropore(6)												
Macropore(9)												
Macropore(11)												
Macropore(12)												

Sensitivity classes		
Class	Index	Sensitivity
I	$0.00 \leq I < 0.05$	small to negligible
II	$0.05 \leq I < 0.20$	Medium
III	$0.20 \leq I < 1.00$	High
IV	$ I \geq 1.0$	Very High

S5: Correlation matrix of calibrated parameters

	$k_{trans\,spas}$	θ_L	p_{pop}	$p_{stochastic}$	p_{clipp}	θ_{min}	χ_{hf}	p_{clow}	p_{stoch}	k_h	c_{rain}	l_{c1}	t_{RA}	l_{c2}	c_{max}	p_{lup}	a_{avg}	$t_{p2l0bas}$	k_l	l_t	t_{c10}	k_{grupp}	q_{cl}	g_{epd}	g_{max}	m_{trans}	kB^{-1}	m_t	a_{wet}	d_p	LAI_{ortho}	g_s	l_{c1}	p_{max}	w_{max}	q_{col}	k_{wet}	k_{s6}		
$K_{trans\,spas}$																																								
θ_L	-0.3	-0.2	0	0	-0.3	0	0.4	0.2	0	0.1	0.1	-0.4	0.1	0	0	0.3	0.3	-0.2	-0.1	0	-0.5	0	0.2	0.4	0.3	0.1	0.1	0.2	0	0	0.2	0.2	-0.2	-0.1	-0.4	0	0.3	0.1		
p_{pop}		0	0.1	-0.1	-0.1	0	0	0	0.3	-0.1	0	0.2	0.1	0.2	0	0	-0.3	-0.1	0.2	-0.1	0.2	0	-0.4	0.1	-0.1	-0.1	0.2	0.4	0.3	-0.3	-0.2	0.1	0.5	-0.3	0.1	-0.3	-0.5	0.1		
p_{stoch}			0	0.2	-0.1	0.1	-0.3	0.3	0	0.1	-0.1	0.4	0.4	0	0	0.1	0.4	0.2	0.3	0.2	0	0	-0.3	-0.1	0	-0.2	-0.3	0.2	0.3	-0.2	-0.3	0	0	-0.2	0	-0.1	0.2			
p_{clipp}				0	-0.1	-0.3	0.3	0	-0.2	0.4	-0.1	0	-0.2	-0.1	0.2	0.2	-0.3	0	0.1	0.2	0.3	0.4	-0.2	-0.2	0.5	0.2	-0.2	0.2	0.4	-0.5	0	0.4	0	-0.2	0.3	-0.2	0	0.3		
θ_{min}					-0.3	0	0.4	-0.2	0.1	0.4	-0.1	-0.2	0.1	0.1	0	-0.4	0.5	0.3	-0.4	0	-0.3	0	0.3	0.3	-0.4	0.1	-0.4	0.4	0.3	-0.2	-0.3	0.5	0.4	0.2	0.3	-0.1	-0.2			
χ_{hf}						-0.4	-0.1	0.2	-0.2	-0.2	0.3	0.2	-0.1	-0.3	0	0.3	-0.3	-0.1	0.2	0.1	0.2	0	-0.2	-0.2	0.4	0.2	-0.1	-0.6	0	0.4	-0.1	-0.1	-0.1	-0.1	0.3	0.1	0.2			
p_{clow}							-0.3	-0.2	0.6	-0.1	0.1	0	-0.1	0.1	-0.1	0	0.2	0	0	-0.1	0	0.1	-0.1	-0.4	-0.5	-0.2	0.1	-0.2	0.1	-0.2	0	-0.2	0.2	-0.2	0	0	-0.4			
p_{stoch}								-0.1	-0.1	0.6	-0.2	-0.7	0	-0.2	0.1	-0.3	0.1	0	-0.5	0.2	0.2	-0.3	0.4	0.6	0	0	0.2	0.2	-0.3	0	-0.1	0.1	0.1	0.2	0.2	0	0.2			
p_{stoch}									-0.2	0.1	-0.1	0	0.1	-0.4	0.1	0.4	-0.3	0.3	0.1	-0.2	0.4	-0.2	-0.1	0	0.2	0.4	0	-0.2	0	0	-0.1	-0.2	-0.1	-0.5	-0.2	0.3	0.3			
k_h											-0.1	0	0.2	0	0.1	-0.1	-0.2	0.3	0.2	0	0.1	0.1	-0.3	0.1	-0.3	-0.4	0.2	0.1	0.1	0.2	0.3	0.3	0.3	0	-0.1	-0.2	-0.3			
c_{rain}												-0.3	-0.3	-0.2	-0.5	-0.1	-0.3	0.4	0.1	-0.2	0.2	0.5	-0.5	-0.1	0.4	-0.1	-0.1	0	0.2	0	0	-0.1	0.5	0.3	-0.1	0	0.3			
l_{c1}													0.3	-0.1	0.2	0.5	0.7	-0.2	-0.6	0.4	-0.6	-0.2	0.6	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2	0	0.1	-0.1	0.2	0	-0.4	0	-0.3	0		
t_{RA}														-0.1	0.3	0.1	0.2	0	0	0.6	0	0	0.2	-0.2	-0.4	0.3	-0.1	0	-0.1	0.2	0.3	0.1	0.1	-0.1	0	0	-0.2	0		
l_{c2}															-0.1	-0.1	0.1	0.2	0.2	0.2	0.1	-0.5	-0.1	-0.1	0	-0.2	-0.2	0.3	-0.1	-0.4	-0.2	0.2	-0.2	-0.3	-0.2	-0.2	0.2			
c_{max}																0.4	-0.1	-0.1	0	0.2	-0.1	-0.5	0.5	0.2	0.1	-0.1	-0.2	-0.1	0.3	0	0	0.1	0.3	-0.1	0	0.3	-0.5	-0.4		
p_{lup}																	0.6	-0.2	-0.2	0.3	-0.4	-0.1	0.5	0	0.5	0.1	-0.3	-0.1	0.1	-0.1	0.2	0.2	0	0	-0.4	0	-0.4	-0.1		
a_{avg}																		-0.3	-0.5	0.4	-0.6	0	0.5	-0.2	-0.1	0.1	-0.2	-0.2	-0.3	0.1	0.2	-0.2	-0.3	-0.1	-0.7	-0.2	0	0.1		
$t_{p2l0bas}$																		0	-0.3	0.4	-0.1	-0.2	-0.1	0	-0.4	-0.2	-0.4	0.3	0.5	-0.1	-0.4	0.3	0.4	0.3	0	-0.2	0.2			
k_l																			-0.2	0.4	0.1	-0.4	0.1	0.2	0.2	0.5	0.2	0.2	-0.1	-0.2	0.3	0.1	-0.1	0.1	0.1	0.2	-0.3			
l_t																				-0.1	0	0.3	-0.4	-0.2	0.3	-0.5	0	0	-0.2	0.1	0.3	-0.2	-0.2	0.3	-0.1	-0.2	0.1			
t_{c10}																					0.1	-0.6	0.1	-0.1	0.2	0	0.2	0.1	-0.2	-0.1	0.1	0.1	0	0.6	0.2	-0.1	0.3			
k_{grupp}																							-0.5	-0.1	0.1	0.1	0.3	0.2	-0.2	-0.1	0.5	0.3	-0.4	0.1	0.1	-0.2	0.3	0.2		
q_{cl}																								0	-0.1	0	-0.4	-0.2	-0.2	0.1	-0.1	-0.1	-0.1	-0.3	0.3	0	-0.3			
g_{epd}																									0	0.1	0.3	0.3	0.1	0	0.2	0.1	0	-0.1	0.3	0.4	0.2	0		
g_{max}																										0.2	0	0	0.4	-0.2	0	0.2	0	-0.1	-0.1	0	-0.1	-0.1		
m_{trans}																											0.2	0.4	-0.2	-0.2	0.4	0.4	-0.4	-0.5	0	0.2	0.2	0.2		
kB^{-1}																												0.1	-0.2	0.3	0.4	0.1	0.1	0	0	0	0.5	-0.1		
m_t																													-0.2	-0.6	-0.1	0.5	-0.4	-0.4	0.1	0	0.2	0.1		
a_{wet}																															0	-0.2	0	0.4	-0.1	0.2	-0.1	-0.3	0	
d_p																																0.3	-0.5	0.1	0.4	0	0.1	0.1	-0.2	
LAI_{ortho}																																								
g_s																																								
l_{c1}																																								
p_{max}																																								
w_{max}																																								
q_{col}																																								
k_{wet}																																								
k_{s6}																																								

S6: Result of parameter contribution to variable performance with LMG Approach

Category	Parameter	Soilresp(cal)	Soilresp(val)	Stemp5	Stemp30	SL (cal)	SL	VMC5	VMC30	Nrad	LH	SH	LAI	SnowD	SP (cal)	SP (val)
plant growth	MCoefCoarseRoot	2.121416	1.477459	8.237431	12.1217	1.187035	17.74539	1.958169	4.767888	6.843652	2.5908	3.96741	10.120669	0.7853312	7.533316	6.719465
water/abiotic	ThetaPowerCoef	7.31755	2.090769	7.294556	3.988291	5.82293	2.310807	9.194762	2.728837	1.641421	2.517004	13.08791	1.845788	9.9324373	2.711138	4.553528
temp and decom-abiotic	TemQ10	3.38563	3.591051	15.32889	5.032576	3.499937	4.164385	1.835659	1.754209	6.103535	1.248388	1.856529	7.562064	0.974746	11.13657	3.54019
water-abiotic	Saturation activity	19.032887	6.029802	3.726173	8.712364	2.779985	1.768566	6.311641	5.844128	13.70476	3.935608	5.333488	6.856898	2.1444549	1.165058	2.954025
soil thermal	ThScaleLog(1)	2.77317	5.571461	4.079623	5.135376	4.40426	3.929442	4.940231	5.749493	10.63224	4.292136	7.725473	8.078626	9.7169917	2.218961	3.019597
soil organic	RateCoefHumus	2.002456	4.926929	2.882412	1.993718	2.652958	6.900096	3.326349	2.480241	3.123797	6.954205	7.417158	8.072348	2.1838908	4.72409	2.614537
meteorological	PrecA0Corr	3.926877	6.32134	3.140031	1.147461	2.66219	1.225755	7.812461	5.822728	1.504695	3.863147	3.205525	1.508219	1.7608698	9.293432	8.184454
plant	AlbedoLeaf	3.637218	2.044274	7.800618	5.18149	3.673719	10.14206	7.674131	1.644069	8.028443	4.908113	5.794787	5.340018	2.5878091	7.580291	10.59164
soil organic	RateCoefLitter1	2.283223	4.270437	3.114548	5.069016	6.191558	1.756832	1.220147	3.971254	3.271041	7.293449	3.626779	8.778116	1.2721331	1.795226	1.437049
soil organic	RateCoefSurfL1	4.098293	2.965316	5.875754	3.252724	1.77197	12.68042	7.161687	5.493897	2.456879	5.269038	3.192613	2.106959	1.449582	2.74919	9.2759
plant growth	GrowthCoef	10.574973	21.048423	2.033687	2.959492	11.60148	2.642283	13.57133	11.97936	5.986806	10.26584	5.410165	7.162934	3.3258733	2.559314	10.2463
Drainage and deep percola	GWSourceFlow	7.342453	10.080261	1.7985	5.581834	4.069777	3.404689	7.94457	3.722327	11.74869	5.1041	11.87913	4.499984	4.1570726	7.660973	11.73978
transpiration (plant)	Conduct Max	3.597613	8.882092	3.841812	8.000887	2.412481	8.196215	4.953836	3.441733	7.459955	4.108898	3.651364	4.448836	2.4006713	3.50104	1.712176
plant	MobileAlloCoef	3.726829	7.44953	4.444536	5.736773	5.692012	4.188876	9.603209	12.94847	7.071648	3.708091	7.459666	2.539816	4.4515116	9.891208	8.456312
snowpack	MeltCoefAirTemp	7.115477	2.370553	14.26561	8.392565	15.5446	4.61058	4.321144	7.912447	2.800823	5.317808	5.136222	2.393013	40.1541276	16.568312	4.167339
radiation/ET	Albedo Wet	2.933628	3.97973	5.651772	5.521492	7.196675	2.909862	2.061132	5.983924	1.994771	18.91448	2.283797	1.521929	4.0062391	2.491929	1.494299
plant	LAI enh Coef	10.300507	2.741922	3.166416	8.150327	9.233269	3.870245	3.35022	8.524324	2.152355	3.188891	3.261322	11.081197	3.8636574	2.712412	2.13573
plant	LeafRate1	3.8298	4.158654	3.317631	4.021919	9.603164	7.553502	2.759323	5.230672	3.4745	6.520004	5.710656	6.082587	4.8326011	3.70754	7.157681