

Supplementary material

S1. Soil carbon (C), nitrogen (N) and phosphorus (P) transformations

S1.1. Decomposition

$$D_{Si,j,l,C} = D'_{Si,j,l,C} M_{i,d,l,C} f_{tg,l}(S_{i,l,C} / G_{i,l,C})$$

$$D_{Zi,j,l,C} = D'_{Zi,j,l,C} M_{i,d,l,C} f_{tg,l}(Z_{i,l,C} / G_{i,l,C})$$

$$D_{Ai,l,C} = D'_{Ai,l,C} M_{i,d,l,C} f_{tg,l}(A_{i,l,C} / G_{i,l,C})$$

$$S_{i,l,C} = \sum_j S_{i,j,l,C}$$

$$Z_{i,l,C} = \sum_j Z_{i,j,l,C}$$

$$G_{i,l,C} = S_{i,l,C} + Z_{i,l,C} + A_{i,l,C}$$

$$M_{i,d,l,C} = M_{i,a,l,C} + q_m (M_{i,a,l,C} G_{ix,l,C} - M_{ix,a,l,C} G_{i,l,C}) / (G_{ix,l,C} + G_{i,l,C})$$

$$M_{i,a,l,C} = \sum_n M_{i,n,a,l,C}$$

$$D'_{Si,j,l,C} = \{D_{Si,j,C}[S_{i,j,l,C}]\} / \{[S_{i,j,l,C}] + K_{mD}(1.0 + [\Sigma M_{i,d,l,C}] / K_{iD})\}$$

$$D'_{Zi,j,l,C} = \{D_{Zi,j,C}[Z_{i,j,l,C}]\} / \{[Z_{i,j,l,C}] + K_{mD}(1.0 + [M_{i,d,l,C}] / K_{iD})\}$$

$$D'_{Ai,l,C} = \{D_{Ai,C}[A_{i,l,C}]\} / \{[A_{i,l,C}] + K_{mD}(1.0 + [M_{i,d,l,C}] / K_{iD})\}$$

$$\delta S_{i,j,k,l,C} / \delta t = \beta \sum_n (U_{i,n,l,C} - R_{hi,n,l}) (S'_{i,j,k,l,C} / S'_{i,j,l,C}) \{(S'_{i,j,l,C} / S_{i,j,l,C}) / (S'_{i,j,l,C} / S_{i,j,l,C} + K_{is})\}$$

$$f_{tg,l} = T_{sl} \{e^{[B - H_a(RT_{sl})]}\} / \{1 + e^{[(H_{dl} - ST_{sl})(RT_{sl})]} + e^{[(ST_{sl} - H_{dh})(RT_{sl})]}\}$$

decomposition of litter, POC,
humus

[A1a]

decomposition of microbial
residues

[A1b]

decomposition of adsorbed SOC

[A1c]

total C in all kinetic components of
litter, POC, humus

[A2a]

total C in all kinetic components of
microbial residues

[A2b]

total C in substrate-microbe
complexes

[A2c]

redistribution of active microbial
biomass from each substrate-
microbe complex *i* to other
substrate-microbe complexes *ix*
according to concentration
differences (priming)

[A3a]

substrate and water constraint on *D*
from colonized litter, POC and
humus, microbial residues and
adsorbed SOC

[A4a]

[A4b]

[A4c]

colonized litter determined by
microbial growth into uncolonized
litter

[A5]

Arrhenius function for *D* and *R_h*

[A6]

$D_{Si,j,l,N,P} = D_{Si,j,l,C}(S_{i,j,l,N,P}/S_{i,j,l,C})$	N and P coupled with C during D	[A7a]
$D_{Zi,j,l,N,P} = D_{Zi,j,l,C}(Z_{i,j,l,N,P}/Z_{i,j,l,C})$		[A7b]
$D_{Ai,l,N,P} = D_{Ai,l,C}(A_{i,l,N,P}/A_{i,l,C})$		[A7c]
$Y_{i,l,C} = k_{ts}(G_{i,l,C} F_s [Q_{i,l,C}]^b - X_{i,l,C})$	Freundlich sorption of DOC	[A8]
$Y_{i,l,N,P} = Y_{i,l,C}(Q_{i,l,N,P}/Q_{i,l,C})$	$(Y_{i,l,C} > 0)$ adsorption of DON, DOP	[A9]
$Y_{i,l,N,P} = Y_{i,l,C}(X_{i,l,N,P}/X_{i,l,C})$	$(Y_{i,l,C} < 0)$ desorption of DON, DOP	[A10]
S1.2. Microbial growth		
$R_h = \sum_i \sum_n \sum_l R_{hi,n,l}$		[A11]
$\mathbf{R}_{hi,n,l} = \mathbf{R}'_{hn} \min\{C_{Ni,n,l,a}/C_{Nj}, C_{Pi,n,l,a}/C_{Pj}\}$	R_h constrained by microbial N, P	[A12]
$R'_{hi,n,l} = M_{i,n,a,l,C} \{\mathbf{R}_{hi,n,l} [Q_{i,l,C}]\} / \{(K_m \varphi_C + [Q_{i,l,C}])\} f_{tg} f_{vg}$	R_h constrained by substrate DOC	[A13]
$R_{hi,n,l} = R'_{hi,n,l} (U_{O2i,n,l}/U'_{O2i,n,l})$	R_h constrained by O ₂	[A14]
$f_{vg} = 1.0 - 6.67(1.0 - e^{(M\psi_s/(RT_{sl}))})$	ψ_s constraints on microbial growth	[A15]
$U'_{O2i,n,l} = 2.67 R'_{hi,n,l}$	O ₂ demand driven by potential R_h	[A16]
$U_{O2i,n,l} = U'_{O2i,n,l} [O_{2mi,n,l}] / ([O_{2mi,n,l}] + K_{O_2})$	active uptake coupled with radial diffusion of O ₂	[A17a]
$= 4\pi n M_{i,n,a,l,C} D_{sO2l} [\mathbf{r}_m r_{wl} / (r_{wl} - \mathbf{r}_m)] ([O_{2sl}] - [O_{2mi,n,l}])$		[A17b]
$R_{mi,n,j,l} = R_m M_{i,n,j,l,N} f_{tm}$		[A18]
$f_{tm} = e^{[y(T_{sl} - 298.16)]}$		[A19]
$R_{gi,n,l} = R_{hi,n,l} - \sum_j R_{mi,n,j,l}$		[A20]
$U_{i,n,l,C} = \min(R_{hi,n,l}, \sum_j R_{mi,n,j,l}) + R_{gi,n,l} (1 + \Delta G_x/E_m)$	DOC uptake driven by R_g	[A21]
$U_{i,n,l,N,P} = U_{i,n,l} Q_{i,l,N,P} / Q_{i,l,C}$	DON,DOP uptake driven by $U_{i,n,l,C}$	[A22]
$D_{Mi,n,j,l,C} = D_{Mi,j} M_{i,n,j,C} f_{tg}$	first-order decay of microbial C,	[A23]

$$D_{Mi,n,j,N,P} = \mathbf{D}_{Mi,j} M_{i,n,j,l,N,P} f_{tg,l} f_{di,n,lN,P}$$

$$\delta M_{i,n,j,l,C}/\delta t = F_j U_{i,n,lC} - F_j R_{hi,n,l} - D_{Mi,n,j,l,C}$$

$$\delta M_{i,n,j,l,C}/\delta t = F_j U_{i,n,lC} - R_{mi,n,j,l} - D_{Mi,n,j,l,C}$$

S1.3. Microbial nutrient exchange

$$U_{NH4i,n,j,l} = (M_{i,n,j,l,C} \mathbf{C}_{Nj} - M_{i,n,j,l,N})$$

$$U'_{NH4i,n,j,l} = \min \{(M_{i,n,j,l,C} \mathbf{C}_{Nj} - M_{i,n,j,l,N}), \\ U'_{NH4i,n,j,l} a_{i,n,j,l} ([NH4^+_{i,n,j,l}] - [NH4^+_{mn}])/([NH4^+_{i,n,j,l}] - [NH4^+_{mn}] + K_{NH4})\}$$

$$U_{NO3i,n,j,l} = \min \{(M_{i,n,j,l,C} \mathbf{C}_{Nj} - (M_{i,n,j,l,N} + U_{NH4i,n,j,l})), \\ U'_{NO3i,n,j,l} ([NO3^-_{i,n,j,l}] - [NO3^-_{mn}])/([NO3^-_{i,n,j,l}] - [NO3^-_{mn}] + K_{NO3})\}$$

$$U_{PO4i,n,j,l} = (M_{i,n,j,l,C} \mathbf{C}_{Pj} - M_{i,n,j,l,P})$$

$$U'_{PO4i,n,j,l} = \min \{(M_{i,n,j,l,C} \mathbf{C}_{Pj} - M_{i,n,j,l,P}), \\ U'_{PO4i,n,j,l} ([H2PO4^-_{i,n,j,l}] - [H2PO4^-_{mn}])/([H2PO4^-_{i,n,j,l}] - [H2PO4^-_{mn}] + K_{PO4})\}$$

$$\Phi_{i,n=fj,l} = \max \{0, M_{i,n=fj,l,C} \mathbf{C}_{Nj} - M_{i,n=fj,l,N} - \max \{0, U_{i,n=fj,l,N}\}\}$$

$$R_{\Phi_{i,n=fj,l}} = \mathbf{E}_{\Phi} \Phi_{i,n=fj,l}$$

$$\delta M_{i,n,j,l,N}/\delta t = F_j U_{i,n,l,N} + U_{NH4i,n,j,l} + U_{NO3i,n,j,l} + \Phi_{i,n=fj,l} - D_{Mi,n,j,l,N}$$

$$\delta M_{i,n,j,l,P}/\delta t = F_j U_{i,n,l,P} + U_{PO4i,n,j,l} - D_{Mi,n,j,l,P}$$

$$M_{i,n,a,l,C} = M_{i,n,j=labile,l,C} + M_{i,n,j=resistant,l,C} F_r/F_1$$

S1.4. Humification

$$H_{Si,j=lignin,l,C} = D_{Si,j=lignin,l,C}$$

$$H_{Si,j=lignin,l,N,P} = D_{Si,j=lignin,l,N,P}$$

$$H_{Si,j \neq lignin,l,C} = H_{Si,j=lignin,l,C} \mathbf{L}_{hj}$$

$$H_{Si,j \neq lignin,l,N,P} = H_{Si,j \neq lignin,l,C} S_{i,l,N,P}/S_{i,l,C}$$

partial release of microbial N, P [A24]

$[R_{hi,n,l} > R_{mi,n,j,l}]$ growth [A25a]

$[R_{hi,n,l} < R_{mi,n,j,l}]$ senescence [A25b]

$U_{NH4} < 0$ mineralization [A26a]

$U_{NH4} > 0$ immobilization [A26b]

$U_{NO3} > 0$ immobilization [A26c]

$U_{PO4} < 0$ mineralization [A26d]

$U_{PO4} > 0$ immobilization [A26e]

N_2 fixation driven by N deficit of diazotrophic population [A27] [A28]

growth vs. losses of microbial N, P [A29a]

[A29b]

[A30]

decomposition products of litter added to POC depending on lignin [A31]

[A32]

[A33]

[A34]

$H_{Mi,n,j,l,C} = D_{Mi,n,j,l,C} \mathbf{F}_h$	decomposition products of microbes added to humus depending on clay	[A35]
$H_{Mi,n,j,l,N,P} = H_{Mi,n,j,l,C} M_{i,n,j,l,N,P} / M_{i,n,j,l,C}$		[A36]

S1.5. Definition of variables in sections S1.1-S1.4 (Eqs. A1-A36)

Variable	Definition	Unit	Value	Reference
<i>Subscripts</i>				
<i>i</i>	substrate-microbe complex: coarse woody litter, fine non-woody litter, POC, humus			
<i>j</i>	kinetic component: labile <i>l</i> , resistant <i>r</i> , active <i>a</i>			
<i>l</i>	soil or litter layer			
<i>n</i>	microbial functional type: heterotrophic (bacteria, fungi), autotrophic (nitrifiers, methanotrophs), diazotrophic, obligate aerobe, facultative anaerobes (denitrifiers), obligate anaerobes (methanogens)			
<i>Variables</i>				
$A_{i,l,C}$	mass of adsorbed SOC	g C m^{-2}		
$[A_{i,l,C}]$	concentration of adsorbed SOC in soil	g C Mg^{-1}		
a	microbial surface area	$\text{m}^2 \text{ m}^{-2}$		
B	parameter such that $f_{lg} = 1.0$ at $T_l = 298.15 \text{ K}$	26.230		
b	Freundlich exponent for sorption isotherm	0.85		(Grant et al., 1993a, b)
β	specific colonization rate of uncolonized substrate	-	2.5	(Grant et al., 2010)
$C_{N,P,i,n,a,l}$	ratio of $M_{i,n,a,N,P}$ to $M_{i,n,a,C}$	g N or P g C^{-1}		
$C_{N,P,j}$	maximum ratio of $M_{i,n,j,N,P}$ to $M_{i,n,j,C}$ maintained by $M_{i,n,j,C}$	g N or P g C^{-1}	0.22 and 0.13 (N), 0.022 and 0.013 (P) for $j = \text{labile}$ and resistant , respectively	(Grant et al., 1993a, b)

$D_{Mi,j}$	specific decomposition rate of $M_{i,n,j}$ at 30°C	$\text{g C g C}^{-1} \text{ h}^{-1}$	0.0125 and 0.00035 for $j =$ labile and resistant, respectively	(Grant et al., 1993a, b)
$D_{Mi,n,j,l,C}$	decomposition rate of $M_{i,n,j,l,C}$	$\text{g C m}^{-2} \text{ h}^{-1}$		
$D_{Mi,n,j,l,N,P}$	decomposition rate of $M_{i,n,j,l,N,P}$	$\text{g N or P m}^{-2} \text{ h}^{-1}$		
$D_{\text{SO}_2 l}$	aqueous dispersivity–diffusivity of O ₂ during microbial uptake in soil	$\text{m}^2 \text{ h}^{-1}$		
$D_{A_i,l,C}$	decomposition rate of $A_{i,l,C}$ by $M_{i,d,l,C}$ producing Q in (Eq. A13)	$\text{g C m}^{-2} \text{ h}^{-1}$		
$D_{A_j,C}$	specific decomposition rate of $A_{i,l,C}$ by $M_{i,d,l,C}$ at 25°C and saturating [$A_{i,l,C}$]	$\text{g C g C}^{-1} \text{ h}^{-1}$	0.025	(Grant et al., 1993a, b)
$D_{A_i,j,l,N,P}$	decomposition rate of $A_{i,l,N,P}$ by $M_{i,d,l,C}$	$\text{g N or P m}^{-2} \text{ h}^{-1}$		
$D'_{A_i,j,l,C}$	specific decomposition rate of $S_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ at 25°C	$\text{g C g C}^{-1} \text{ h}^{-1}$		
$D_{S_{i,j},l,C}$	decomposition rate of $S_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ producing Q in (Eq. A13)	$\text{g C m}^{-2} \text{ h}^{-1}$		
$D_{S_j,C}$	specific decomposition rate of $S_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ at 25°C and saturating [$S_{i,l,C}$]	$\text{g C g C}^{-1} \text{ h}^{-1}$	1.0, 1.0, 0.15, and 0.025 for $j =$ protein, carbohydrate, cellulose, and lignin	(Grant et al., 1993a, b)
$D_{S_{i,j},l,N,P}$	decomposition rate of $S_{i,j,l,N,P}$ by $\Sigma_n M_{i,n,a,l}$	$\text{g N or P m}^{-2} \text{ h}^{-1}$		
$D'_{S_{i,j},l,C}$	specific decomposition rate of $S_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ at 25°C	$\text{g C g C}^{-1} \text{ h}^{-1}$		
$D_{Z_{i,j},l,C}$	decomposition rate of $Z_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ producing Q in (Eq. A13)	$\text{g C m}^{-2} \text{ h}^{-1}$		
$D_{Z_{i,j},N,P}$	decomposition rate of $Z_{i,j,l,N,P}$ by $\Sigma_n M_{i,n,a,l}$	$\text{g N or P m}^{-2} \text{ h}^{-1}$		
$D_{Z_j,C}$	specific decomposition rate of $Z_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ at 25°C and saturating [$Z_{i,l,C}$]	$\text{g C g C}^{-1} \text{ h}^{-1}$	0.25 and 0.05 for $j =$ labile and resistant biomass	(Grant et al., 1993a, b)
$D'_{Z_{i,j},l,C}$	specific decomposition rate of $Z_{i,j,l,C}$ by $\Sigma_n M_{i,n,a,l}$ at 25°C	$\text{g C g C}^{-1} \text{ h}^{-1}$		

ΔG_x	energy yield of C oxidation with different reductants x	kJ g C ⁻¹	37.5 ($x = O_2$); 4.43 ($x = DOC$)
E_m	energy requirement for growth of $M_{i,n,a,l}$	kJ g C ⁻¹	25
E_f	energy requirement for non-symbiotic N ₂ fixation by heterotrophic diazotrophs ($n = f$)	g C g N ⁻¹	5 (Waring and Running, 1998)
F_h	fraction of products from microbial decomposition that are humified (function of clay content)		0.167 + 0.167*clay
F_l	fraction of microbial growth allocated to labile component $M_{i,n,l}$	0.55	(Grant et al., 1993a, b)
F_r	fraction of microbial growth allocated to resistant component $M_{i,n,r}$	0.45	(Grant et al., 1993a, b)
F_s	equilibrium ratio between $Q_{i,l,C}$ and $H_{i,l,C}$		
$f_{d,i,n,N,P}$	fraction of N or P released with $D_{Mi,n,j,l,C}$ during decomposition	dimensionless	0.33 $U_{NH4} > 0$ 1.00 $U_{NH4} < 0$ 0.33 $U_{PO4} > 0$ 1.00 $U_{PO4} < 0$
$f_{tg,l}$	temperature function for microbial growth respiration	dimensionless	
$f_{tm,l}$	temperature function for maintenance respiration	dimensionless	
$f_{\psi gl}$	soil water potential function for microbial, root or mycorrhizal growth respiration	dimensionless	(Pirt, 1975)
$\Phi_{i,n=f,j,l}$	non-symbiotic N ₂ fixation by heterotrophic diazotrophs ($n = f$)	g N m ⁻² h ⁻¹	
$G_{i,l,C}$	total C in substrate-microbe complex	g C Mg ⁻¹	
[H ₂ PO ₄ ⁻]	concentration of H ₂ PO ₄ ⁻ in soil solution	g P m ⁻³	

H_a	energy of activation	J mol ⁻¹	65 x 10 ³	(Addiscott, 1983)
H_{dh}	energy of high temperature deactivation	J mol ⁻¹	225 x 10 ³	
H_{dl}	energy of low temperature deactivation	J mol ⁻¹	198 x 10 ³	
$H_{Mi,n,j,l,C}$	transfer of microbial C decomposition products to humus	g C m ⁻² h ⁻¹		
$H_{Mi,n,j,l,N,P}$	transfer of microbial N or P decomposition products to humus	g N or P m ⁻² h ⁻¹		
$H_{Si,j,l,C}$	transfer of C hydrolysis products to particulate OM	g C m ⁻² h ⁻¹		
$H_{Si,j,l,N,P}$	transfer of N or P hydrolysis products to particulate OM	g N or P m ⁻² h ⁻¹		
K_iS	inhibition constant for microbial colonization of substrate	-	0.5	(Grant et al., 2010)
K_{NH_4}	M-M constant for NH ₄ ⁺ uptake at microbial surfaces	g N m ⁻³	0.40	
K_{NO_3}	M-M constant for NO ₃ ⁻ uptake at microbial surfaces	g N m ⁻³	0.35	
K_{PO_4}	M-M constant for H ₂ PO ₄ ⁻ uptake at microbial surfaces	g P m ⁻³	0.125	
K_{iD}	inhibition constant for [M _{i,n,a}] on S _{i,C} , Z _{i,C}	g C m ⁻³	25	(Lizama and Suzuki, 1991 ; Grant et al., 1993a, b)
K_{mD}	Michaelis–Menten constant for D _{Si,j,C}	g C Mg ⁻¹	75	
K_{mQ_C}	Michaelis–Menten constant for R' _{hi,n} on [Q _{i,C}]	g C m ⁻³	36	
K_{O_2}	Michaelis–Menten constant for reduction of O _{2s} by microbes, roots and mycorrhizae	g O ₂ m ⁻³	0.064	(Griffin, 1972)
k_{ts}	equilibrium rate constant for sorption	h ⁻¹	0.01	(Grant et al., 1993a, b)
L_{bj}	ratio of nonlignin to lignin components in humified hydrolysis products		0.10, 0.05, and 0.05 for j = protein, carbohydrate, and cellulose, respectively	(Schulten and Schnitzer, 1997)
M	molecular mass of water	g mol ⁻¹	18	

$M_{i,d,l,C}$	heterotrophic microbial C used for decomposition	g C m^{-2}	
$M_{i,n,j,l,C}$	microbial C	g C m^{-2}	
$M_{i,n,j,l,N}$	microbial N	g N m^{-2}	
$M_{i,n,j,l,P}$	microbial P	g P m^{-2}	
$M_{i,n,a,l,C}$	active microbial C from heterotrophic population n associated with $G_{i,l,C}$	g C m^{-2}	
$[M_{i,n,a,l,C}]$	concentration of $M_{i,n,a}$ in soil water = $M_{i,n,a,l,C} / \theta_l$	g C m^{-3}	
$[\text{NH}_4^+_{i,n,j,l}]$	concentration of NH_4^+ at microbial surfaces	g N m^{-3}	
$[\text{NH}_4^+_{mn}]$	concentration of NH_4^+ at microbial surfaces below which $U_{\text{NH}_4} = 0$	g N m^{-3}	0.0125
$[\text{NO}_3^-_{i,n,j,l}]$	concentration of NH_4^+ at microbial surfaces	g N m^{-3}	
$[\text{NO}_3^-_{mn}]$	concentration of NO_3^- at microbial surfaces below which $U_{\text{NO}_3} = 0$	g N m^{-3}	0.03
$[\text{H}_2\text{PO}_4^-_{i,n,j,l}]$	concentration of H_2PO_4^- at microbial surfaces	g N m^{-3}	
$[\text{H}_2\text{PO}_4^-_{mn}]$	concentration of H_2PO_4^- at microbial surfaces below which $U_{\text{PO}_4} = 0$	g N m^{-3}	0.002
$[\text{O}_{2mi,n,l}]$	O_2 concentration at heterotrophic microsites	$\text{g O}_2 \text{ m}^{-3}$	
$[\text{O}_{2sl}]$	O_2 concentration in soil solution	$\text{g O}_2 \text{ m}^{-3}$	
$Q_{i,l,C}$	DOC from products of $D_{Si,j,l,C}$ [A3] and $D_{Zi,j,l,C}$) [A5]	g C m^{-2}	
$[Q_{i,l,C}]$	solution concentration of $Q_{i,l,C}$	g C Mg^{-1}	
$Q_{i,l,N,P}$	DON and DOP from products of $(D_{Si,j,l,N,P} + D_{Zi,j,l,N,P})$	g N or P m^{-2}	
q_m	constant for reallocating $M_{i,a,l,C}$ to $M_{i,d,l,C}$	-	0.5

R	gas constant	J mol ⁻¹ K ⁻¹	8.3143
$R_{\phi_{i,n=f,j,l}}$	respiration for non-symbiotic N ₂ fixation by heterotrophic diazotrophs ($n = f$)	g C m ⁻² h ⁻¹	
$R_{gi,n,l}$	growth respiration of $M_{i,n,a,l}$ on $Q_{i,l,C}$ under nonlimiting O ₂ and nutrients	g C g C ⁻¹ h ⁻¹	
R_h	total heterotrophic respiration of all $M_{i,n,a,l}$ under ambient DOC, O ₂ , nutrients, θ and temperature	g C m ⁻² h ⁻¹	
$R_{hi,n,l}$	heterotrophic respiration of $M_{i,n,a,l}$ under ambient DOC, O ₂ , nutrients, θ and temperature	g C m ⁻² h ⁻¹	
$R_{hi,n,l}'$	specific heterotrophic respiration of $M_{i,n,a,l}$ under nonlimiting O ₂ , DOC, θ and 25°C	g C g C ⁻¹ h ⁻¹	
$R_{h'n}$	specific heterotrophic respiration of $M_{i,n,a,l}$ under nonlimiting DOC, O ₂ , nutrients, θ and 25°C	g C g C ⁻¹ h ⁻¹	0.125
$R_{h'i,n,l}'$	heterotrophic respiration of $M_{i,n,a,l}$ under nonlimiting O ₂ and ambient DOC, nutrients, θ and temperature	g C m ⁻² h ⁻¹	(Shields et al., 1973)
R_m	specific maintenance respiration at 25°C	g C g N ⁻¹ h ⁻¹	0.0115
$R_{mi,n,j,l}$	maintenance respiration by $M_{i,n,j,l}$	g C m ⁻² h ⁻¹	
r_{wl}	radius of r_m + water film at current water content	m	
r_m	radius of heterotrophic microsite	m	2.5×10^{-6}
r_{wl}	thickness of water films	m	
S	change in entropy	J mol ⁻¹ K ⁻¹	710
$[S_{i,j,l,C}]$	concentration of $S_{i,j,l,C}$ in soil	g C Mg ⁻¹	(Sharpe and DeMichele, 1977)
$S_{i,j,l,C}$	mass of colonized litter, POC or humus C	g C m ⁻²	
$S'_{i,j,l,C}$	mass of uncolonized litter, POC or humus C	g C m ⁻²	

$S_{i,j,l,N,P}$	mass of litter, POC or humus N or P	g N or P m ⁻²	
T_{sl}	soil temperature	K	
$U_{i,n,l,C}$	uptake of $Q_{i,l,C}$ by $\Sigma_n M_{i,n,a,l}$ under limiting nutrient availability	g C m ⁻² h ⁻¹	
$U_{i,n,N,P}$	uptake of $Q_{i,l,N,P}$ by $\Sigma_n M_{i,n,a,l}$ under limiting nutrient availability	g N or P m ⁻² h ⁻¹	
$U_{\text{NH}_4i,n,j,l}$	NH ₄ ⁺ uptake by microbes	g N m ⁻² h ⁻¹	
U'_{NH_4}	maximum U_{NH_4} at 25 °C and non-limiting NH ₄ ⁺	g N m ⁻² h ⁻¹	5.0 x 10 ⁻³
$U_{\text{NO}_3i,n,j,l}$	NO ₃ ⁻ uptake by microbes	g N m ⁻² h ⁻¹	
U'_{NO_3}	maximum U_{NO_3} at 25 °C and non-limiting NO ₃ ⁻	g N m ⁻² h ⁻¹	5.0 x 10 ⁻³
$U_{O_2i,n}$	O ₂ uptake by $M_{i,n,a,l}$ under ambient O ₂	g m ⁻² h ⁻¹	
$U'_{O_2i,n}$	O ₂ uptake by $M_{i,n,a,l}$ under nonlimiting O ₂	g m ⁻² h ⁻¹	
$U_{\text{PO}_4i,n,j,l}$	H ₂ PO ₄ ⁻ uptake by microbes	g N m ⁻² h ⁻¹	
U'_{PO_4}	maximum U_{PO_4} at 25 °C and non-limiting H ₂ PO ₄ ⁻	g N m ⁻² h ⁻¹	5.0 x 10 ⁻³
$X_{i,l,C}$	adsorbed C hydrolysis products	g C Mg ⁻¹	
$X_{i,l,N,P}$	adsorbed N or P hydrolysis products	g P Mg ⁻¹	
y	selected to give a Q_{10} for f_{tm} of 2.25	0.081	
ψ_s	soil or residue water potential	MPa	
$Y_{i,l,C}$	sorption of C hydrolysis products	g C m ⁻² h ⁻¹	
$Y_{i,l,N,P}$	sorption of N or P hydrolysis products	g P m ⁻² h ⁻¹	
$[Z_{i,j,l,C}]$	concentration of $Z_{i,j,l,C}$ in soil	g C Mg ⁻¹	

$Z_{i,j,l,C}$	mass of microbial residue C in soil	g C m^{-2}
$Z_{i,j,l,N,P}$	mass of microbial residue N or P in soil	g P m^{-2}

S2. Soil-plant water relations

S2.1. Canopy transpiration

$Rn_{ci} + LE_{ci} + H_{ci} + G_{ci} = 0$	canopy energy balance	[B1a]
$LE_{ci} = L (e_a - e_{ci(T_{ci}, \psi_{ci})})/r_{ai}$	LE from canopy evaporation	[B1b]
$LE_{ci} = L (e_a - e_{ci(T_{ci}, \psi_{ci})})/(r_{ai} + r_{ci}) - LE_{ci}$ from Eq. (B1b)	LE from canopy transpiration	[B1c]
$H_{ci} = \rho C_p (T_a - T_{ci})/r_{ai}$	H from canopy energy balance	[B1d]
$r_{cmini} = 0.64 (C_b - C_i' i)/V_c'$	r_c driven by rates of carboxylation	[B2a]
$r_{ci} = r_{cmini} + (r_{cmaxi} - r_{cmini}) e^{(-\beta \psi_{ti})}$	vs. diffusion	[B2b]
$r_{ai} = \{(ln((z_u - z_{di})/z_{ri})^2 / (\mathbf{K}^2 u_a)\}/(1 - 10 Ri)$	r_c constrained by water status	[B3a]
$Ri = \{g (z_u - z_{ri}) / (u_a^2 T_a)\} (T_a - T_c)$	r_a driven by windspeed, surface	[B3b]
$\psi_{ti} = \psi_{ci} - \psi_{ri}$	r_a adjusted for stability vs. buoyancy	
		[B4]

S2.2. Root/moss/mycorrhizal water uptake

$U_{wi} = \sum_l \sum_x U_{wi,r,l}$		[B5]
$U_{wi,r,l} = (\psi_{ci}' - \psi_{sl}') / (\Omega_{si,r,l} + \Omega_{fi,r,l} + \sum_x \Omega_{ai,r,l,x})$	U_w along hydraulic gradient	[B6]
$\psi_{ci}' = \psi_{ci} + 0.01 z_{bi}$		[B7]
$\psi_{sl}' = \psi_{sl} - 0.01 z_l$		[B8]
$\Omega_{si,r,l} = \ln\{(d_{i,r,l}/r_{i,r,l})/(2\pi L_{i,r,l} \kappa_{fi,r,l})\} \theta_{wl}/\theta_{pl}$		[B9]
$\Omega_{fi,r,l} = \Omega_{ri,r,l}/L_{i,r,l}$		[B10]
$\Omega_{ai,r,l,x=1} = \Omega_{ai,r} z_l / \{n_{i,r,l,1} (r_{i,r,l,1} / r_{i,r,l}^4) + \gamma \Omega_{ai,r} z_{bi} / \{n_{i,r,l,1} (r_{bi} / r_{b,i})^4\} \sum_{i,r,l} (M_{i,r,l}) / M_{i,r,l}\}$		[B11]
$\Omega_{ai,r,l,x=2} = \Omega_{ai,r} (L_{i,r,l,2} / n_{i,r,l,2}) / \{n_{i,r,l,2} (r_{i,r,l,2} / r_{i,r,l}^4)\}$		[B12]
$\delta L_{i,r,l,1} / \delta t = \delta M_{i,r,l,1} / \delta t v_r / \{\rho_r (1 - \theta_{Pl,r}) (\pi r_{i,r,l,1}^2)\}$		[B13]

S2.3. Canopy water potential

$$(e_a - e_{i(T_c)})/(r_{ai} + r_{ci}) \text{ (Eq. B1)} = \sum_l \sum_r (\psi_c' - \psi_s') / (\Omega_{si,r,l} + \Omega_{ri,r,l} + \sum_x \Omega_{ai,r,l,x}) + X_{ci} \delta \psi_{ci} / \delta t$$

ψ_c solved when transpiration from [B1-B4] equals uptake from [B5-B13] + change in storage [B14]

S2.4. Definition of variables in sections S2.1-S2.3 (Eqs. B1-B14)

Variable	Definition	Unit	Equation	Value	Reference
<i>Subscripts</i>					
<i>I</i>	plant species or functional type: coniferous, deciduous, annual, perennial, C ₃ , C ₄ , monocot, dicot etc.				
<i>J</i>	branch or tiller				
<i>K</i>	Node				
<i>L</i>	soil or canopy layer				
<i>M</i>	leaf azimuth				
<i>n</i>	leaf inclination				
<i>o</i>	leaf exposure (sunlit vs. shaded)				
<i>r</i>	root/moss/mycorrhizae				
<i>Variables</i>					
β	stomatal resistance shape parameter	MPa ⁻¹	-5.0		(Grant and Flanagan, 2007)
C_b	[CO ₂] in canopy air	μmol mol ⁻¹			
$C_{i,l}$	[CO ₂] in canopy leaves at $\psi_{c,l} = 0$ MPa	μmol mol ⁻¹	0.70 C_b		(Larcher, 2003)
$d_{i,r,l}$	half distance between adjacent roots/mosses	m			
E_{ci}	canopy transpiration	m ³ m ⁻² h ⁻¹			

e_a	atmospheric vapor density at T_a and ambient humidity	g m^{-3}		
$e_{ci}(T_{ci}, \psi_{ci})$	canopy vapor density at T_{ci} and ψ_{ci}	g m^{-3}		
G_{ci}	canopy storage heat flux	W m^{-2}		
H_{ci}	canopy sensible heat flux	W m^{-2}		
K	von Karman's constant		0.41	
$\kappa_{ri,r,l}$	hydraulic conductivity between soil and root/moss surface	$\text{m}^2 \text{ MPa}^{-1} \text{ h}^{-1}$		
γ	scaling factor for bole axial resistance from primary root/moss axial resistance	-	1.6×10^4	(Grant et al., 2007)
L	latent heat of evaporation	J g^{-1}	2460	
LE_{ci}	latent heat flux between canopy and atmosphere	W m^{-2}		
$L_{i,r,l}$	length of roots/mosses/mycorrhizae	m m^{-2}		
$M_{i,r,l}$	mass of roots/mosses/mycorrhizae	g m^{-2}		
$n_{i,r,l,x}$	number of primary ($x = 1$) or secondary ($x = 2$) axes	m^{-2}		
$\Omega_{ai,r}$	axial resistivity to water transport along root/moss/mycorrhizal axes	MPa h m^{-4}	4.0×10^9 deciduous	(Larcher, 2003)
			1.0×10^{10}	
			coniferous	
$\Omega_{ai,r,l,x}$	axial resistance to water transport along axes of primary ($x = 1$) or secondary ($x = 2$) roots/mosses/mycorrhizae	MPa h m^{-1}		
$\Omega_{ri,r}$	radial resistivity to water transport from surface to axis of roots/mosses/mycorrhizae	MPa h m^{-2}	1.0×10^4	(Doussan et al., 1998)
$\Omega_{ri,r,l}$	radial resistance to water transport from surface to axis of roots/mosses/mycorrhizae	MPa h m^{-1}		

$\Omega_{si,r,l}$	radial resistance to water transport from soil to surface of roots/mosses/mycorrhizae	MPa h m ⁻¹	
θ_{wl}	soil water content	m ³ m ⁻³	
θ_{pl}	soil porosity	m ³ m ⁻³	
$\theta_{p_{i,r}}$	root porosity	m ³ m ⁻³	
Ri	Richarson number		(van Bavel and Hillel, 1976)
Rn_{ci}	canopy net radiation	W m ⁻²	
r_{ai}	aerodynamic resistance to vapor flux from canopy	s m ⁻¹	
r_{bi}	radius of bole at ambient ψ_{c_i}	m	
$r_{b'_i}$	radius of bole at $\psi_{c_i} = 0$ MPa	m	
r_{ci}	canopy stomatal resistance to vapor flux	s m ⁻¹	
r_{cmaxi}	canopy cuticular resistance to vapor flux	s m ⁻¹	5.0 x 10 ³ (Larcher, 2003)
r_{cmini}	minimum r_{c_i} at $\psi_{c_i} = 0$ MPa	s m ⁻¹	
$r_{i,r,l,x}$	radius of primary ($x=1$) or secondary ($x=2$) roots/mosses/mycorrhizae at ambient $\psi_{r_i,l,z}$	m	
$r'_{i,r}$	radius of secondary roots/mosses/mycorrhizae at $\psi_{r_i,l,z} = 0$ MPa	m	2.0 x 10 ⁻⁴ tree 1.0 x 10 ⁻⁴ bush 0.05 x 10 ⁻⁴ mycorrhizae
ρ_r	root specific density	g C g FW ⁻¹	0.05 (Grant, 1998)
T_a	air temperature	K	
T_c	canopy temperature	K	

U_{wi}	total water uptake from all rooted soil layers	$\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$		
$U_{wi,r,l}$	water uptake by root/moss/mycorrhizal surfaces in each soil layer	$\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$		
u_a	wind speed measured at z_u	m s^{-1}		
V_{ci}'	potential canopy CO ₂ fixation rate at $\psi_{ci} = 0$ MPa	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
v_r	root specific volume	$\text{m}^3 \text{ g FW}^{-1}$	10^{-6}	(Grant, 1998)
X_{ci}	canopy capacitance	$\text{m}^3 \text{ m}^{-2} \text{ MPa}^{-1}$		
ψ_{ci}	canopy water potential	MPa		
ψ_{ci}'	$\psi_{ci} +$ canopy gravitational potential	MPa		
ψ_{pi}	canopy osmotic potential	MPa		
ψ_{sl}	soil water potential	MPa		
ψ_{sl}'	$\psi_{sl} +$ soil gravitational potential	MPa		
ψ_t	canopy turgor potential	MPa	1.25 at $\psi_c = 0$	
z_{bi}	length of bole from soil surface to top of canopy	m		
z_{di}	canopy zero-plane displacement height	m		(Perrier, 1982)
z_l	depth of soil layer below surface	m		
z_r	canopy surface roughness	m		(Perrier, 1982)
z_u	height of wind speed measurement	m		

S3. Gross primary productivity and autotrophic respiration

S3.1. C₃ gross primary productivity

$$GPP = \sum_{i,j,k,l,m,n,o} (V_{ci,j,k,l,m,n,o} = V_{gi,j,k,l,m,n,o}) A_{i,j,k,l,m,n,o}$$

solve for $C_{ii,j,k,l,m,n,o}$ at which [C1]
 $V_{ci,j,k,l,m,n,o} = V_{gi,j,k,l,m,n,o}$

$V_{\text{gi},j,k,l,m,n,o} = (C_b - C_{\text{ii},j,k,l,m,n,o})/r_{\text{li},j,k,l,m,n,o}$	diffusion	[C2]
$V_{\text{ci},j,k,l,m,n,o} = \min\{V_{\text{bi},j,k,l,m,n,o}, V_{\text{ji},j,k,l,m,n,o}\}$	carboxylation	[C3]
$r_{\text{li},j,k,l,m,n,o} = r_{\text{lmini},j,k,l,m,n,o} + (r_{\text{lmaxi}} - r_{\text{lmini},j,k,l,m,n,o}) e^{(-\beta \psi_{ti})}$	r_l is leaf-level equivalent of r_c	[C4]
$r_{\text{lmini},j,k,l,m,n,o} = (C_b - \mathbf{C}_i' i)/V_{\text{c}'_{i,j,k,l,m,n,o}}$	minimum r_l is driven by carboxylation	[C5]
$V_{\text{bi},j,k,l,m,n,o} = V_{\text{bmaxi},j,k}(C_{\text{ci},j,k,l,m,n,o} - I_{i,j,k})/(C_{\text{ci},j,k,l,m,n,o} + K_{\text{ci}}) f_{\psi_{i,j,k,l,m,n,o}} f_{\text{Ci}}$	CO_2 , water, temperature and nutrient constraints on V_b	[C6a]
$V_{\text{bmax}_{i,j,k}} = \mathbf{V}_{\text{b}'_i} \mathbf{F}_{\text{rubisco}_i} M_{i,j,k,\text{prot}} / A_{i,j,k} f_{\text{tbi}}$		[C6b]
$I_{i,j,k} = 0.5 O_c V_{\text{omax}_{i,j,k}} \mathbf{K}_{\text{c}_i} / (V_{\text{bmax}_{i,j,k}} \mathbf{K}_{\text{o}_i})$		[C6c]
$V_{\text{omax}_{i,j,k}} = \mathbf{V}_{\text{o}'_i} \mathbf{F}_{\text{rubisco}_i} M_{i,j,k,\text{prot}} / A_{i,j,k} f_{\text{toi}}$		[C6d]
$K_{\text{c}_i} = \mathbf{K}_{\text{c}_i} f_{\text{kci}} (1 + O_c / (\mathbf{K}_{\text{o}_k} f_{\text{tkoi}}))$		[C6e]
$V_{i,j,k,l,m,n,o} = J_{i,j,k,l,m,n,o} Y_{i,j,k,l,m,n,o} f_{\psi_{i,j,k,l,m,n,o}} f_{\text{Ci}}$	water, temperature and nutrient constraints on V_j	[C7]
$J_{i,j,k,l,m,n,o} = (\boldsymbol{\epsilon} I_{i,l,m,n,o} + J_{\text{maxi},j,k} - ((\boldsymbol{\epsilon} I_{i,l,m,n,o} + J_{\text{maxi},j,k})^2 - 4\alpha\boldsymbol{\epsilon} I_{i,l,m,n,o} J_{\text{maxi},j,k})^{0.5})/(2\alpha)$		[C8a]
		[C8b]
$J_{\text{maxi},j,k} = \mathbf{V}_{\text{j}'_i} \mathbf{F}_{\text{chlorophyll}_i} M_{i,j,k,\text{prot}} / A_{i,j,k} f_{\text{tji}}$		
$f_{\psi_{i,j,k,l,m,n,o}} = (r_{\text{lmin}_{i,j,k,l,m,n,o}} / r_{i,j,k,l,m,n,o})^{0.5}$	non-stomatal effect related to stomatal effect	[C9]
$f_{\text{tbi}} = \exp[\mathbf{B}_v - \mathbf{H}_{av}/(RT_{ci})] / \{1 + \exp[(\mathbf{H}_{dl} - \mathbf{S}T_{ci})/(RT_{ci})] + \exp[(ST_{ci} - \mathbf{H}_{dh})/(RT_{ci})]\}$	Arrhenius functions for carboxylation, oxygenation and electron transport	[C10a]
$f_{\text{toi}} = \exp[\mathbf{B}_o - \mathbf{H}_{ao}/(RT_{ci})] / \{1 + \exp[(\mathbf{H}_{dl} - ST_{ci})/(RT_{ci})] + \exp[(ST_{ci} - \mathbf{H}_{dh})/(RT_{ci})]\}$	temperature sensitivity of $\mathbf{K}_{\text{c}_i}, \mathbf{K}_{\text{o}_i}$	[C10b]
$f_{\text{tji}} = \exp[\mathbf{B}_j - \mathbf{H}_{aj}/(RT_{ci})] / \{1 + \exp[(\mathbf{H}_{dl} - ST_{ci})/(RT_{ci})] + \exp[(ST_{ci} - \mathbf{H}_{dh})/(RT_{ci})]\}$		[C10c]
$f_{\text{kci}} = \exp[\mathbf{B}_{kc} - \mathbf{H}_{akc}/(RT_{ci})]$		[C10d]
$f_{\text{tkoi}} = \exp[\mathbf{B}_{ko} - \mathbf{H}_{ako}/(RT_{ci})]$		[C10e]
$f_{\text{Ci}} = \min\{\sigma_{Ni,j}/(\sigma_{Ni,j} + \sigma_{Ci,j}/\mathbf{K}_{iC_N}), \sigma_{Pi,j}/(\sigma_{Pi,j} + \sigma_{Ci,j}/\mathbf{K}_{iC_P})\}$	product inhibition of V_b, V_j from σ_N and σ_P vs. σ_C in shoots	[C11]

$$\delta M_{L_{Rij,k}} / \delta t = \delta M_{L_{ij,k}} / \delta t \min \{ [N'_{leaf} + (N_{leaf} - N'_{leaf}) f_{iCl}] / N_{prot}, [P'_{leaf} + (P_{leaf} - P'_{leaf}) f_{iCl}] / P_{prot} \}$$

leaf structural protein growth [C12]

S3.2. Autotrophic respiration

$$R_a = \sum_i \sum_j (R_{ci,j} + R_{si,j}) + \sum_i \sum_z (R_{ci,r,l} + R_{si,r,l}) + E_{N,P} (U_{NH4i,r,l} + U_{NO3i,r,l} + U_{PO4i,r,l})$$

total autotrophic respiration [C13]

$$R_{ci,j} = R_c' \sigma_{Ci,j} f_{ta}$$

[C14a]

$$R_{ci,r,l} = R_c' \sigma_{C,i,r,l} f_{ta,i,l} (U_{O2i,r,l} / U'_{O2i,r,l})$$

[C14b]

$$U_{O2i,r,l} = U'_{O2i,r,l} [O_{2ri,r,l}] / ([O_{2ri,r,l}] + K_O_2)$$

[C14c]

$$= U_{w_{i,r,l}} [O_{2sl}] + 2\pi L_{i,r,l} D_{sO2} ([O_{2sl}] - [O_{2ri,r,l}]) \ln \{(r_{sl} + r_{ri,r,l}) / r_{ri,r,l}\} + 2\pi L_{i,r,l} D_{rO2} ([O_{2qri,r,l}] - [O_{2ri,r,l}]) \ln (r_{qri,r,l}) / r_{ri,r,l}$$

[C14d]

$$U'_{O2i,r,l} = 2.67 R_a'_{i,r,l}$$

[C14e]

$$R_{si,j} = - \min \{0.0, R_{ci,j} - R_{mi,j}\}$$

remobilization when $R_m > R_c$ [C15]

$$R_{mi,j} = \sum_z (N_{i,j,z} R_m' f_{tm})$$

maintenance respiration [C16]

$$R_{gi,j} = \max \{0.0, \min \{R_{ci,j} - R_{mi,j}\} \min \{1.0, \max \{0.0, \psi_{i,j} - \psi_t'\}\}\}$$

growth when $R_m < R_c$ [C17]

S3.3. Growth and senescence

$$l_{i,j,z,C} = R_{si,j} M_{L_{Ni,j}} / M_{L_{Rij}}$$

[C18]

$$l_{i,j,z,N} = l_{i,j,z,C} N_{prot} (1.0 - X_{mx} f_{xNi,j})$$

[C19a]

$$l_{i,j,z,P} = l_{i,j,z,C} P_{prot} (1.0 - X_{mx} f_{xPi,j})$$

[C19b]

$$f_{xNi,j} = \sigma_{Ci,j} / (\sigma_{Ci,j} + \sigma_{Ni,j} / K_{xN})$$

[C19c]

senescence drives litterfall of non-remobilizable material
litterfall of N and P is driven by that of C but reduced by translocation to σ_N and σ_P according to ratios of σ_N and σ_P with σ_C

[C19d]

$$f_{xPi,j} = \sigma_{Ci,j} / (\sigma_{Ci,j} + \sigma_{Pi,j} / K_{xP})$$

[C19d]

$$\delta M_{Bi,j} / \delta t = \sum_z [R_{gi,j} (1 - Y_{gi,z}) / Y_{gi,z}] - R_{si,j} - l_{i,j,C}$$

branch growth driven by R_g [C20a]

$$\delta M_{Ri,r,l} / \delta t = [R_{gi,r,l} (1 - Y_{gi,r}) / Y_{gi,r}] - R_{si,r,l} - l_{i,r,l,C}$$

root growth driven by R_g [C20b]

$$\delta A_{L,i,j,k,l}/\delta t = \chi (M_{L,i,j,k,l}/y_i)^{-0.33} \delta M_{L,i,j,k,l}/\delta t \min\{1, \max\{0, \psi_{ti} - \psi_t'\}\}$$

$$\delta L_{i,r,l,l}/\delta t = (\delta M_{R,i,r,l,l}/\delta t)/y_i v_r / \{\rho_r (1 - \theta_{P,i,r}) (\pi r_{r,i,r,l,l}^2)\}$$

$$\delta L_{i,r,l,2}/\delta t = (\delta M_{R,i,r,l,2}/\delta t) v_r / \{\rho_r (1 - \theta_{P,i,r}) (\pi r_{r,i,r,l,2}^2)\}$$

$$f_{tai} = T_{ci} \{ \exp[\mathbf{B}_v - \mathbf{H}_{av}/(RT_{ci})] \} / \{ 1 + \exp[(H_{dl} - ST_{ci})/(RT_{ci})] + \exp[(ST_{ci} - H_{dh})/(RT_{ci})] \}$$

$$f_{tm} = e^{(0.0811*(T_{ci} - 298.15))}$$

S3.4. Root/moss/mycorrhizal nutrient uptake

$$U_{NH4i,r,l} = \{ U_{wi,r,l} [NH_4^+] + 2\pi L_{i,r,l} D_{eNH4l} ([NH_4^+] - [NH_4^+_{i,r,l}]) / \ln(d_{i,r,l} / r_{r,i,r,l}) \}$$

$$= \mathbf{U}'_{NH4} (U_{O2i,r,l} / U'_{O2i,r,l}) A_{i,r,l} ([NH_4^+_{i,r,l}] - [NH_4^+_{mn}]) / ([NH_4^+_{i,r,l}] - [NH_4^+_{mn}] + K_{NH4}) f_{tl,l} f_{in,r,l}$$

$$U_{NO3i,r,l} = \{ U_{wi,r,l} [NO_3^-_l] + 2\pi L_{i,r,l} D_{eNO3l} ([NO_3^-_l] - [NO_3^-_{i,r,l}]) / \ln(d_{i,r,l} / r_{r,i,r,l}) \}$$

$$= \mathbf{U}'_{NO3} (U_{O2i,r,l} / U'_{O2i,r,l}) A_{i,r,l} ([NO_3^-_{i,r,l}] - [NO_3^-_{mn}]) / ([NO_3^-_{i,r,l}] - [NO_3^-_{mn}] + K_{NO3}) f_{tl,l} f_{in,r,l}$$

$$U_{PO4i,r,l} = \{ U_{wi,r,l} [H_2PO_4^-_l] + 2\pi L_{i,r,l} D_{ePO4l} ([H_2PO_4^-_l] - [H_2PO_4^-_{i,r,l}]) / \ln(d_{i,r,l} / r_{r,i,r,l}) \}$$

$$= \mathbf{U}'_{PO4} (U_{O2i,r,l} / U'_{O2i,r,l}) A_{i,r,l} ([H_2PO_4^-_{i,r,l}] - [H_2PO_4^-_{mn}]) / ([H_2PO_4^-_{i,r,l}] - [H_2PO_4^-_{mn}] + K_{PO4}) f_{gl}$$

$$f_{ip,r,l}$$

$$f_{in,r,l} = \sigma_{Ci,r,l} / (\sigma_{Ci,r,l} + \sigma_{Ni,r,l} / K_{NiC})$$

$$f_{ip,r,l} = \sigma_{Ci,r,l} / (\sigma_{Ci,r,l} + \sigma_{Pi,r,l} / K_{PiC})$$

leaf expansion driven by leaf mass growth

[C21a]

root extension of primary and secondary axes driven by root mass growth

[C21b]

[C21c]

Arrhenius function for R_a

[C22a]

temperature function for R_m

[C22b]

Root/moss/mycorrhizal N and P uptake from mass flow + diffusion coupled with active

[C23a]

uptake of NH_4^+ , NO_3^- and $H_2PO_4^-$ constrained by O_2 uptake, as for microbial N and P uptake in (Eq. A26)

[C23b]

[C23c]

[C23d]

[C23e]

[C23f]

product inhibition of U_{NH4} , U_{NO3} and U_{PO4} determined by σ_N and σ_P vs. σ_C in roots

[C23g]

[C23h]

S3.5. Definition of variables in sections S3.1-S3.4 (Eqs. C1-C23)

Variable	Definition	Unit	Value	Reference
<i>Subscripts</i>				
<i>i</i>	species or functional type: evergreen, coniferous, deciduous, annual, perennial, C ₃ , C ₄ , monocot, dicot, legume etc.			
<i>j</i>	branch or tiller			
<i>k</i>	Node			

- l* soil or canopy layer
- m* leaf azimuth
- n* leaf inclination
- o* leaf exposure (sunlit *vs.* shaded)
- z* organ including leaf, stem, root, moss mycorrhizae

Variables

<i>A</i>	leaf, root/moss/mycorrhizal surface area	$\text{m}^2 \text{ m}^{-2}$		
β	shape parameter for stomatal effects on CO_2 diffusion and non-stomatal effects on carboxylation	MPa^{-1}	-5.0	(Grant and Flanagan, 2007)
<i>B</i>	parameter such that $f_t = 1.0$ at $T_c = 298.15 \text{ K}$		17.533	
B_j	parameter such that $f_{j i} = 1.0$ at $T_c = 298.15 \text{ K}$		17.363	
B_{kc}	parameter such that $f_{tkci} = 1.0$ at $T_c = 298.15 \text{ K}$		22.187	
B_{ko}	parameter such that $f_{tkoi} = 1.0$ at $T_c = 298.15 \text{ K}$		8.067	
B_o	parameter such that $f_{toi} = 1.0$ at $T_c = 298.15 \text{ K}$		24.221	
B_v	parameter such that $f_{tvi} = 1.0$ at $T_c = 298.15 \text{ K}$		26.238	
<i>C_b</i>	[CO_2] in canopy air	$\mu\text{mol mol}^{-1}$		
<i>C_{c(b4)}</i>	[CO_2] in C ₄ bundle sheath	μM		
<i>C_{c(m4)}</i>	[CO_2] in C ₄ mesophyll in equilibrium with $C_{ii,j,k,l,m,n,o}$	μM		
<i>C_c</i>	[CO_2] in canopy chloroplasts in equilibrium with $C_{ii,j,k,l,m,n,o}$	μM		
$C_{i(m4)}'$	[CO_2] in C ₄ mesophyll air when $\psi_{ci} = 0$	$\mu\text{mol mol}^{-1}$	0.45 x <i>C_b</i>	

$C_{i(m4)}$	[CO ₂] in C ₄ mesophyll air	μmol mol ⁻¹		
$C_{i,j,z=l}$	C content of leaf ($z = l$)	g C m ⁻²		
C'	[CO ₂] in canopy leaves when $\psi_{ci} = 0$	μmol mol ⁻¹	0.70 x C_b	(Larcher, 2003)
C_i	[CO ₂] in canopy leaves	μmol mol ⁻¹		
$D_e \text{NH}_4l$	effective dispersivity-diffusivity of NH ₄ ⁺ during root/moss/mycorrhizal uptake	m ² h ⁻¹		
$D_e \text{NO}_3l$	effective dispersivity-diffusivity of NO ₃ ⁻ during root/moss/mycorrhizal uptake	m ² h ⁻¹		
$D_e \text{PO}_4l$	effective dispersivity-diffusivity of H ₂ PO ₄ ⁻ during root/moss/mycorrhizal uptake	m ² h ⁻¹		
D_{rO_2}	aqueous diffusivity of O ₂ from root aerenchyma to root or mycorrhizal surfaces	m ² h ⁻¹		
D_{sO_2}	aqueous diffusivity of O ₂ from soil to root or mycorrhizal surfaces	m ² h ⁻¹		
$d_{i,r,l}$	half distance between adjacent roots assumed equal to uptake path length	m	$(\pi L_{s,z} / \Delta z)^{-1/2}$	(Grant, 1998)
$E_{N,P}$	energy cost of nutrient uptake	g C g N ⁻¹ or P ⁻¹	2.15	(Veen, 1981)
$f_{C(c3)}$	C ₃ product inhibition of RuBP carboxylation activity in C ₄ bundle sheath or C ₃ mesophyll	–		
$f_{C(m4)}$	C ₄ product inhibition of PEP carboxylation activity in C ₄ mesophyll	–		
F_{chl}	fraction of leaf protein in chlorophyll	–	0.025	
f_{iC}	N,P inhibition on carboxylation, leaf structural N,P growth	–		
f_{iN}	N inhibition on root/moss/mycorrhizal N uptake	–		

f_{ip}	P inhibition on root/moss/mycorrhizal P uptake	–	
F_{rubisco}	fraction of leaf protein in rubisco	–	0.125
f_{ta}	temperature effect on $R_{\text{ai},j}$	–	
f_{tb}	temperature effect on carboxylation	–	
f_{tg}	temperature function for root/moss/mycorrhizal growth respiration	dimensionless	
f_{tj}	temperature effect on electron transport	–	
f_{tkc}	temperature effect on K_{c_i}	–	(Bernacchi et al., 2001, 2003)
f_{tko}	temperature effect on K_{o_i}	–	(Bernacchi et al., 2001, 2003)
f_{tm}	temperature effect on $R_{\text{mi},j}$	–	$Q_{10} = 2.25$
f_{to}	temperature effect on oxygenation	–	
f_{tv}	temperature effect on carboxylation	–	
f_{xN}	fraction of \mathbf{X}_{mx} N translocated out of leaf or root/moss during senescence	–	
f_{xp}	fraction of \mathbf{X}_{mx} P translocated out of leaf or root/moss during senescence	–	
$f_{\psi i}$	non-stomatal water effect on carboxylation	–	(Medrano et al., 2002)
$f_{\psi i}$	non-stomatal water effect on carboxylation	–	
H_a	energy of activation	J mol^{-1}	57.5×10^3

H_{aj}	energy of activation for electron transport	J mol ⁻¹	43 x 10 ³	(Bernacchi et al., 2001, 2003)
H_{akc}	parameter for temperature sensitivity of K_{c_i}	J mol ⁻¹	55 x 10 ³	(Bernacchi et al., 2001, 2003)
H_{ako}	parameter for temperature sensitivity of K_{o_i}	J mol ⁻¹	20 x 10 ³	(Bernacchi et al., 2001, 2003)
H_{ao}	energy of activation for oxygenation	J mol ⁻¹	60 x 10 ³	(Bernacchi et al., 2001, 2003)
H_{av}	energy of activation for carboxylation	J mol ⁻¹	65 x 10 ³	(Bernacchi et al., 2001, 2003)
H_{dh}	energy of high temperature deactivation	J mol ⁻¹	222.5 x 10 ³	
H_{dh}	energy of high temperature deactivation	J mol ⁻¹	220 x 10 ³	
H_{dl}	energy of low temperature deactivation	J mol ⁻¹	198.0 x 10 ³	
H_{dl}	energy of low temperature deactivation	J mol ⁻¹	190 x 10 ³	
I	Irradiance	μmol m ⁻² s ⁻¹		
$J_{(b4)}$	electron transport rate in C ₄ bundle sheath	μmol m ⁻² s ⁻¹		
$J_{(m4)}$	electron transport rate in C ₄ mesophyll	μmol m ⁻² s ⁻¹		
J	electron transport rate in C ₃ mesophyll	μmol m ⁻² s ⁻¹		
J_{max}'	specific electron transport rate at non-limiting I and 25°C when $\psi_{ci} = 0$ and nutrients are nonlimiting	μmol g ⁻¹ s ⁻¹	400	
$J_{max(b4)}$	electron transport rate in C ₄ bundle sheath at non-limiting I	μmol m ⁻² s ⁻¹		
$J_{max(m4)}$	electron transport rate in C ₄ mesophyll at non-limiting I	μmol m ⁻² s ⁻¹		

J_{\max}	electron transport rate at non-limiting I , ψ_{ci} , temperature and N,P	$\mu\text{mol m}^{-2} \text{s}^{-1}$		
$K_{c(b4)}$	Michaelis-Menten constant for carboxylation in C ₄ bundle sheath	μM	30.0 at 25°C and zero O ₂	(Lawlor, 1993)
$K_{c(m4)}$	Michaelis-Menten constant for carboxylation in C ₄ mesophyll	μM	3.0 at 25°C	(Lawlor, 1993)
K_c	Michaelis-Menten constant for carboxylation at zero O ₂	μM	12.5 at 25 °C	(Farquhar et al., 1980)
K_c	Michaelis-Menten constant for carboxylation at ambient O ₂	μM		
K_{iC_N}	inhibition constant for growth in shoots from σ_C vs. σ_N	g C g N^{-1}	100	(Grant, 1998)
K_{iC_P}	inhibition constant for growth in shoots from σ_C vs. σ_P	g C g P^{-1}	1000	(Grant, 1998)
$K_{IzC4(b4)}$	constant for CO ₂ product inhibition of C ₄ decarboxylation in C ₄ bundle sheath	μM	1000.0	
$K_{IzC4(m4)}$	constant for C ₄ product inhibition of PEP carboxylation activity in C ₄ mesophyll	μM	5×10^6	
$K_{I\pi_{lf}}$	constant for C ₃ product inhibition of RuBP carboxylation activity in C ₄ bundle sheath or C ₃ mesophyll caused by $[\pi_{fi,j}]$	g C g N^{-1}	100	
$K_{I\pi_{lf}}$	constant for C ₃ product inhibition of RuBP carboxylation activity in C ₄ bundle sheath or C ₃ mesophyll caused by $[\pi_{fl,j}]$	g C g P^{-1}	1000	
K_{iN_C}	inhibition constant for N uptake in roots/mosses from $\sigma_{C,i,j}$ vs. $\sigma_{N,j}$	g N g C^{-1}	0.1	(Grant, 1998)

K_{iP_C}	inhibition constant for P uptake in roots/mosses from $\sigma_{Ci,j}$ vs. $\sigma_{Pi,j}$ roots	g P g C ⁻¹	0.01	(Grant, 1998)
K_{NH_4}	M-M constant for NH ₄ ⁺ uptake at root/moss/mycorrhizal surfaces	g N m ⁻³	0.40	(Barber and Silberbush, 1984)
K_{NO_3}	M-M constant for NO ₃ ⁻ uptake at root/moss/mycorrhizal surfaces	g N m ⁻³	0.35	(Barber and Silberbush, 1984)
K_{PO_4}	M-M constant for H ₂ PO ₄ ⁻ uptake root/moss/mycorrhizal surfaces	g P m ⁻³	0.125	(Barber and Silberbush, 1984)
K_o	Michaelis-Menten constant for root or mycorrhizal O ₂ uptake	g m ⁻³	0.064	(Griffith, 1972)
K_o	inhibition constant for O ₂ in carboxylation	μM	500 at 25 °C	(Farquhar et al., 1980)
K_{xN}	inhibition constant for remobilization of leaf or root/moss N during senescence	g N g C ⁻¹	0.1	
K_{xP}	inhibition constant for remobilization of leaf or root/moss P during senescence	g P g C ⁻¹	0.01	
L	root length	m m ⁻²		
l_C	C litterfall from leaf or root/moss	g C m ⁻² h ⁻¹		
$l_{N,P}$	N or P litterfall from leaf or root/moss	g C m ⁻² h ⁻¹		
M_B	branch C phytomass	g C m ⁻²		
M_L	leaf C phytomass	g C m ⁻²		
M_{L_N}, M_{L_R}	non-remobilizable, remobilizable leaf C phytomass	g C m ⁻²		
M_R	root C phytomass	g C m ⁻²		
M_{iprot}	leaf protein phytomass calculated from leaf N, P contents	g N m ⁻²		

N, P	N or P content of organ z	g N m^{-2}	
N_{prot}	N content of protein remobilized from leaf or root	g N C^{-1}	0.4
$[\text{NH}_4^+_{i,r,l}]$	concentration of NH_4^+ at root/moss/mycorrhizal surfaces	g N m^{-3}	
$[\text{NH}_4^+_{mn}]$	concentration of NH_4^+ at root/moss/mycorrhizal surfaces below which $U_{\text{NH}_4} = 0$	g N m^{-3}	0.0125 (Barber and Silberbush, 1984)
$[\text{NO}_3^-_{i,r,l}]$	concentration of NH_4^+ at root/moss/mycorrhizal surfaces	g N m^{-3}	
$[\text{NO}_3^-_{mn}]$	concentration of NO_3^- at root/moss/mycorrhizal surfaces below which $U_{\text{NO}_3} = 0$	g N m^{-3}	0.03 (Barber and Silberbush, 1984)
$[\text{H}_2\text{PO}_4^-_{i,r,l}]$	concentration of H_2PO_4^- root/moss/mycorrhizal surfaces	g N m^{-3}	
$[\text{H}_2\text{PO}_4^-_{mn}]$	concentration of H_2PO_4^- at root/moss/mycorrhizal surfaces below which $U_{\text{PO}_4} = 0$	g N m^{-3}	0.002 (Barber and Silberbush, 1984)
N_{leaf}	maximum leaf structural N content	g N g C^{-1}	0.10
N'_{leaf}	minimum leaf structural N content	g N g C^{-1}	$0.33 \times N_{\text{leaf}}$
N_{lf}	total leaf N	$\text{g N m}^{-2} \text{ leaf}$	
$[N_{\text{chl(b4)}}]'$	ratio of chlorophyll N in C_4 bundle sheath to total leaf N	g N g N^{-1}	0.05
$[N_{\text{chl(m4)}}]'$	ratio of chlorophyll N in C_4 mesophyll to total leaf N	g N g N^{-1}	0.05
$[N_{\text{pep(m4)}}]'$	ratio of PEP carboxylase N in C_4 mesophyll to total leaf N	g N g N^{-1}	0.025
$[N_{\text{rub(b4)}}]'$	ratio of RuBP carboxylase N in C_4 bundle sheath to total leaf N	g N g N^{-1}	0.025
O_{2q}	aqueous O_2 concentration in root or mycorrhizal aerenchyma	g m^{-3}	
O_{2r}	aqueous O_2 concentration at root or mycorrhizal surfaces	g m^{-3}	

O_{2s}	aqueous O ₂ concentration in soil solution	g m ⁻³	
O_c	[O ₂] in canopy chloroplasts in equilibrium with O ₂ in atm.	μM	
P_{leaf}	maximum leaf structural P content	g P g C ⁻¹	0.10
P'_{leaf}	minimum leaf structural P content	g P g C ⁻¹	0.33 x P_{leaf}
P_{prot}	P content of protein remobilized from leaf or root	g P C ⁻¹	0.04
$[\pi_{lf}]$	concentration of nonstructural root P uptake product in leaf	g P g C ⁻¹	
θ_p	root or mycorrhizal porosity	m ³ m ⁻³	0.1 – 0.5
R	gas constant	J mol ⁻¹ K ⁻¹	8.3143
R	gas constant	J mol ⁻¹ K ⁻¹	8.3143
R_a	total autotrophic respiration	g C m ⁻² h ⁻¹	
R'_a	R_a under nonlimiting O ₂	g C m ⁻² h ⁻¹	
R'_c	specific autotrophic respiration of $\sigma_{C_{ij}}$ at $T_{ci} = 25$ °C	g C g C ⁻¹ h ⁻¹	0.015
R_c	autotrophic respiration of $\sigma_{C_{ij}}$ or $\sigma_{C_{i,r,l}}$	g C m ⁻² h ⁻¹	
R_g	growth respiration	g C m ⁻² h ⁻¹	
r_{lf}	leaf stomatal resistance	s m ⁻¹	
r_{lfmaxi}	leaf cuticular resistance	s m ⁻¹	
$r_{lfmini,j,k,l,m,n,o}$	leaf stomatal resistance when $\psi_{ci} = 0$	s m ⁻¹	
$r_{l,j,k,l,m,n,o}$	leaf stomatal resistance	s m ⁻¹	
r_{lmaxi}	leaf cuticular resistance	s m ⁻¹	

$r_{\min i,j,k,l,m,n,o}$	leaf stomatal resistance when $\psi_{ci} = 0$	s m^{-1}		
R_m'	specific maintenance respiration of $\sigma_{Ci,j}$ at $T_{ci} = 25^\circ\text{C}$	$\text{g C g N}^{-1} \text{ h}^{-1}$	0.0115	(Barnes et al., 1997)
$R_{mi,j}$	above-ground maintenance respiration	$\text{g C m}^{-2} \text{ h}^{-1}$		
$r_{qi,r,l}$	radius of root aerenchyma	m		
$r_{ri,r,l}$	root/moss/mycorrhizal radius	m	1.0×10^{-4} or 5.0×10^{-6}	
$R_{si,j}$	respiration from remobilization of leaf C	$\text{g C m}^{-2} \text{ h}^{-1}$		
r_{sl}	thickness of soil water films	m		
ρ_r	dry matter content of root/moss biomass	g g^{-1}	0.125	
S	change in entropy	$\text{J mol}^{-1} \text{ K}^{-1}$	710	(Sharpe and DeMichele, 1977)
S	change in entropy	$\text{J mol}^{-1} \text{ K}^{-1}$	710	
σ_C	nonstructural C product of CO ₂ fixation	g C g C^{-1}		
σ_N	nonstructural N product of root/moss/mycorrhizal uptake	g N g C^{-1}		
σ_P	nonstructural P product of root/moss/mycorrhizal uptake	g P g C^{-1}		
T_c	canopy temperature	K		
T_c	canopy temperature	°C		
$U_{\text{NH}_4i,r,l}$	NH ₄ ⁺ uptake by roots/mosses/mycorrhizae	$\text{g N m}^{-2} \text{ h}^{-1}$		
U'_{NH_4}	maximum U_{NH_4} at 25 °C and non-limiting NH ₄ ⁺	$\text{g N m}^{-2} \text{ h}^{-1}$	5.0×10^{-3}	(Barber and Silberbush, 1984)
$U_{\text{NO}_3i,r,l}$	NO ₃ ⁻ uptake by roots/mosses/mycorrhizae	$\text{g N m}^{-2} \text{ h}^{-1}$		

U'_{NO_3}	maximum U_{NO_3} at 25 °C and non-limiting NO_3^-	$\text{g N m}^{-2} \text{ h}^{-1}$	5.0×10^{-3}	(Barber and Silberbush, 1984)
$U_{\text{PO}_4i,r,l}$	H_2PO_4^- uptake by roots/mosses/mycorrhizae	$\text{g N m}^{-2} \text{ h}^{-1}$		
U'_{PO_4}	maximum U_{PO_4} at 25 °C and non-limiting H_2PO_4^-	$\text{g N m}^{-2} \text{ h}^{-1}$	5.0×10^{-3}	(Barber and Silberbush, 1984)
$U_{\text{O}_2i,r,l}$	O_2 uptake by roots and mycorrhizae under ambient O_2	$\text{g O m}^{-2} \text{ h}^{-1}$		
$U'_{\text{O}_2i,l,r}$	O_2 uptake by roots and mycorrhizae under nonlimiting O_2	$\text{g O m}^{-2} \text{ h}^{-1}$		
$U_{w,i,r,l}$	root/moss/mycorrhizal water uptake	$\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$		
$V_{\phi(b4)i,j,k}$	CO_2 leakage from C ₄ bundle sheath to C ₄ mesophyll	$\text{g C m}^{-2} \text{ h}^{-1}$		
V_b'	specific rubisco carboxylation at 25 °C	$\mu\text{mol g}^{-1} \text{ rubisco s}^{-1}$	45	(Farquhar et al., 1980)
$V_{b(b4)i,j,k}$	CO_2 -limited carboxylation rate in C ₄ bundle sheath	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
$V_{b(m4)i,j,k,l,m,n,o}$	CO_2 -limited carboxylation rate in C ₄ mesophyll	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
$V_{b(i,j,k,l,m,n,o)}$	CO_2 -limited leaf carboxylation rate	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
$V_{b\max(b4)}'$	RuBP carboxylase specific activity in C ₄ bundle sheath at 25°C when $\psi_{ci} = 0$ and nutrients are nonlimiting	$\mu\text{mol g}^{-1} \text{ s}^{-1}$	75	
$V_{b\max(b4)i,j,k}$	CO_2 -nonlimited carboxylation rate in C ₄ bundle sheath	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
$V_{b\max(m4)}'$	PEP carboxylase specific activity in C ₄ mesophyll at 25°C when $\psi_{ci} = 0$ and nutrients are nonlimiting	$\mu\text{mol g}^{-1} \text{ s}^{-1}$	150	
$V_{b\max(m4)i,j,k}$	CO_2 -nonlimited carboxylation rate in C ₄ mesophyll	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		
$V_{b\max i,j,k}$	leaf carboxylation rate at non-limiting CO_2 , ψ_{ci} , T_c and N,P	$\mu\text{mol m}^{-2} \text{ s}^{-1}$		

$V_{c(b4)i,j,k,l,m,n,o}$	CO ₂ fixation rate in C ₄ bundle sheath	μmol m ⁻² s ⁻¹
$V_{c(m4)i,j,k,l,m,n,o}$	CO ₂ fixation rate in C ₄ mesophyll	μmol m ⁻² s ⁻¹
$V_{c0(m4)}_{i,j,k,l,m,n,o}$	CO ₂ fixation rate in C ₄ mesophyll when $\psi_{ci} = 0$ MPa	μmol m ⁻² s ⁻¹
$V_{ci,j,k,l,m,n,o}$	leaf CO ₂ fixation rate	μmol m ⁻² s ⁻¹
$V'_{ci,j,k,l,m,n,o}$	leaf CO ₂ fixation rate when $\psi_{ci} = 0$	μmol m ⁻² s ⁻¹
$V_{g(m4)i,j,k,l,m,n,o}$	CO ₂ diffusion rate into C ₄ mesophyll	μmol m ⁻² s ⁻¹
$V_{gi,j,k,l,m,n,o}$	leaf CO ₂ diffusion rate	μmol m ⁻² s ⁻¹
V'_j	specific chlorophyll e ⁻ transfer at 25 °C	μmol g ⁻¹ chlorophyll s ⁻¹ 450 (Farquhar et al., 1980)
$V_{j(b4)i,j,k,l,m,n,o}$	irradiance-limited carboxylation rate in C ₄ bundle sheath	μmol m ⁻² s ⁻¹
$V_{j(m4)i,j,k,l,m,n,o}$	irradiance-limited carboxylation rate in C ₄ mesophyll	μmol m ⁻² s ⁻¹
$V_{ji,j,k,l,m,n,o}$	irradiance-limited leaf carboxylation rate	μmol m ⁻² s ⁻¹
V'_o	specific rubisco oxygenation at 25 °C	μmol g ⁻¹ rubisco s ⁻¹ 9.5 (Farquhar et al., 1980)
$V_{omaxi,j,k}$	leaf oxygenation rate at non-limiting O ₂ , ψ_{ci} , T_c and N,P	μmol m ⁻² s ⁻¹
$V_{\chi C4(b4)i,j,k}$	decarboxylation of C ₄ fixation product in C ₄ bundle sheath	g C m ⁻² h ⁻¹
$V_{\chi C4(m4)}$	transfer of C ₄ fixation product between C ₄ mesophyll and bundle sheath	g C m ⁻² h ⁻¹
[N_f]	concentration of nonstructural root/moss/mycorrhizal N uptake product in leaf	g N g C ⁻¹

v_r	specific volume of root biomass	$\text{m}^3 \text{ g}^{-1}$		
$W_{\text{lf(b4)}}$	C_4 bundle sheath water content	g m^{-2}		
$W_{\text{lf(m4)}}$	C_4 mesophyll water content	g m^{-2}		
X_{mx}	maximum fraction of remobilizable N or P translocated out of leaf or root during senescence	-	0.6	(Kimmins, 2004)
$Y_{(\text{b4})}$	carboxylation yield from electron transport in C_4 bundle sheath	$\mu\text{mol CO}_2 \mu\text{mol e}^{-1}$		
$Y_{(\text{m4})}$	carboxylation yield from electron transport in C_4 mesophyll	$\mu\text{mol CO}_2 \mu\text{mol e}^{-1}$		
Y_g	fraction of $\sigma_{\text{Ci},j}$ used for growth expended as $R_{g,j,z}$ by organ z	g C g C^{-1}	0.28 ($z = \text{leaf}$), 0.24 ($z = \text{root and other non-foliar}$), 0.20 ($z = \text{wood}$)	(Waring and Running, 1998)
y	plant population	m^{-2}		
Y	carboxylation yield	$\mu\text{mol CO}_2 \mu\text{mol e}^{-1}$		
Γ	CO_2 compensation point	μM		
$\Gamma_{(\text{b4})}$	CO_2 compensation point in C_4 bundle sheath	μM		
$\Gamma_{(\text{m4})}$	CO_2 compensation point in C_4 mesophyll	μM		
α	shape parameter for response of J to I	-	0.7	
α	shape parameter for response of J to I	-	0.75	
χ	area:mass ratio of leaf growth	m g^{-3}	0.0125	(Grant and Hesketh, 1992)

$\chi_{C4(b4)}$	non-structural C ₄ fixation product in C ₄ bundle sheath	g C m ⁻²		
$\chi_{C4(m4)}$	non-structural C ₄ fixation product in C ₄ mesophyll	g C m ⁻²		
$[\chi_{C3(b4)}]$	concentration of non-structural C ₃ fixation product in C ₄ bundle sheath	g g ⁻¹		
$[\chi_{C4(m4)}]$	concentration of non-structural C ₄ fixation product in C ₄ mesophyll	μM		
ϵ	quantum yield	μmol e ⁻ μmol quanta ⁻¹	0.45	(Farquhar et al., 1980)
ε	quantum yield	μmol e ⁻ μmol quanta ⁻¹	0.45	(Farquhar et al., 1980)
$\kappa_{Cc(b4)}$	conductance to CO ₂ leakage from C ₄ bundle sheath	h ⁻¹	20	
ψ_t	canopy turgor potential	MPa	1.25 at $\psi_c = 0$	

2

3 **S4. Soil water, heat and gas fluxes**4 **S4.1. Surface water flux**

5
$$\frac{\Delta(d_w A)}{\Delta t} = \sum_i Q_{w,in_i} + \sum_i Q_{w,out_i} + P - E_{res} - E_{surf}; \text{ kinematic wave theory of overland flow}$$
 [D1]

6
$$Q_{w_i} = v_i (d_w - d_{sw}) L_i$$
 [D2]

7
$$v_i = \frac{R^{0.67} S_i^{0.5}}{z_r}$$
 [D3]

8
$$R = \frac{s_r d_{mw}}{s_r^2 + 1}$$
 [D4]

9
$$S_i = \frac{2abs[(Z + d_{sw} + d_{mw})_{s_i} - (Z + d_{sw} + d_{mw})_{d_i}]}{L_{s_i} + L_{d_i}}$$
 [D5]

10
$$E_{res} = \frac{e_{air} - e_{res}(\psi_{res} T_{res})}{r_{a_{res}} + r_{s_{res}}}$$
 [D6]

11
$$E_{surf} = \frac{e_{air} - e_{surf}(\psi_{surf} T_{surf})}{r_{a_{surf}} + r_{s_{surf}}}$$
 [D7]

12 Where, subscripts i =dimensions ($i=x, y$), s =source cell, d =destination cell, in =flow into the grid cells, and out =flow out of the grid cells; d_w =depth of surface
 13 water (m); A =area of landscape position (m^2); t =time (h); Q_w =surface water flux ($m^3 m^{-2} h^{-1}$); P =precipitation flux ($m^3 m^{-2} h^{-1}$); E_{res} =evaporation flux from
 14 surface residue ($m^3 m^{-2} h^{-1}$); E_{surf} =evaporation flux from soil surface ($m^3 m^{-2} h^{-1}$); v =velocity of surface water flow ($m h^{-1}$); d_{sw} = maximum depth of surface
 15 water storage (m); L =length of grid cells (m); R =ratio of cross-sectional area to perimeter of surface flow (m); S =slope ($m m^{-1}$); z_r =Manning's roughness
 16 coefficient ($=0.01 m^{-1/3} h$); s_t =slope of channel sides during surface flow ($m m^{-1}$); Z =surface elevation (m); d_{sw} = maximum depth of surface water storage (m);
 17 d_{mw} =depth of mobile surface water (m); e_{air} =atmospheric vapour density ($g m^{-3}$); e_{res} =vapour density at surface residue ($g m^{-3}$) at current residue water potential
 18 (ψ_{res}) and temperature (T_{res}); $r_{a_{res}}$ =boundary layer resistance to evaporation from surface residue ($h m^{-1}$); $r_{s_{res}}$ =surface resistance to evaporation from surface
 19 residue ($h m^{-1}$); e_{surf} =vapour density at soil surface ($g m^{-3}$) at current soil surface water potential (ψ_{surf}) and temperature (T_{surf}); $r_{a_{surf}}$ =boundary layer resistance to
 20 evaporation from soil surface ($h m^{-1}$); and $r_{s_{surf}}$ =surface resistance to evaporation from soil surface ($h m^{-1}$).

21 **S4.2. Sub-surface water flux**

22
$$\frac{\Delta\theta_w}{\Delta t} = \sum_i (Q_{w_{mat,in,i}} + Q_{w_{mac,in,i}} - Q_{w_{mat,out,i}} - Q_{w_{mac,out,i}}) + \sum_j (Q_{w_{b,mat,in,j}} + Q_{w_{b,mac,in,j}} - Q_{w_{b,mat,out,j}} - Q_{w_{b,mac,out,j}}) + Q_f - U_w$$
; 3D continuity equation for water balance of each soil layer [D8]

23
$$Q_{w_{mat,i}} = K'_{mat,i} (\psi_{s_s} - \psi_{s_d})$$
; soil matrix water flow [D9]

24
$$K'_{mat,i} = \frac{2K_{mat,s_i} K_{mat,d_i}}{K_{mat,s_i} L_{d_i} + K_{mat,d_i} L_{s_i}}$$
; when both the source and destination grid cells are either saturated or unsaturated (Richard's equation) [D10]

25 $K'_{mat_i} = \frac{2K_{mat_s i}}{L_{s_i} + L_{d_i}}$; when the source cell is saturated and the destination cell is unsaturated (Green-Ampt equation) [D11]

26 $K'_{mat_i} = \frac{2K_{mat_d i}}{L_{s_i} + L_{d_i}}$; when the source cell is unsaturated and the destination cell is saturated (Green-Ampt equation) [D12]

27 $K_{mat_i} = K_{s,mat} \left(\frac{q-p+1}{q} \right)^{1.33} \left[\frac{\sum_{p=1}^{p=q} \frac{2p-1}{\psi_p^2}}{\sum_{r=p}^{r=q} \frac{2r+1-2p}{\psi_r^2}} \right]$; Green and Corey (1971) model used in MCM simulation of *ecosys* [D13]

28 $p = \text{Int} \left[q \frac{(\theta_s - \theta_p)}{\theta_s} \right] + 1$ [D14]

29 $n(k) = 1 + 0.001k$ [D15]

30 $m(k) = 1 - \frac{1}{n(k)}$ [D16]

31 $\alpha(k) = \frac{m(k)^{1-m(k)}}{\psi_{in}}$ (van Genuchten 1978) [D17]

32 $S_{e_{fc,sim}}(k) = \left[1 + (\alpha(k)\psi_{fc})^{n(k)} \right]^{-m(k)}$ (van Genuchten 1980) [D18]

33 $S_{e_{wp,sim}}(k) = \left[1 + (\alpha(k)\psi_{wp})^{n(k)} \right]^{-m(k)}$ (van Genuchten 1980) [D19]

34 $\theta_r(k) = \max \left[0, \frac{\theta_s - \theta_{v,fc} + \theta_{v,wp}}{S_{e_{fc,sim}}(k) - S_{e_{wp,sim}}(k)} \right]$ [D20]

- 35 $\theta_{v,fc_{sim}}(k) = \theta_r(k) + [\theta_s - \theta_r(k)]S_{e_{fc,sim}}(k)$ (van Genuchten 1980) [D21]
- 36 $\theta_{v,fc_{sim}}(k) = \theta_r(k) + [\theta_s - \theta_r(k)]S_{e_{fc,sim}}(k)$ (van Genuchten 1980) [D22]
- 37 $K_{mat_i} = K_{s,mat} S_e^{0.5} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2$; where $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha \psi_m)^n \right]^{-m}$; Mualem-van Genuchten model (Mualem, 1976; van Genuchten, 1980)
- 38 used in VGM simulation of *ecosys* (Mezbahuddin et al., 2016) [D23]
- 39 $K_{mat_i} = K_{s,mat} S_e^{0.5} \left[\frac{1 - \left(1 - (S_e S_c)^{\frac{1}{m}} \right)^m}{1 - \left(1 - S_c^{\frac{1}{m}} \right)^m} \right]^2$; where $S_e = \frac{1}{S_c} [1 + (\alpha \psi_m)^n]^{-m}$ and $S_c = [1 + (\alpha \psi_e)^n]^{-m}$; modified Mualem-van Genuchten model (Ippisch et al., 2006) used in VGM simulation of *ecosys* (Mezbahuddin et al., 2016) [D24]
- 40 $Q_{v_{mac_i}} = K'_{mac_i} (\psi_{g_s} - \psi_{g_d})$; soil macropore water flow [D25]
- 42 $K'_{mac} = \frac{2K_{mac_s} K_{mac_d}}{K_{mac_s} L_{d_i} + K_{mac_d} L_{s_i}}$ [D26]
- 43 $K_{mac} = N_{mac} K_{mac}^*$ [D27]
- 44 $K_{mac}^* = \frac{\pi R^4}{8\eta}$; Hagen-Poiseuille's theory of laminar flow in tubes [D28]
- 45 $N_{mac} = \theta_{mac} \pi R^2$ [D29]

46
$$Q_{w_{b,mat_j}} = \frac{K_{b,mat_j} [\psi'_b - \psi_{s_b} + 0.01(d_{z_b} - WTD_x)]}{L_{t_j}}$$
; lateral discharge occurs when $d_{z_b} < WTD_x$ and $\psi_{s_b} > \psi'_b + 0.01(d_{z_b} - WTD_x)$ and lateral
 47 recharge occurs when $d_{z_b} > WTD_x$ [D30]

48
$$Q_{w_{b,mac_j}} = \frac{K_{b,mac_j} 0.01 [d_{z_b} - L_{z_b} (\theta_{w,mac} - 0.5) - WTD_x]}{L_{t_j}}$$
; lateral discharge occurs when $d_{z_b} < WTD_x$ and lateral recharge occurs when $d_{z_b} > WTD_x$
 49 [D31]

50 Where, subscripts i =dimensions ($i=x, y, z$), j =dimensions ($j=x, y$), s =source cell, d =destination cell, in =flow into the grid cells, and out =flow out of the grid cells;
 51 b =boundary grid cell; mat =soil matrix/micropore; mac =soil macropore; θ_w =soil water content ($m^3 m^{-3}$); Q_w =sub-surface water flux ($m^3 m^{-2} h^{-1}$); Q_f =freeze-thaw
 52 flux (a positive flux represents thaw and a negative flux represents freeze) ($m^3 m^{-2} h^{-1}$); U_w =total root water uptake flux ($m^3 m^{-2} h^{-1}$); K =hydraulic conductance
 53 ($m MPa^{-1} h^{-1}$); ψ_s =total soil water potential (MPa); K =hydraulic conductivity ($m^2 MPa^{-1} h^{-1}$); L =length of the grid cells (m); $K_{s,mat}$ =saturated soil matrix hydraulic
 54 conductivity ($m^2 MPa^{-1} h^{-1}$); p =individual pore class [1,2,3,...,q; where q =total number of pore classes (=100)]; ψ_p =matric potential of pore class p ; ψ_r =matric
 55 potential of pore class r ($r=p \rightarrow q$); n =van Genuchten parameter that describes the mean slope of the desorption curve or the range of pore size distribution; α =
 56 the inverse of the pressure head at the air-entry value (i.e. $\alpha \approx 1$ /air entry potential) that governs the shape of van Genuchten desorption curve (-MPa $^{-1}$); k =number
 57 of iteration (1,2,3,...,19000); ψ_{in} =matric potential at inflection point (-MPa); $S_{e_{fc,sim}}$ =simulated relative degree of saturation at field capacity; ψ_{fc} =matric
 58 potential at field capacity (-MPa); $S_{e_{wp,sim}}$ =simulated relative degree of saturation at wilting point; ψ_{wp} =matric potential at wilting point (-MPa); θ =residual soil
 59 water content ($m^3 m^{-3}$); θ_s =soil water content at saturation ($m^3 m^{-3}$); $\theta_{v,fc}$ =observed input for soil water content at field capacity ($m^3 m^{-3}$); $\theta_{v,wp}$ =observed input
 60 for soil water content at wilting point ($m^3 m^{-3}$); $\theta_{v,fc,sim}$ =simulated soil water content at field capacity ($m^3 m^{-3}$); $\theta_{v,wp,sim}$ =simulated soil water content at wilting
 61 point ($m^3 m^{-3}$); θ =ambient soil water content ($m^3 m^{-3}$); ψ_m =matric potential as a function of θ (-MPa); ψ_c =matric potential very close to saturation (= -0.0001
 62 MPa); ψ_g =gravitational soil water potential (MPa); N_{mac} =number of macropore channels (m^{-2}); K^*_{mac} =individual macropore hydraulic conductivity ($m^4 MPa^{-1} h^{-1}$
 63 macropore channel $^{-1}$); η =dynamic viscosity of water (MPa h); θ_{mac} =volumetric macropore fraction ($m^3 m^{-3}$); R =radius of a macropore channel (m); ψ =soil water
 64 potential at saturation (MPa) (=0 and -0.0005 MPa for van Genuchten and modified Campbell model respectively); d_z =depth of the mid-point of a grid cell from
 65 the surface (m); L_z =vertical thickness of a grid cell (m); WTD_x =depth of the water table depth at the adjacent watershed with which modeled grid cells exchange
 66 water laterally (m); and L_t =lateral distance over which lateral discharge/recharge occurs (m), MCM = modified Campbell model, VGM = van Genuchten model.

67 S4.3. Water table depth

68
$$WTD = -[d_{z,sat} - L_{z,sat} (1 - \frac{\theta_g}{\theta_g^*})]$$
; negative sign represents depth below the surface of the a particular grid cell [D32]

69 Where, WTD=water table depth (m); $d_{z,\text{sat}}$ =depth to the bottom of the layer immediately above the uppermost saturated layer (m); $L_{z,\text{sat}}$ =vertical thickness of the
 70 layer immediately above the uppermost saturated layer (m); θ_g =current air-filled porosity of the layer immediately above the uppermost saturated layer ($\text{m}^3 \text{ m}^{-3}$);
 71 and θ_g^* =air-filled porosity at air-entry potential of the layer immediately above the uppermost saturated layer ($\text{m}^3 \text{ m}^{-3}$).

72 S4.4. Heat flux

73 $R_n + LE + H + G = 0$; energy balance for each of the canopy, snow, residue and soil surface [D33]

74 $\sum G_{c,in_i} - \sum G_{c,out_i} + L_v Q_f + c(T - T_{frz}) = 0$; 3D general heat flux equation in snowpack, surface residue and soil layers [D34]

75 $T_{frz} = \frac{-9.095895 \times 10^4}{\psi_m - 333}$ (for residue layer) = $\frac{-9.095895 \times 10^4}{\psi_m + \psi_o - 333}$ (for soil layers)
 = T'_{frz} (for snowpack) [D35]

76 $G_{c_i} = \frac{2\kappa_{s,d_i}(T_s - T_d)}{L_{s_i} + L_{d_i}} + c_{w_s} T_s Q_{w_i}$ [D36]

77 $D_{\text{snowpack}} = \frac{V_{\text{sweq}} \frac{\rho_w}{\rho_{oldsnow}} + V_{ice} + V_{water}}{A_{\text{snowpack}}}$ [D37]

78 $\rho_{oldsnow} = \min(0.5, \rho_{freshsnow} + 0.25 \frac{V_{snow}}{A_{\text{snowpack}}})$ [D38]

79

80 Where, subscripts i =dimensions ($i=x, y, z$), s =source cell, d =destination cell, in =flow into the grid cells, and out =flow out of the grid cells; R_n =net radiation (W m^{-2});
 81 LE =latent heat flux (W m^{-2}); H =sensible heat flux (W m^{-2}); and G =ground heat flux (W m^{-2}); G_c =conductive heat flux ($\text{MJ m}^{-2} \text{ h}^{-1}$); L_v =latent heat of
 82 evaporation ($=2460 \text{ MJ m}^{-3}$); Q_f =freeze-thaw flux (a positive flux represents thaw and a negative flux represents freeze) ($\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$); c =heat capacity of
 83 residue/soil layers (solid + liquid + void) or the snowpack (snow + ice + water) ($\text{MJ m}^{-2} \text{ K}^{-1}$); T =ambient temperature of soil/residue layers or the snowpack (K);
 84 T_{frz} =freezing temperature of soil/residue layers or the snowpack (K); ψ_m =matric water potential of residue/soil layers (-MPa); ψ_o =osmotic potential of soil layers
 85 (-MPa); T'_{frz} =freezing temperature of free water ($=273.15 \text{ K}$); κ =thermal conductivity ($\text{MJ m}^{-1} \text{ h}^{-1} \text{ K}^{-1}$); L =length of the residue layer/ a soil layer/ the snowpack
 86 (m); c_w =heat capacity of water ($=4.19 \text{ MJ m}^{-2} \text{ K}^{-1}$); Q_w =water flux ($\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$); D_{snowpack} =depth of snowpack (m); V_{sweq} =volume of snow water equivalent (m^3);

87 ρ_w =density of water ($=1 \text{ Mg m}^{-3}$); $\rho_{oldsnow}$ =density of settled snow (Mg m^{-3}); V_{ice} =volume of ice in snowpack ($\text{m}^3 \text{ m}^{-3}$); V_{water} =volume of water in snowpack ($\text{m}^3 \text{ m}^{-3}$)
 88 $A_{snowpack}$ =snowpack basal area (m^2); $\rho_{freshsnow}$ =density of freshly fallen snow ($=0.083 \text{ Mg m}^{-3}$); V_{snow} =volume of snow in the snowpack (m^3)

89 **S4.5. Gas flux**

90 $Q_{ds\gamma_s} = \alpha_{gs_s} D_{d\gamma} \left(S'_\gamma f_{T_{d\gamma_s}} [\gamma_{gs}]_s - [\gamma_{ss}]_s \right)$; volatilization-dissolution between aqueous and gaseous phases in soil [D39]

91 $Q_{dr\gamma_s} = \alpha_{gr_s} D_{d\gamma} \left(S'_\gamma f_{T_{d\gamma_s}} [\gamma_{gr}]_s - [\gamma_{sr}]_s \right)$; volatilization-dissolution between aqueous and gaseous phases in roots [D40]

92 $Q_{gs\gamma, surf} = g_{a,surf} \left\{ [\gamma_a] - \left\{ 2[\gamma_{gs}]_{surf} D_{gs\gamma, surf} / L_{surf} + g_{a,surf} [\gamma_a] \right\} / \left\{ 2D_{gs\gamma, surf} / L_{surf} + g_{a,surf} \right\} \right\}$; convective-conductive gas flux between soil surface
 93 and the atmosphere [D41]

94 $Q_{gs\gamma_i} = -Q_{w_i} [\gamma_{gs}]_s + \frac{2D_{gs\gamma_i} \left([\gamma_{gs}]_s - [\gamma_{gs}]_d \right)}{L_{s_i} + L_{d_i}}$; 3D convective-conductive gas flux between two adjacent grid cells [D42]

95 $Q_{gr\gamma_{i=z}} = \frac{D_{gr\gamma_{i=z}} \left([\gamma_{gr}]_d - [\gamma_a] \right)}{\sum_{1,i=z} L_{d_{i=z}}}$; convective-conductive gas flux between root and the atmosphere [D43]

96 $D_{gs\gamma_i} = \frac{D'_{gs\gamma} f_{T_{gs}} \left[0.5(\theta_{gs} + \theta_{gd}) \right]^2}{\theta_P^{0.67}}$; 3D gaseous diffusivity between two adjacent grid cells as functions of air-filled porosities in those cells [D44]

97 $D_{gr\gamma_{i=z}} = \frac{D'_{gr\gamma} f_{T_{gs}} \theta_{pr_s}^{1.33} A_{r_s}}{A_{i=x,y}}$; gaseous diffusivity as a function of air-filled porosity in the roots/mycorrhizae [D45]

98 Where, subscripts i =dimensions ($i=x, y, z$), s =source cell, d =destination cell, $surf$ =soil surface layer; $Q_{ds\gamma}$ =volatilization – dissolution of gas γ between aqueous
 99 and gaseous phases in soil ($\text{g m}^{-2} \text{ h}^{-1}$); α_{gs} =air-water interfacial area in soil ($\text{m}^2 \text{ m}^{-2}$); $D_{d\gamma}$ = volatilization - dissolution transfer coefficient for gas γ ($\text{m}^2 \text{ h}^{-1}$); S'_γ
 100 =Ostwald solubility coefficient of gas γ at 30°C (0.0293 for $\gamma=\text{O}_2$) (Wilhelm et al., 1977); $f_{T_{d\gamma}}$ =temperature dependence of S'_γ (Wilhelm et al., 1977);
 101 $[\gamma_{gs}]$ =gaseous concentration of gas γ in soil (g m^{-3}); $[\gamma_{ss}]$ =aqueous concentration of gas γ in soil (g m^{-3}); $Q_{dr\gamma}$ = volatilization – dissolution of gas γ between

102 aqueous and gaseous phases in root/moss ($\text{g m}^{-2} \text{ h}^{-1}$); α_{gr} =air-water interfacial area in root/mycorrhizae ($\text{m}^2 \text{ m}^{-2}$) (Skopp, 1985); $[\gamma_{\text{gr}}]$ =gaseous concentration of
 103 gas γ in root/mycorrhizae (g m^{-3}); $[\gamma_{\text{sr}}]$ =aqueous concentration of gas γ in root/moss/mycorrhizae (g m^{-3}); $Q_{\text{gs}\gamma}$ =gaseous flux of gas γ in soil ($\text{g m}^{-2} \text{ h}^{-1}$); Q_w =sub-
 104 surface water flux ($\text{m}^3 \text{ m}^{-2} \text{ h}^{-1}$); $D_{\text{gs}\gamma}$ =gaseous diffusivity of gas γ in soil ($\text{m}^2 \text{ h}^{-1}$) (Millington and Quirk, 1960); L =thickness of grid cells (m); $Q_{\text{gr}\gamma}$ =gaseous flux of
 105 gas γ between root/mycorrhizae and the atmosphere ($\text{m}^2 \text{ h}^{-1}$); $D_{\text{gr}\gamma}$ =gaseous diffusivity of gas γ in root/mycorrhizae ($\text{m}^2 \text{ h}^{-1}$) (Luxmoore et al., 1970a,b); g_a =
 106 boundary layer conductance (m h^{-1}); $[\gamma_a]$ =atmospheric concentration of gas γ (g m^{-3}); $D'_{\text{g}\gamma}$ =diffusivity of gas γ in air at 0°C ($\text{m}^2 \text{ h}^{-1}$) ($6.43 \times 10^{-2} \text{ m}^2 \text{ h}^{-1}$ for $\gamma=\text{O}_2$)
 107 (Campbell, 1985); f_{T_g} =temperature dependence of $D'_{\text{g}\gamma}$ (Campbell, 1985); θ_g =air-filled porosity ($\text{m}^3 \text{ m}^{-3}$); θ_p =total porosity of soil ($\text{m}^3 \text{ m}^{-3}$); θ_{pr} =
 108 root/mycorrhizal porosity representing aerenchyma fraction ($\text{m}^3 \text{ m}^{-3}$); A_r =root cross-sectional area (m^2); and A =area of landscape position (m^2).

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