

1 This supplement describes equations and parameters of each submodule of ED (v3.0). For most modules, the  
2 descriptions are based on Moorcroft et al., (2001), Hurtt et al., (2002) and Albani et al., (2006) and updated as  
3 appropriate.

## 4 5 **S1. Plant functional type**

6 In ED, we refine PFTs previously developed in Moorcroft et al., (2001), Hurtt et al., (2002) and Albani et al.,  
7 (2006). Here we include seven major types, namely early-successional broadleaf trees (EaSBT), middle-successional  
8 broadleaf trees (MiSBT), late-successional broadleaf trees (LaSBT), northern and southern pines (NSP), late-  
9 successional conifers (LaSC), C3 shrubs and grasses (C3ShG), and C4 shrubs and grasses (C4ShG). The broadleaf  
10 PFTs (i.e., EaSBT, MiSBT, and LaSBT) are further distinguished between tropical and non-tropical subtypes in  
11 terms of leaf traits (e.g., leaf lifespan, specific leaf area, and leaf photosynthesis rate) and mortality rate. The  
12 geographic boundary of tropical and non-tropical subtypes is delineated by whether the multi decade average air  
13 temperature during the coldest month of the year is above or below 18 °C.

14  
15 These PFTs primarily differ in their phenology, leaf physiological traits, allometry, mortality rate, and dispersal  
16 distance. Regarding their phenology, needleleaf PFTs (i.e., NSP and LaSC) are evergreen, and broadleaf PFTs (both  
17 tropical and non-tropical subtypes) and grass PFTs are cold-deciduous and drought-deciduous. For leaf traits,  
18 broadleaf tropical subtypes have longer lifespans but lower average specific leaf area and carboxylation rates than  
19 non-tropical subtypes. Needleleaf PFTs have longer lifespan than broadleaf PFTs, and grass and shrub PFTs have  
20 the shortest leaf lifespans (less than 1 year). The seven major PFTs all use different allometric equations, but  
21 broadleaf PFT subtypes share the same allometry, and grass and shrub PFTs are limited terms of maximum height.  
22 Grass PFTs have the highest mortality rates, followed by broadleaf PFTs and needleleaf PFTs. Dispersal distance  
23 also varies across PFTs, where the EaSBT disperses more seedlings to non-local patches than either the MiSBT and  
24 LaSBT, and the NSP is more than the LaSC. All PFTs are differentiated by their photosynthetic pathways and C3  
25 and C4 photosynthesis processes are modelled separately (see later discussion in S3 on the leaf physiology  
26 submodule). Moreover, needleleaf PFTs are characterized by slower leaf and root decay rates than broadleaf PFTs  
27 and also utilize different allometry equations. Here, broadleaf trees are split into early-, mid- and late-successional  
28 types, which differ not only in terms of their leaf and root decay rates but also in wood density and respective  
29 allometry. The empirical relationship between leaf nitrogen content and leaf longevity, and the relationship between  
30 specific leaf area and leaf longevity, follow Moorcroft et al., 2001, which follows Reich et al., 1997.

31  
32 Spatial distribution of PFTs is mechanistically determined by individual competition for light, water, and nutrients.  
33 No quasi-equilibrium climate–vegetation relationships, such as satellite-based PFT maps or climatic envelope  
34 thresholds, are used to constrain presence or absence of PFTs. All PFTs could potentially coexist in any location  
35 over the globe and are initialized with the same density; the subsequent competition determines when and where  
36 specific PFTs dominate the ecosystems. The competitive advantage of each PFT results from plant traits such as  
37 photosynthesis efficiency, height growth rate, and reproduction strategies. These advantages vary with climate

38 conditions and across stages of ecosystem succession. For example, leaf physiological traits exhibit trade-offs across  
 39 PFTs (Reich et al., 1997). Compared to needleleaf PFTs, broadleaf PFTs have a relatively larger leaf area per leaf  
 40 weight and higher carbon assimilation rate per leaf area, but higher carbon demand for leaf turnover. Moreover, the  
 41 early-successional PFT rapidly accumulates carbon, quickly grows in height, and disperses seeds over long  
 42 distances. These characteristics lead to its dominance during the early successional state of recently disturbed  
 43 ecosystems. However, its intolerance of shade makes it less competitive as the canopy closes, eventually being  
 44 replaced by mid- and late-successional PFTs which have lower mortality in shade but grow more slowly in height.  
 45

46 Table S1.1. Summary of PFT-dependent parameters.  $V_{cmax}$  is used in the leaf physiology submodule;  $\rho(x)$ ,  
 47  $DBH_{max}$ ,  $a_h$ ,  $b_h$ ,  $a_l$ ,  $b_l$ ,  $a_s$ ,  $b_s$ ,  $l(x)$ ,  $\alpha_l(x)$  and  $\beta_r(x)$  are used in the plant allocation submodule;  $m(x)$  is used in  
 48 reproduction; *phenology*,  $T_{crit}(x)$  and  $T_{free}(x)$  are used in the leaf phenology and freezing submodule; and  $\mu_{DI}(x)$  is  
 49 used in the mortality submodule. Note that C4ShG is C4 shrubs and grasses, C3ShG is C3 shrubs and grasses,  
 50 EaSBT is early-successional broadleaf trees, MiSBT is middle-successional broadleaf trees, LaSBT is late-  
 51 successional broadleaf trees, NSP is northern and southern pines, and LaSC is late-successional conifers. TRO and  
 52 NTRO are tropical and non-tropical variants of EaSBT, MiSBT, LaSBT.

Parameters	Description	C4ShG	C3ShG	EaSBT		MiSBT		LaSBT		NSP	LaSC
				TRO	NTRO	TRO	NTRO	TRO	NTRO		
$V_{cmax}$	Maximum rate of Rubisco carboxylation ( $\mu\text{ mol m}^{-2}\text{ s}^{-1}$ )	20	80	50	60	45	55	40	50	21	19
$\rho(x)$	Wood density ( $\text{g cm}^{-3}$ )	0.53	0.53	0.53	0.53	0.71	0.71	0.90	0.90	0.70	0.70
$DBH_{max}$	Corresponding DBH at maximum canopy height (cm)	0.35	0.35	68.31	68.31	68.31	68.31	68.31	68.31	42.09	42.09
$a_h$	Coefficient of height allometry	-	-	-	-	-	-	-	-	27.14	22.19
$b_h$	Coefficient of height allometry	-	-	-	-	-	-	-	-	-0.0388	-0.0445
$a_l$	Coefficient of leaf biomass allometry	-	-	-	-	-	-	-	-	0.024	0.045
$b_l$	Coefficient of leaf biomass allometry	-	-	-	-	-	-	-	-	1.899	1.683
$a_s$	Coefficient of structural biomass allometry	-	-	-	-	-	-	-	-	0.147	0.162
$b_s$	Coefficient of structural biomass allometry	-	-	-	-	-	-	-	-	2.238	2.154
$l(x)$	Specific leaf area ( $\text{m}^2\text{ kg}^{-1}\text{ C}$ )	22.03	22.03	16.02	28.50	11.64	26.55	9.66	24.42	5.55	5.55
$\alpha_l(x)$	Leaf biomass decay rate ( $\text{yr}^{-1}$ )	2.0	2.0	1.0	3.5	0.5	3.0	0.33	2.5	0.1	0.1
$\alpha_r(x)$	Fine root decay rate ( $\text{yr}^{-1}$ )	2.0	2.0	1.0	0.1	0.5	0.1	0.33	0.1	0.1	0.1
$\beta_r(x)$	Respiration coefficient	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

$m(x)$	Non-local dispersal rate	1.0	1.0	1.0	1.0	0.5	0.5	0.2	0.2	0.78	0.2
<i>phenology</i>	C-cold deciduous										
	D-drought-deciduous	C, D	C, D	C, D	C, D	C, D	C, D	C, D	C, D	E	E
	E-evergreen										
$T_{crit}(x)$	Temperature threshold triggering leaf drop (°C)	15	5	10	10	10	10	10	10	-	-
$T_{free}(x)$	Temperature threshold of freezing resistance (°C)	-	-	-15	-15	-15	-15	-15	-15	-80	-80
$\mu_{DI}(x)$	Density independent mortality (yr <sup>-1</sup> )	0.081	0.081	0.081	0.032	0.054	0.032	0.025	0.014	0.014	0.014

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54

55 **S2. Plant allocation submodule**

56 Regardless of PFT type, each individual plant consists of both active tissue ( $B_a$ ) and structural tissue ( $B_s$ ).  $B_a$   
 57 includes leaf biomass ( $B_l$ ), sapwood biomass ( $B_{sw}$ ), and fine root biomass ( $B_r$ ). The biomass in each active tissue  
 58 component governs plant functioning. For example, leaf biomass determines the number of leaves available for  
 59 photosynthesis, and the fine root biomass determines the amount of water uptake from soil. Distribution of  $B_a$  to  $B_l$ ,  
 60  $B_{sw}$ , and  $B_r$  is based on ratio factors of  $q_l(\mathbf{z}, \mathbf{x})$ ,  $q_r(\mathbf{z}, \mathbf{x})$  and  $q_{sw}(\mathbf{z}, \mathbf{x})$ , respectively. Assuming  $B_l$  and  $B_r$  are equal  
 61 for all PFTs, and the sapwood cross-sectional area is proportional to total leaf area, then  $q_l(\mathbf{z}, \mathbf{x})$ ,  $q_r(\mathbf{z}, \mathbf{x})$  and  
 62  $q_{sw}(\mathbf{z}, \mathbf{x})$  are given by:

$$q_l(\mathbf{z}, \mathbf{x}) = \frac{B_l}{B_a} = \frac{1}{2 + 0.00128l(\mathbf{x})h} \quad \text{Eq. S2.1}$$

$$q_r(\mathbf{z}, \mathbf{x}) = \frac{B_r}{B_a} = \frac{1}{2 + 0.00128l(\mathbf{x})h} \quad \text{Eq. S2.2}$$

$$q_{sw}(\mathbf{z}, \mathbf{x}) = \frac{B_{sw}}{B_a} = \frac{0.00128l(\mathbf{x})h}{2 + 0.00128l(\mathbf{x})h} \quad \text{Eq. S2.3}$$

63 Where  $l(\mathbf{x})$  is dependent on PFT-specific leaf area, and  $h$  is plant height.

64  
 65 When the plant maintains a positive carbon balance, after taking into account respiration and decay costs from  
 66 carbon fixation by photosynthesis, the gained carbon will be allocated towards the growth of  $B_a$  and  $B_s$ . The  
 67 allocation fraction to  $B_a$ , defined as  $q_a(\mathbf{z}, \mathbf{x})$ , is based on empirical allometry equations, which ensure  $B_a$  and  $B_s$  stay  
 68 on a given allometric trajectory. However, a negative carbon balance in the plant could result in  $B_a$  departing from  
 69 its allometric trajectory as  $B_a$  needs to decrease in order to compensate for respiration and decay costs. In this case,  
 70 subsequent carbon gains will all be allocated to  $B_a$  until it resumes its allometry (i.e.,  $q_a(\mathbf{z}, \mathbf{x}) = 1$ ).

71  
 72 Empirical allometry equations depict the relationship between plant height ( $h$ ), leaf biomass ( $B_l$ ) structural tissue  
 73 ( $B_s$ ), and Diameter at Breast Height ( $DBH$ ). For broadleaf PFTs and grass and shrub PFTs, the allometry equations  
 74 from Moorcroft et al., 2001 are used:

$$h = \begin{cases} 2.34DBH^{0.64} & \text{if } (DBH \leq DBH_{max}) \\ 2.34DBH_{max}^{0.64} & \text{if } (DBH > DBH_{max}) \end{cases} \quad \text{Eq. S2.4}$$

$$B_l = \begin{cases} 0.0419DBH^{1.56}\rho(\mathbf{x})^{0.55} & \text{if } (DBH \leq DBH_{max}) \\ 0.0419DBH_{max}^{1.56}\rho(\mathbf{x})^{0.55} & \text{if } (DBH > DBH_{max}) \end{cases} \quad \text{Eq. S2.5}$$

$$B_s = \begin{cases} 0.069h^{0.572}DBH^{1.94}\rho(\mathbf{x})^{0.931} & \text{if } (DBH \leq DBH_{max}) \\ 0.069h_{max}^{0.572}DBH^{1.94}\rho(\mathbf{x})^{0.931} & \text{if } (DBH > DBH_{max}) \end{cases} \quad \text{Eq. S2.6}$$

75 Where  $DBH_{max}$  is the corresponding  $DBH$  when  $h$  reaches its max (note that this is not the maximum  $DBH$  the  
 76 plant can grow), and  $\rho(\mathbf{x})$  is PFT-dependent wood density.

77  
 78 For the PFTs of NSP and LaSC, the allometry equations from Albani et al., 2006 are used:

$$h = 1.3 + a_h(1 - e^{b_h DBH}) \quad \text{Eq. S2.7}$$

$$B_l = \begin{cases} a_l DBH^{b_l} & \text{if } (DBH \leq DBH_{max}) \\ a_l DBH_{max}^{b_l} & \text{if } (DBH > DBH_{max}) \end{cases} \quad \text{Eq. S2.8}$$

$$B_s = a_s DBH^{b_s} \quad \text{Eq. S2.9}$$

79 Where  $a_h, b_h, a_l, b_l, a_s$  and  $b_s$  are allometry coefficients.

80

81 With ratio  $q_l$  from Eq. S2.1 and leaf biomass calculated from Eq. S2.5 or S2.8, the active tissue biomass on the  
82 allometric trajectory is:

$$B_a^{opt} = q_l(\mathbf{z}, \mathbf{x}) B_l^* \quad \text{Eq. S2.10}$$

83 Thus, when the plant is in positive carbon balance and  $B_a$  is not smaller than  $B_a^{opt}$ , the allocation fraction of new  
84 carbon to  $B_a$  is calculated as:

$$q_a(\mathbf{z}, \mathbf{x}) = \frac{\frac{dB_a^{opt}}{dB_s}(B_s)}{1 + \frac{dB_a^{opt}}{dB_s}(B_s)} \quad \text{Eq. S2.11}$$

85

86

### 87 S3. Leaf physiology submodule

88 The leaf physiology submodule estimates leaf-level photosynthesis and transpiration rates as key inputs to other  
89 submodules (e.g., growth and hydrological submodules). This submodule uses light, CO<sub>2</sub>, air temperature, and air  
90 humidity as environmental inputs, and generates carbon assimilation and transpiration per leaf area as outputs. Three  
91 processes are coupled in this submodule: 1) photosynthesis, which describes carbon assimilation with consideration  
92 of light availability, leaf temperature, air humidity, and CO<sub>2</sub> supply; 2) stomatal conductance, which describes CO<sub>2</sub>  
93 diffusion from ambient air to leaf intercellular space and associated water vapor loss; and 3) leaf energy balance,  
94 which describes the energy budget (i.e., absorbed radiation, emitted thermal radiation, and sensible and latent heat  
95 loss) for each leaf and determines leaf temperature.

#### 96 S3.1. Photosynthesis process

97 Photosynthesis processes are separately modelled for C3 and C4 PFTs. The Farquhar, von Caemmerer & Berry  
98 model (Farquhar et al., 1980) is used to describe the C3 photosynthetic pathway. When soil moisture and nutrients  
99 are not limited, net photosynthesis rate per unit leaf area is the difference between the gross photosynthesis rate,  $A$ ,  
100 and mitochondrial respiration,  $R_d$ . As shown in Eq. S3.1, the gross photosynthesis rate is co-limited by three  
101 processes: (1) Rubisco-limited photosynthesis rate ( $A_c$ ); (2) Light-limited or RuBP regeneration-limited  
102 photosynthesis rate ( $A_j$ ); and (3) Product-limited or triose phosphate utilization-limited photosynthesis rate ( $A_e$ ).

$$A_n = A - R_d = (A_c, A_j, A_e) - R_d \quad \text{Eq. S3.1}$$

103

104 The Rubisco-limited photosynthesis rate,  $A_c$ , is given by:

$$A_c = \frac{V_{cmax}(c_i - \Gamma^*)}{\left[ c_i + K_c \left( 1 + \frac{o_i}{K_o} \right) \right]} \quad \text{Eq. S3.2}$$

105 where  $V_{cmax}$  is the maximum rate of Rubisco carboxylation,  $c_i$  and  $o_i$  are the intercellular concentrations of CO<sub>2</sub>,  
106 and O<sub>2</sub>, respectively,  $\Gamma^*$  is the CO<sub>2</sub> compensation point, and  $K_c$  and  $K_o$  are the Michaelis-Menten constants of  
107 Rubisco for CO<sub>2</sub> and O<sub>2</sub>, respectively. The RuBP regeneration-limited photosynthesis rate  $A_j$  is given by:

$$A_j = \frac{J(c_i - \Gamma^*)}{4(c_i + 2\Gamma^*)} \quad \text{Eq. S3.3}$$

108 Where  $J$  is the electron transport rate and given by:

$$\theta J^2 - (I_{PSII} + J_{max})J + I_{PSII}J_{max} = 0 \quad \text{Eq. S3.4}$$

$$I_{PSII} = \frac{1-f}{2} \alpha I \quad \text{Eq. S3.5}$$

$$I = 4.55 \cdot \phi I_{g0} e^{-f_{sha} K_L J_h^\infty L_{ttl}(h)} \xi \quad \text{Eq. S3.6}$$

109 In Eq. S3.4,  $\theta$  is the curvature of the light response curve,  $I_{PSII}$  is the light utilized in electron transport by  
110 photosystem II, and  $J_{max}$  is the maximum rate of electron transport. In Eq. S3.5,  $\alpha$  is leaf absorbance (set at 0.85),  
111 and  $f$  is the correction factor for spectral light quality (set at 0.15). In Eq. S3.6,  $I$  is incident photosynthetically  
112 active radiation (PAR, in unit of  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) at leaf level with height  $h$ ,  $I_{g0}$  is total shortwave radiation at the  
113 patch's canopy top,  $f_{sha}$  is the degree of shading, and  $K_L$  is light extinction coefficient.  $L_{ttl}(h)$  is cumulative LAI

114 from the canopy top to leaf height, calculated by summing the leaf area of all cohort plants higher than  $h$ .  $\xi$  is a  
 115 coefficient representing the proportion of PAR in shortwave radiation.

116

117 The export-limited photosynthesis rate ( $A_e$ ) is related to the rate of triose phosphate utilization ( $T_p$ ), and it is given  
 118 by:

$$A_e = 3 \cdot T_p \quad \text{Eq. S3.7}$$

119

120 A model from von Caemmerer et al., 1999 is used to describe C4 photosynthesis. When soil moisture and nutrients  
 121 are not limited, net photosynthesis rate per unit leaf area is the difference between  $A$  and  $R_d$ . The gross  
 122 photosynthesis rate ( $A$ ) is co-limited by: (1) Enzyme-limited photosynthesis rate ( $A_c$ ) and (2) Light- and electron  
 123 transport-limited photosynthesis rate ( $A_j$ ).

$$A_n = A - R_d = (A_c, A_j) - R_d \quad \text{Eq. S3.8}$$

124 The enzyme-limited photosynthesis rate ( $A_c$ ) is given by solving a quadratic equation:

$$aA_c^2 + bA_c + c = 0 \quad \text{Eq. S3.9}$$

125 Where

$$a = 1 - \frac{\alpha_o K_c}{0.047 K_o} \quad \text{Eq. S3.10}$$

$$b = - \left\{ \left( (V_p - R_m + g_{bs} C_m) + (V_{cmax} - R_d) + g_{bs} K_c \left( 1 + \frac{O_m}{K_o} \right) \right) \right. \\ \left. + \left( \frac{\alpha_o}{0.047} \left( \gamma_* V_{cmax} + R_d \frac{K_c}{K_o} \right) \right) \right\} \quad \text{Eq. S3.11}$$

$$c = (V_{cmax} - R_d)(V_p - R_m + g_{bs} C_m) - \left( V_{cmax} g_{bs} \gamma_* O_m + R_d g_{bs} K_c \left( 1 + \frac{O_m}{K_o} \right) \right) \quad \text{Eq. S3.12}$$

126 Where  $\alpha_o$  in Eq. S3.10 is the fraction of PSII activity in the bundle sheath. In Eq. S3.11 and S3.12,  $C_m$  and  $O_m$  are  
 127 the partial pressure of CO<sub>2</sub> and O<sub>2</sub> in the mesophyll,  $C_m$  equals the CO<sub>2</sub> intercellular partial pressure ( $C_i$ ), if  
 128 assuming mesophyll conductance, is infinite.  $g_{bs}$  is bundle sheath conductance to CO<sub>2</sub>,  $R_m$  is mesophyll  
 129 mitochondrial respiration, and  $\gamma_*$  is half of the reciprocal of Rubisco specificity.  $V_p$  is the rate of  
 130 phosphoenolpyruvate (PEP) carboxylation, given by:

$$V_p = \min \left\{ \left( \frac{C_m V_{pmax}}{C_m + K_p} \right), V_{pr} \right\} \quad \text{Eq. S3.13}$$

131 where  $V_{pmax}$  is the maximum PEP carboxylation rate,  $K_p$  is the Michaelis-Menten constant for CO<sub>2</sub>, and  $V_{pr}$  is a  
 132 constant representing when PEP regeneration is limiting.

133

134 The light- and electron transport-limited photosynthesis rate ( $A_j$ ) is given by:

$$A_j = \min \left\{ \left( \frac{xJ}{2} + g_{bs} C_m - 0.5 \cdot R_d \right), \left( \frac{(1-x)J}{3} - R_d \right) \right\} \quad \text{Eq. S3.14}$$

135 where  $x$  is a partitioning factor of the electron transport rate. The electron transport rate ( $J$ ) is estimated using Eq.  
 136 S3.4-S3.6, but with  $J_{max}$  value of C4 pathway.

137

138 Table S3.1. Photosynthetic parameters at 25 °C for C3 and C4 pathways and coefficients to characterize temperature  
 139 dependency functions.  
 140

Parameter	Eqn	Unit	Temperature dependence	Coefficients					
				$k_{25}$	$Q_{10}$	$E_a$ (J mol <sup>-1</sup> )	$H_a$ (J mol <sup>-1</sup> )	$H_d$ (J mol <sup>-1</sup> )	$S_v$ (J mol <sup>-1</sup> K <sup>-1</sup> )
C3 pathway									
$I^*$	3.2	μmol mol <sup>-1</sup>	A-fun	42.75	-	37,830	-	-	-
$K_c$	3.2	μbar	A-fun	404.4	-	79,430	-	-	-
$K_o$	3.2	mbar	A-fun	278.4	-	36,380	-	-	-
$V_{cmax}$	3.2	μmol mol <sup>-1</sup>	P-fun	Table S1	-	-	71,513	200,000	636.29
$R_d$	3.1	μmol mol <sup>-1</sup>	P-fun	0.015 $V_{cmax}$	-	-	66,400	150650	490
$J_{max}$	3.4	μmol mol <sup>-1</sup>	P-fun	1.54 $V_{cmax}$	-	-	49,884	200,000	637.2
$T_p$	3.7	μmol mol <sup>-1</sup>	P-fun	0.09 $V_{cmax}$	-	-	53,100	150650	490
C4 pathway									
$K_c$	3.10	μbar	A-fun	650	-	-	67,294	-	-
$K_o$	3.10	mbar	A-fun	450	-	-	36,000	-	-
$V_{pr}$	3.13	μmol mol <sup>-1</sup>	Q-fun	80	2.0	-	-	-	-
$K_p$	3.13	μmol mol <sup>-1</sup>	Q-fun	80	2.0	-	-	-	-
$V_{cmax}$	3.11	μmol mol <sup>-1</sup>	P-fun	Table S1	-	-	67,294	144,568	472
$J_{max}$	3.4	μmol mol <sup>-1</sup>	P-fun	5 $V_{cmax}$	-	-	77,900	191,929	627
$V_{pmax}$	3.13	μmol mol <sup>-1</sup>	P-fun	1.4 $V_{cmax}$	-	-	70,373	117,910	376
$R_d$	3.12	μmol mol <sup>-1</sup>	P-fun	0.01 $V_{cmax}$	-	-	67,294	144,568	472

141  
 142 Across these photosynthesis processes, variables  $I^*$ ,  $K_c$ ,  $K_o$ ,  $V_{cmax}$ ,  $V_{pmax}$ ,  $J_{max}$ ,  $T_p$ ,  $R_d$ , and  $V_{pr}$  are temperature  
 143 dependent, and they are described using three types of dependency functions: 1) Arrhenius function (named as A-  
 144 fun); 2) peak model function (named as P-fun); and (3) Q10 function (named as Q-fun). They are given respectively  
 145 by:

$$k_T = k_{25} e^{\frac{E_a(T_l-25)}{298(T_l+273)R}} \quad \text{Eq. S3.12}$$

$$k_T = k_{25} e^{\frac{H_a(T_l-25)}{298(T_l+273)R}} \frac{1 + e^{\frac{298S_v-H_d}{298R}}}{1 + e^{\frac{T_lS_v-H_d}{T_lR}}} \quad \text{Eq. S3.13}$$

$$k_T = k_{25} Q_{10}^{\frac{T_l-298}{10}} \quad \text{Eq. S3.14}$$

146 Where  $k_{25}$  is the base rate of  $k_T$  at the reference temperature of 25 °C and  $T_l$  is leaf temperature in °C.  $E_a$  and  $H_a$   
 147 are both activation energy,  $H_d$  is deactivation energy,  $S_v$  is entropy term and  $Q_{10}$  is the coefficient representing the  
 148 proportional change in metabolic rate per 10°C increase in temperature, and  $R$  is ideal gas constant. The P-fun  
 149 function is modified from A-fun, and shows the reduction in metabolic rate at high temperatures due to the thermal  
 150 breakdown of metabolic processes. Table. S3.1 describes this parameterization based on von Caemmerer 2000;  
 151 Bernacchi et al., 2001; Massad et al., 2007; Kattge et al., 2007; von Caemmerer et al., 2009.



152 **S3.2. Stomatal conductance process**

153 The stomatal conductance model governs the exchange rate of CO<sub>2</sub> and water vapor through leaf stomata,  
 154 determining the leaf intercellular CO<sub>2</sub> concentration and leaf transpiration rates. Here, an empirical model called  
 155 Ball-Berry-Leuning model (Ball, Woodrow & Berry 1987; Leuning et al., 1990, 1995) is used to describe both C3  
 156 and C4 photosynthetic pathways, and it is given by:

$$g_{sw} = g_0 + \frac{a_1 A_n}{(c_s - \Gamma^*) \left(1 + \frac{D_s}{D_0}\right)} \quad \text{Eq. S3.15}$$

157 Where  $g_{sw}$  is the stomatal conductance to water vapor,  $g_0$  is  $g_{sw}$  at CO<sub>2</sub> compensation point, and  $a_1$  and  $D_0$  are  
 158 empirical coefficients.  $D_s$  and  $c_s$  are vapor pressure deficit (VPD) and CO<sub>2</sub> partial pressure at the leaf surface.  $D_s$  is  
 159 estimated as:

$$D_s = e_s(T_l) - e_a \quad \text{Eq. S3.16}$$

160 where  $e_a$  is the vapor pressure of ambient air, and  $e_s(T_l)$  is saturated vapor pressure at leaf temperature  $T_l$ .

161

162 The boundary layer conductance of  $g_{bw}$  to water vapor is estimated by:

$$g_{bw} = 1.4 \cdot 0.147 \sqrt{\frac{u}{d}} = 1.4 \cdot 0.147 \sqrt{\frac{u}{0.72w}} \quad \text{Eq. S3.17}$$

163 where  $u$  is wind speed (in unit of m/s) and  $w$  is leaf width (m). With the stomatal conductance ( $g_{sw}$ ) and the  
 164 boundary layer conductance ( $g_{bw}$ ), the CO<sub>2</sub> concentration at leaf surface ( $c_s$ ) and at the leaf intercellular level ( $c_i$ )  
 165 are estimated as:

$$c_s = c_a - \frac{1.4A_n}{g_{bw}} \quad \text{Eq. S3.18}$$

$$c_i = c_s - \frac{1.6A_n}{g_{sw}} \quad \text{Eq. S3.19}$$

166 where  $c_a$  is the CO<sub>2</sub> concentration of ambient air.

167

168 **S3.3. Leaf energy balance**

169 If heat storage and metabolic heat production are assumed to be negligible, the energy budget of a leaf is:

$$R_{abs} - L_{oe} - H - \lambda E_l = 0 \quad \text{Eq. S3.20}$$

170 where  $R_{abs}$  is the absorbed shortwave and longwave radiation,  $L_{oe}$  is emitted thermal radiation, and  $H$  and  $\lambda E$  are  
 171 sensible and latent heat loss, respectively. These equations are given by:

$$L_{oe} = \varepsilon_s \sigma T_l^4 \quad \text{Eq. S3.21}$$

$$H = c_p g_{ha} (T_l - T_a) \quad \text{Eq. S3.22}$$

$$\lambda E_l = \lambda g_v \frac{e_s(T_l) - e_a}{p_a} \quad \text{Eq. S3.23}$$

172 Where  $\varepsilon_s$  is leaf thermal emissivity,  $\sigma$  is the Stefan-Boltzmann constant,  $c_p$  is specific heat capacity of air,  $T_a$  is the  
 173 air temperature, and  $E$  is the transpiration rate.  $g_{ha}$  and  $g_v$  are heat conductance and vapor conductance,  
 174 respectively, and are given by:

$$g_{ha} = 1.4 \cdot 0.135 \sqrt{\frac{u}{0.72W}} \quad \text{Eq. S3.24}$$

$$g_v = 0.5 \frac{g_{sw}g_{bw}}{g_{sw} + g_{bw}} \quad \text{Eq. S3.25}$$

### 175 S3.4. Coupling and solving three processes

176 The three processes of photosynthesis, stomatal conductance, and leaf energy balance are interdependent. The  
 177 process of photosynthesis requires leaf temperature ( $T_l$ ) and leaf intercellular CO<sub>2</sub> concentration ( $c_i$ ) as inputs, and  
 178 subsequently offers the net carbon assimilation rate ( $A_n$ ) as one of its outputs. The stomatal conductance process  
 179 requires  $T_l$  and  $A_n$  as inputs, and delivers estimates of  $c_i$  and  $g_{sw}$  as outputs. The leaf energy balance process  
 180 requires  $g_{sw}$  as an input and in turn provides an estimate of  $T_l$ . Therefore, all three processes are solved in numerical  
 181 iteration. First,  $A_n$  is obtained when photosynthesis is initialized by setting  $T_l$  and  $c_i$  at air temperature  $T_a$  and  $0.7c_a$ ,  
 182 respectively. Second,  $A_n$  is used in the stomatal conductance process to update  $c_i$ . Steps one and two are solved  
 183 using the Newton-Raphson method until the  $c_i$  is converged upon. Third, the  $c_i$  and  $g_{sw}$  from the steps one and two  
 184 are used in the leaf energy balance process to solve  $T_l$ . These three steps are iterated until  $T_l$  is converged upon. As a  
 185 result, the net carbon assimilation rate ( $A_n$ ) and transpiration rate ( $E_l$ ) are scaled up to the canopy-level and drive the  
 186 growth process in other submodules.

### 187 S3.5. Water and nitrogen constraint

188 Net photosynthesis in Eq. S3.1 and Eq. S3.8 and transpiration rates in Eq. S3.23 are modelled without accounting  
 189 for stress from soil moisture and nitrogen availability. However, low availability of water and nitrogen could  
 190 decrease photosynthesis and transpiration by limiting stomatal conductance ( $g_{sw}$ ), photosynthetic capacity ( $V_{cmax}$ ),  
 191 or both. Following Moorcroft et al., 2001, the net photosynthesis rate,  $A_n(\mathbf{r}, t, c^*)$  and transpiration rate,  $E_l(\mathbf{r}, t, c^*)$   
 192 are adjusted for water and nitrogen stress using a simple approach:

$$A_n(\mathbf{r}, t, c^*) = c^* A_n + (1 - c^*) A_n^c \quad \text{Eq. S3.26}$$

$$E_l(\mathbf{r}, t, c^*) = c^* E_l + (1 - c^*) E_l^c \quad \text{Eq. S3.27}$$

$$c^* = f_w f_N \quad \text{Eq. S3.28}$$

193 where  $A_n^c$  and  $E_l^c$  are net photosynthesis and transpiration when fully constrained, assuming equal to  $A_n$  and  $E_l$  at  
 194 zero light input.  $c^*$  is the combined stress factor of water limitation  $f_w$  and nitrogen limitation  $f_N$ .  $f_w$  and  $f_N$  are  
 195 calculated based on the ratio of water/nitrogen uptake by fine roots and that demanded by leaves. Fine root uptake is  
 196 controlled by fine root biomass, the availability of water, and mineralized nitrogen in soil.  $f_w$  and  $f_N$  are equal to 0  
 197 when demand exceeds supply and set to 1 if there is no limitation in supply.

198

#### 199 **S4. Leaf phenology and freezing submodule**

200 The total leaf area of a cohort is dynamic, resulting not only from prior carbon balance and allocation but also  
201 environmental conditions (i.e., temperature and soil water availability). Three types of dynamic phenology are  
202 considered in the model, including evergreens, where the leaves remain year-around; drought-deciduous, where  
203 leaves are reduced if soil water drops below a critical threshold ( $W_{crit}$ ); and cold-deciduous, where leaves are  
204 reduced if air temperature is below a PFT-dependent threshold ( $T_{crit}(\mathbf{x})$  in Table S1.1). When either drought- or  
205 cold- deciduous phenology is triggered, leaf biomass ( $B_l$ ) is set at zero. A fraction of lost leaf biomass (defined as  
206  $L\_frac$ ) is relocated to a non-respiring, non-decaying, and non-photosynthetic pool called virtual leaf biomass  $B_{lv}$ .  
207 The remaining biomass fraction ( $1 - L\_frac$ ) is then added to the litter pools where the associated carbon and nitrogen  
208 will be cycled within the belowground biochemical submodule. The virtual leaf biomass ( $B_{lv}$ ) is accounted for  
209 within  $B_a$  but does not lead to photosynthesis and respiration. When both soil water and air temperatures are  
210 favourable, leaf biomass  $B_l$  recovers instantly to a level depending on remaining  $B_a$  and allometry (for further  
211 details see the allocation submodule).

212  
213 Exposure to low temperatures can cause tissue damage to twigs and buds, affecting subsequent carbon balance and  
214 survival (DeHayes, 1992; Gu et al., 2008; Sakai and Larcher, 2012; Sakai and Weiser, 1973; Vitasse et al., 2014).  
215 Injury effects are characterized by introducing leaf loss at low temperatures. For cold-deciduous PFTs, freezing  
216 injury will occur if the monthly average air temperature continues to drops below the defined PFT-specific threshold  
217 of resistance ( $T_{free}(\mathbf{x})$  in Table S1.1), the virtual leaf biomass by  $L\_frac$ , which is added to litter pools. Loss of  
218 virtual leaf biomass reduces  $B_a$  accordingly, in turn affecting the amount of leaf biomass can be recovered when air  
219 temperature returns to a favourable level. The resulting leaf loss could affect ongoing carbon assimilation and height  
220 growth, and also may result in competitive disadvantage over others PFTs with more resistance to freezing.

221 **S5. Growth submodule**

222 The growth submodule follows Moorcroft et al., 2001 and provides the growth function for  $g_a(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  and  
 223  $g_s(\mathbf{z}, \mathbf{x}, \bar{r}, t)$ , as a result of the carbon balance between carbon assimilation and respiration. Plants gain carbon  
 224 through leaf photosynthesis and lose carbon by respiration and decay of leaves and roots (decay and respiration of  
 225 sapwood and structural tissues are assumed to be negligible), and devote remaining carbon to production and growth  
 226 of active and structural tissue. This process of net carbon production ( $Prod$ ) is given by:

$$Prod = A(\mathbf{r}, t, c^*)l(\mathbf{x})B_l - R_d l(\mathbf{x})B_l - \beta_r(\mathbf{x})B_r f(T_s) - \alpha_l(\mathbf{x})B_l - \alpha_r(\mathbf{x})B_r \quad \text{Eq. S5.1}$$

227  
 228 On the right-hand side of the equation, the first term represents total gross carbon fixation by all leaves, the second  
 229 and third terms represent biomass and temperature dependent respiration of leaves and fine roots, respectively. The  
 230 last two terms, representing decay of leaves and fine roots, are only related to biomass.  $A(\mathbf{r}, t, c^*)$  and  $R_d$  are the  
 231 gross photosynthesis rate and leaf respiration per unit leaf area given resource  $\mathbf{r}$  (light, water,  $\text{CO}_2$ ) and soil water  
 232 stress ( $c^*$ ) at time  $t$ .  $l(\mathbf{x})$  is specific leaf area (SLA),  $\beta_r$  is the respiration coefficient for fine root, and  $f(T_s)$  is the  
 233 dependence function of respiration on soil temperature ( $T_s$ ).  $\alpha_l$  and  $\alpha_r$  are the decay rates of leaves and fine roots,  
 234 respectively, with values reciprocal to longevity.

235  
 236 The net carbon production ( $Prod$ ) can be positive or negative depending on environmental conditions and leaf  
 237 conditions. This variability results in several cases where carbon is differentially partitioned among the growth of  
 238 active tissues, structural tissues, and reproduction. When  $Prod$  is positive:

$$g_a(\mathbf{z}, \mathbf{x}, \bar{r}, t) = Prod \cdot [1 - rp(\mathbf{x})] \cdot q_a(\mathbf{z}, \mathbf{x}) \quad \text{Eq. S5.2}$$

$$g_s(\mathbf{z}, \mathbf{x}, \bar{r}, t) = Prod \cdot [1 - rp(\mathbf{x})] \cdot [1 - q_a(\mathbf{z}, \mathbf{x})] \quad \text{Eq. S5.3}$$

$$RP(\mathbf{z}, \mathbf{x}, \bar{r}, t) = Prod \cdot rp(\mathbf{x}) \quad \text{Eq. S5.4}$$

239 where  $rp(\mathbf{x})$  defines the fraction of  $Prod$  used for reproduction,  $q_a(\mathbf{z}, \mathbf{x})$  represents the fraction of new growth  
 240 devoted to active tissues  $B_a$  (calculated in Eq. S2.11), and  $RP(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  is total carbon allocated for new seedlings  
 241 (see more details in S6 on the reproduction submodule). A positive  $Prod$  represents situations where a plant's  
 242 carbon fixation from photosynthesis is sufficient for growth and reproduction, even after deducting carbon losses  
 243 due to respiration and decay.

244  
 245 In contrast, negative  $Prod$  occurs when environmental conditions do not favour photosynthesis (e.g., dry air forces  
 246 leaf stomata closed) or when leaf drop is triggered by soil water stress or low air temperatures. In this case:

$$g_a(\mathbf{z}, \mathbf{x}, \bar{r}, t) = Prod \quad \text{Eq. S5.5}$$

$$g_s(\mathbf{z}, \mathbf{x}, \bar{r}, t) = 0 \quad \text{Eq. S5.6}$$

$$RP(\mathbf{z}, \mathbf{x}, \bar{r}, t) = 0 \quad \text{Eq. S5.7}$$

247 where all of  $Prod$  is used for the plant's active tissue.

248

249 **S6. Reproduction submodule**

250 Plants in positive carbon balance maintain enough carbon  $RP(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  to reproduce seedlings. The fecundity  
 251  $F(\mathbf{z}, \mathbf{x}, a, t)$  is calculated as:

$$F(\mathbf{z}, \mathbf{x}, a, t) = \frac{RP(\mathbf{z}, \mathbf{x}, \bar{r}, t)}{B_{a0} + B_{s0}} (1 - \lambda_{SD}) \quad \text{Eq. S6.1}$$

252 where  $B_{a0}$  and  $B_{s0}$  are the initial active and structural biomass of a seedling with functional type  $\mathbf{x}$ , and  $1 - \lambda_{SD}$  is  
 253 the probability of seeding survivorship ( $\lambda_{SD} = 0.95$ ). The dead seedlings will be loaded into the soil pools for later  
 254 carbon and nitrogen decomposition.

255  
 256 Seedling dispersal includes local dispersal, which limits seedlings to the siting patch (i.e. local patch), and non-local  
 257 dispersal, which distributes seedlings to all other patches. Thus, for any patch, it will receive seedlings not only from  
 258 all plants of different sizes in its own cohorts but also from plants in other patches. Dispersed seedlings will form a  
 259 new cohort at the local patch, where plant individual density of the new cohort is represented as:

$$n_i(z_0, \mathbf{x}, a, t) = \frac{1}{G_0} \int_0^\infty F(\mathbf{z}, \mathbf{x}, a, t) n_i(\mathbf{z}, \mathbf{x}, a, t) (1 - m(\mathbf{x})) dz \quad \text{Eq. S6.2}$$

$$+ \frac{1}{G_0} \frac{1}{p_i(a, t)} \int_0^\infty \int_0^\infty F(\mathbf{z}, \mathbf{x}, a, t) n_i(\mathbf{z}, \mathbf{x}, a, t) p_i(a, t) m(\mathbf{x}) da dz$$

260 where  $m(\mathbf{x})$  is the PFT-dependent non-local dispersal rate, representing the fraction of plant seedlings that will be  
 261 dispersed to other non-local patches. The first term on the right-hand side of the equation represents seedlings  
 262 received from all cohorts within the local patch, and the second term represent seedlings from non-local patches.  
 263

264 **S7. Mortality submodule**

265 The plant mortality rate  $\mu(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  includes density-independent  $\mu_{DI}(\mathbf{x})$  and density-dependent  $\mu_{DD}(\mathbf{z}, \mathbf{x}, \bar{r}, t)$   
 266 components, where:

$$\mu(\mathbf{z}, \mathbf{x}, \bar{r}, t) = \mu_{DI}(\mathbf{x}) + \mu_{DD}(\mathbf{z}, \mathbf{x}, \bar{r}, t) \quad \text{Eq. S7.1}$$

267  
 268 The density-independent  $\mu_{DI}(\mathbf{x})$  component is related to disturbance, wood density, and life-history of a PFT, such  
 269 that  $\mu_{DI}(\mathbf{x})$  is the sum of disturbance related ( $\mu_{DI-DIS}(\mathbf{x})$ ) and wood-density related ( $\mu_{DI-\rho}(\mathbf{x})$ ) components.

270  $\mu_{DI-\rho}(\mathbf{x})$  varies by PFT. For example, in comparison to the late-successional broadleaf PFT, the early- and mid-  
 271 successional broadleaf PFTs have relatively higher rates of carbon accumulation and lower wood densities, making  
 272 them susceptible to pathogen attack and to windthrow disturbance. Thus,  $\mu_{DI-\rho}(\mathbf{x})$  decreases for early- to mid- and  
 273 late-successional PFTs. In addition, the tropical variant of the broadleaf PFTs, has higher  $\mu_{DI-\rho}(\mathbf{x})$  than the non-  
 274 tropical variant.  $\mu_{DI}(\mathbf{x})$  for each PFT (as shown in Table. S1.1).

275  
 276 The density-dependent  $\mu_{DD}(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  component of plant mortality is related to the averaged carbon balance over a  
 277 given historical period. This component is calculated as:

$$\mu_{DD}(\mathbf{z}, \mathbf{x}, \bar{r}, t) = \frac{10}{1 + e^{\frac{20 \int_{t-\Delta t}^t Prod(t) dt}{\int_{t-\Delta t}^t Prod_{FS}(t) dt}}} \quad \text{Eq. S7.2}$$

278 where  $\int_{t-\Delta t}^t Prod(t) dt$  is the cumulative carbon balance of a plant from time  $t - \Delta t$  to  $t$ , and  $\int_{t-\Delta t}^t Prod_{FS}(t) dt$  is  
 279 the cumulative carbon balance of the plant under full sun conditions.  $\mu_{DD}(\mathbf{z}, \mathbf{x}, \bar{r}, t)$  is a nonlinear function of light  
 280 competition, namely shading from other plants could result in an increased mortality rate.

281

## 282 S8. Soil biogeochemical submodule

283 The soil biogeochemical submodule tracks belowground carbon and nitrogen dynamics using a simplified Century  
 284 model (Parton, 1996). This submodule primarily follows Moorcroft et al., 2001. For each patch, three carbon pools  
 285 are tracked including the structural litter carbon pool  $C_1(a, t)$ , metabolic litter carbon pool  $C_2(a, t)$  and soil slow  
 286 carbon pool  $C_3(a, t)$ . By assuming nitrogen is mostly bonded in carbon, nitrogen dynamics have the same three  
 287 pools as carbon plus a mineralized nitrogen pool which stores nitrogen in plant-available forms (nitrate and  
 288 ammonium).

289  
 290 Decaying tissues from living plants, and active and structural tissues of dead plants are loaded into structural and  
 291 metabolic litter carbon pools  $C_1(a, t)$  and  $C_2(a, t)$ . A fraction of both decaying active tissues and dead plant active  
 292 tissue enter  $C_1(a, t)$ , with the rest entering  $C_2(a, t)$ . Two litter pools decompose the carbon under different  
 293 decomposition rates; both pools depend on defined intrinsic decomposition rates and soil moisture, but the  
 294 decomposition rate of structural pool is additionally controlled by lignin content in the pool. All decomposed carbon  
 295 from the metabolic litter pool and part of that from the structural litter pool is lost due to heterotrophic respiration  
 296 (RH). The rest of the carbon from the structural litter pool is transported to the slow soil carbon pool, where its  
 297 decomposed at a relative slower rate. Thus, at time  $t$ , change rates of structural, metabolic litter and slow soil carbon  
 298 pools are given:

$$\frac{dC_1(a, t)}{dt} = C_{1,decay}(r, a, t) + C_{1,dead}(r, a, t) - C_{1,decomp}(r, a, t) \quad \text{Eq. S8.1}$$

$$\frac{dC_2(a, t)}{dt} = C_{2,decay}(r, a, t) + C_{2,dead}(r, a, t) - C_{2,decomp}(r, a, t) \quad \text{Eq. S8.2}$$

$$\frac{dC_3(a, t)}{dt} = (1 - r_{stsc})C_{1,decomp}(r, a, t) - C_{3,decomp}(r, a, t) \quad \text{Eq. S8.3}$$

299 Where  $C_{1,decay}(r, a, t)$  and  $C_{1,dead}(r, a, t)$  represent the carbon loaded to the structural litter carbon pool from  
 300 decaying tissues of living plants, and active and structural tissues from dead plants and seedlings, respectively,  
 301  $C_{1,decomp}(r, a, t)$  is decomposed carbon from the structural litter carbon pool.  $C_{2,decay}(r, a, t)$  and  $C_{2,dead}(r, a, t)$   
 302 represent carbon loaded into the metabolic litter carbon pool from decaying tissues of living plants, and active and  
 303 structural tissues from dead plants seedlings, respectively.  $C_{2,decomp}(r, a, t)$  is decomposed carbon from the  
 304 metabolic litter carbon pool. Decomposition rates for the three pools are calculated as:

$$C_{1,decomp}(r, a, t) = A(a, t, T_s, W(a, t))K_1 e^{-3L_s} C_1(a, t) \quad \text{Eq. S8.4}$$

$$C_{2,decomp}(r, a, t) = A(a, t, T_s, W(a, t))K_2 C_2(a, t) \quad \text{Eq. S8.5}$$

$$C_{3,decomp}(r, a, t) = A(a, t, T_s, W(a, t))K_3 C_3(a, t) \quad \text{Eq. S8.6}$$

305 where  $A(a, t, T_s, W(a, t))$  is a combined factor (ranging from 0-1) of soil temperature and moisture,  $K_1$ ,  $K_2$  and  $K_3$   
 306 are constant coefficients, and  $L_s$  is the relative fraction of lignin in the structural carbon pool. Together with Eq.  
 307 S8.1, S8.2 and S8.3, the total heterotrophic respiration at time  $t$  is calculated as:

$$R_h(a, t) = r_{stsc}C_{1,decomp}(r, a, t) + C_{2,decomp}(r, a, t) + C_{3,decomp}(r, a, t) \quad \text{Eq. S8.7}$$

308

309 Nitrogen pools include the structural litter nitrogen pool  $N_1(a, t)$ , metabolic litter nitrogen pool  $N_2(a, t)$ , soil slow  
 310 nitrogen pool  $N_3(a, t)$ , and mineralized nitrogen pool  $N_4(a, t)$ . Nitrogen is assumed to largely be bonded with  
 311 carbon. The carbon to nitrogen ratio is fixed at 150 for the structural litter pool and 10 for the soil slow pool but  
 312 floating for the metabolic pool depending on the PFT's leaf nitrogen content. Nitrogen dynamics across pools are  
 313 similar to carbon dynamics, except that the nitrogen attached to carbon lost during heterotrophic respiration is  
 314 assumed to be mineralized, and subsequently added to the mineralized nitrogen pool  $N_4(a, t)$ :

$$\frac{dN_1(a, t)}{dt} = N_{1,decay}(r, a, t) + N_{1,dead}(r, a, t) - N_{1,immbo}(r, a, t) \quad \text{Eq. S8.8}$$

$$\frac{dN_2(a, t)}{dt} = N_{2,decay}(r, a, t) + N_{2,dead}(r, a, t) - N_{2,min}(r, a, t) \quad \text{Eq. S8.9}$$

$$\frac{dN_3(a, t)}{dt} = N_{1,immbo}(r, a, t) - N_{3,min}(r, a, t) \quad \text{Eq. S8.10}$$

$$\frac{dN_4(a, t)}{dt} = N_{2,min}(r, a, t) + N_{3,min}(r, a, t) - N_{up}(r, a, t) - N_{lea}(r, a, t) \quad \text{Eq. S8.11}$$

315 Where  $N_{1,decay}(r, a, t)$  and  $N_{1,dead}(r, a, t)$  are nitrogen inputs into the structural litter nitrogen pool from decaying  
 316 tissues of living, and active and structural tissue from dead plants and seedlings, respectively.  $N_{1,immbo}(r, a, t)$  is  
 317 decomposed nitrogen which will be transported to the soil slow nitrogen pool.  $N_{2,decay}(r, a, t)$  and  $N_{2,dead}(r, a, t)$   
 318 are nitrogen inputs to the metabolic litter nitrogen pool from either the decaying tissue of living plants and seedlings  
 319 or the active and structural tissue from them once dead.  $N_{2,min}(r, a, t)$  and  $N_{3,min}(r, a, t)$  are mineralized nitrogen  
 320 from the metabolic litter and soil slow pools, and  $N_{up}(r, a, t)$  is nitrogen uptake by plants.  $N_{lea}(r, a, t)$  is leached  
 321 nitrogen, which is assumed to be linearly related to the percolation and runoff rate  $perc(a, t)$  which is calculated in  
 322 hydrology submodule. Nitrogen flows in the above equations are calculated stoichiometrically as a product of the  
 323 corresponding carbon flow and carbon to nitrogen ratio.

324



325 **S9. Hydrology submodule**

326 The hydrology submodule tracks incoming soil water flow from precipitation and snow melt and outgoing flow  
 327 through percolation, runoff, and evapotranspiration from the soil and plant canopy. At time  $t$ , soil water change rate  
 328 is given by:

$$\frac{dW(a, t)}{dt} = P(a, t) + SM(a, t) - perc(a, t) - E_{soil, canopy}(a, t) - W_{up}(a, t) \quad \text{Eq. S9.1}$$

329 where  $W(a, t)$  is soil water availability,  $P(a, t)$  and  $SM(a, t)$  are incoming water flux from snowmelt, and  $perc(t)$   
 330 is water loss due to percolation and runoff,  $E_{soil, canopy}(a, t)$  is water loss due to evaporation from the soil and  
 331 canopy, and  $W_{up}(a, t)$  is plant water uptake for transpiration.

332

333  $W_{up}(a, t)$  equals the total transpiration of all leaves:

$$W_{up}(a, t) = \int_0^{\infty} E_l(\mathbf{r}, t, c^*) l(\mathbf{x}) B_l n_l(\mathbf{z}, \mathbf{x}, a, t) dz \quad \text{Eq. S9.2}$$

334 where  $E_l(\mathbf{r}, t, c^*)$  is the leaf transpiration rate per leaf area, given in the leaf physiology submodule.

335

336 When the monthly average air temperature drops below the freezing point, precipitation falls as snow to accumulate  
 337 snowpack; no water is loaded into the soil. When the monthly average air temperature rises above the freezing point,  
 338 precipitation falls as rain and snowpack start to melt at a rate linearly related to air temperature until depletion; both  
 339 precipitation and snowmelt are loaded into the soil. The snowmelt and snowpack change rate is given by:

$$\frac{dSP(a, t)}{dt} = P_s(a, t) - SM(a, t) \quad \text{Eq. S9.3}$$

$$SM(a, t) = \begin{cases} 0, & T_a < 0^\circ\text{C or } SP(a, t) = 0 \\ T_a k_{melt}, & T_a \geq 0^\circ\text{C and } SP(a, t) > 0 \end{cases} \quad \text{Eq. S9.4}$$

340 where  $SP(a, t)$  is snowpack,  $P_s(a, t)$  equals to  $P(a, t)$  when air temperature is below the freezing point and  
 341 otherwise equal to zero.  $k_{melt}$  is the coefficient constant of the melting rate, set at  $100 \text{ mm } ^\circ\text{C}^{-1} \text{ month}^{-1}$ .  
 342 Snowmelt ceases when cumulated snowpack is depleted.

343

344 Percolation and runoff rate  $perc(a, t)$  is related to hydraulic conductivity, which is a nonlinear function of soil  
 345 water availability. This relationship is given as:

$$perc = K_{sat, MvG} S_e(a, t)^{L_{MvG}} (1 - (1 - S_e(a, t))^{\frac{1}{m_{MvG}}})^{m_{MvG}} \quad \text{Eq. S9.5}$$

$$S_e(a, t) = \frac{\frac{W(a, t)}{d_{soil}} - \theta_{res, MvG}}{\theta_{sat, MvG} - \theta_{res, MvG}} \quad \text{Eq. S9.6}$$

346 Where  $K_{sat, MvG}$  is saturated hydraulic conductivity,  $\theta_{res, MvG}$  and  $\theta_{sat, MvG}$  are residual and saturated volumetric  
 347 water content.  $S_e(a, t)$  is effective volumetric saturation,  $d_{soil}$  is soil depth (in mm).  $L_{MvG}$  and  $m_{MvG}$  are Mualem–  
 348 van Genuchten (MvG) coefficients (van Genuchten, 1980), specified by gridded soil hydraulic data external to ED  
 349 (e.g. Montzka et al., 2017).

350

351 Evaporation from the soil and canopy is estimated using a model developed by Mu et al., 2011, with the sum  
 352 represented as:

$$E_{soil,canopy}(a, t) = E_{canopy}(a, t) + E_{soil}(a, t) \quad \text{Eq. S9.7}$$

353  
 354 Both  $E_{soil}(a, t)$  and  $E_{canopy}(a, t)$  are estimated based on the Penman-Monteith (P-M) equation (Monteith, 1965):

$$\lambda E = \frac{s \cdot R + \frac{\rho \cdot c_p \cdot (e_{sat} - e)}{r_a}}{s + \gamma \cdot \left(1 + \frac{r_s}{r_a}\right)} \quad \text{Eq. S9.8}$$

355 Where  $s$  is slope of the curve relating saturated water vapor pressure ( $e_{sat}$ ) to temperature,  $R$  is available energy  
 356 partitioned between sensible heat, latent heat, and soil heat fluxes,  $\rho$  is air density,  $c_p$  is the specific heat capacity of  
 357 air,  $\gamma$  is the psychrometric constant,  $r_a$  is aerodynamic resistance,  $r_s$  is an effective resistance to evaporation from the  
 358 land surface. Calculations of  $r_a$  and  $r_s$  are different for soil and canopy.

359  
 360 Canopy evaporation ( $E_{canopy}(a, t)$ ) comes from wet canopy which intercepts precipitation. Based on the P-M  
 361 equation,  $E_{canopy}(a, t)$  is given by:

$$E_{canopy}(a, t) = \frac{1}{\lambda} \left[ \frac{s \cdot R_{canopy} + \frac{\rho \cdot c_p \cdot (e_{sat} - e)}{rhrc}}{s + \frac{P_a \cdot c_p \cdot rvc}{\lambda \cdot \varepsilon \cdot rhrc}} \right] \cdot F_c \cdot F_{wet} \quad \text{Eq. S9.9}$$

362 where  $R_{canopy}$  is part of  $R$  in Eq. S9.8 allocated to canopy,  $F_c$  is the patch fraction covered by plants, and  $F_{wet}$  is the  
 363 wet fraction of the land surface, correlated to air relative humidity (Fisher et al., 2008).  $rhrc$  and  $rvc$  are  
 364 aerodynamic resistance and wet canopy resistance to evaporation from wet canopy. Calculation of  $F_c$ ,  $R_c$ ,  $F_{wet}$ ,  
 365  $rhrc$ , and  $rvc$  can be found in Mu et al., 2011.

366  
 367 Soil evaporation  $E_{soil}(a, t)$  consists of potential evaporation from both the saturated soil surface and moist soil  
 368 surface, thereby  $E_{soil}(a, t)$  equals to:

$$E_{soil}(a, t) = E_{wet\_soil}(a, t) + E_{pot\_soil}(a, t) \left( \frac{e_{sat} - e}{100} \right)^{(e_{sat} - e)/200} \quad \text{Eq. S9.10}$$

369  
 370 Then  $E_{wet\_soil}(a, t)$  and  $E_{pot\_soil}(a, t)$  are estimated as:

$$E_{wet\_soil}(a, t) = \frac{1}{\lambda} \left[ \frac{s \cdot R_{soil} + \frac{\rho \cdot c_p \cdot (1 - F_c) \cdot (e_{sat} - e)}{ras}}{s + \frac{\gamma \cdot rtot}{ras}} \right] \cdot F_{wet} \quad \text{Eq. S9.11}$$

$$E_{pot\_soil}(a, t) = \frac{1}{\lambda} \left[ \frac{s \cdot R_{soil} + \frac{\rho \cdot c_p \cdot (1 - F_c) \cdot (e_{sat} - e)}{ras}}{s + \frac{\gamma \cdot rtot}{ras}} \right] \cdot (1 - F_{wet}) \quad \text{Eq. S9.12}$$

371 Where  $R_{soil}$  is the portion of  $R$  in Eq. S9.8 allocated to the soil surface,  $ras$  is the aerodynamic resistance at the soil  
372 surface, and  $rtot$  is the sum of the soil surface resistance and aerodynamic resistance to water vapor transport.  
373 Calculation of  $ras$  and  $rtot$  is related to air temperature, and further details can be found in Mu et al., 2011.  
374  
375  $E_{soil}(a, t)$  and  $E_{canopy}(a, t)$  are calculated separately for day and night, using the same equations but different  
376 parameter values. The sum of both day and night evaporation is then weighted by the daytime fraction.  
377

378 **S10. Disturbance and fire submodule**

379 The disturbance submodule describes the impacts of natural disturbance (treefall, hurricane, and fire) on patch and  
 380 cohort dynamics as well as the associated carbon cycle. Disturbance impact on patch demography has been depicted  
 381 in the patch dynamic PDE equation, where the second term on the right-hand side denotes changes in the proportion  
 382 of patch natural disturbance. Currently three types of disturbance are included: treefall, hurricane, and fire. The  
 383 disturbance rate  $\lambda_i(\mathbf{a}, t)$  is given by:

$$\lambda_i(\mathbf{a}, t) = \max(\lambda_{treefall} + \lambda_{hurricane}, \lambda_{fire}(\mathbf{a}, t)) \quad \text{Eq. S10.1}$$

384 Where  $\lambda_{treefall}$  is set as  $0.014 \text{ yr}^{-1}$  and  $0.012 \text{ yr}^{-1}$  for tropical and non-tropical regions, respectively.  $\lambda_{hurricane}$  is  
 385 specified either by an internal parameter or via external data.  $\lambda_{fire}(\mathbf{a}, t)$  is either calculated within the fire submodule  
 386 or specified by external data.

387 Disturbance reduces the area of all patches proportionally and then forms a new patch. The boundary conditions of  
 388 area and carbon, nitrogen and water pools for this new patch are represented as:

$$p_i(0, t) = \int_0^\infty \lambda_i(\mathbf{a}, t) p_i(\mathbf{a}, t) d\mathbf{a} \quad \text{Eq. S10.2}$$

$$PL_i(0, t) = \int_0^\infty PL_i(\mathbf{a}, t) \frac{\lambda_i(\mathbf{a}, t) p_i(\mathbf{a}, t)}{p_i(0, t)} d\mathbf{a} \quad \text{Eq. S10.3}$$

389 where  $PL$  represents each pool of soil carbon, nitrogen, and water. As the above two equation shows, the new patch  
 390 proportionally inherits pools from the source patches.

391  
 392 In addition to area and pool changes, disturbance also removes a fraction of the plants within involved patches.  
 393 Some plants from the reduced patch area survive the disturbance and are relocated to the new patch; the rest of  
 394 plants die and their carbon and nitrogen are loaded into the soil pools. The individual density of surviving plants is  
 395 represented as:

$$n_i(\mathbf{z}, \mathbf{x}, 0, t) = \int_0^\infty S(\mathbf{x}) n_i(\mathbf{z}, \mathbf{x}, \mathbf{a}, t) \lambda_i(\mathbf{a}, t) d\mathbf{a} \quad \text{Eq. S10.4}$$

396 where  $S(\mathbf{x})$  is survivorship dependent on the disturbance and PFT type. For non-fire related disturbance (i.e., treefall  
 397 or hurricane), survivorship is differentiated by tree height. Thereby  $S(\mathbf{x})$  is given by:

$$S(\mathbf{x}) = \begin{cases} s_{lt}(\mathbf{x}), & h(\mathbf{z}, \mathbf{x}, \mathbf{a}, t) < h_{treefall} \\ s_{gt}(\mathbf{x}), & h(\mathbf{z}, \mathbf{x}, \mathbf{a}, t) \geq h_{treefall} \end{cases} \quad \text{Eq. S10.5}$$

398 Where  $h(\mathbf{z}, \mathbf{x}, \mathbf{a}, t)$  is the height of a cohort,  $h_{treefall}$  is a defined height threshold, and  $s_{lt}(\mathbf{x})$  and  $s_{gt}(\mathbf{x})$  are the  
 399 survivorship rate (scaled from 0 to 1) for a plant with a height above  $h_{treefall}$  or below it, respectively. Currently,  
 400  $s_{lt}(\mathbf{x})$  and  $s_{gt}(\mathbf{x})$  are the same for all PFTs, (i.e., values are 1.0 and 0.0, respectively), and  $h_{treefall}$  is set as 0,  
 401 meaning all plants will not survive in treefall disturbance.

402  
 403 For fire-related disturbance, survivorship is different for grasses where:

$$S(\mathbf{x}) = \begin{cases} 1.0, & \mathbf{x} = \text{C3ShG or C4ShG} \\ 0.3, & \text{otherwise.} \end{cases} \quad \text{Eq. S10.6}$$

404

405 Total carbon of dead plants involved in disturbance is given by:

$$C_{rem,dis}(t) = \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) + B_s(\mathbf{z}, \mathbf{x}, a, t)][1 - S(\mathbf{x})]n_i(\mathbf{z}, \mathbf{x}, a, t)\lambda_i(a, t)d\mathbf{z} da \quad \text{Eq. S10.7}$$

406

407 Total carbon of dead plants involved in disturbance is given by:

$$C_{rem,dis}(t) = \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) + B_s(\mathbf{z}, \mathbf{x}, a, t)][1 - S(\mathbf{x})]n_i(\mathbf{z}, \mathbf{x}, a, t)\lambda_i(a, t)d\mathbf{z} da \quad \text{Eq. S10.7}$$

408

409 The total carbon of dead plants is partitioned between soil carbon pools and emissions:

$$C_{rem,dis}(t) = [1 - C_{rem,dis}(t)]C_{rem,dis}(t) + f_{loss}C_{rem,dis}(t) \quad \text{Eq. S10.8}$$

410 Where the two terms on the right-hand side of the equation represent the carbon partitioned to soil carbon pools and

411 to CO<sub>2</sub> emissions, respectively.  $f_{loss}$  is the fraction of carbon lost as emissions.  $f_{loss}$  is set as 0.3 for fire-related

412 disturbance (i.e. smoke fraction) and 0 for treefall- and hurricane-related disturbance, which means no carbon will

413 lost as emissions.

414

415 Fire disturbance rate  $\lambda_{fire}(a, t)$  can be either specified by external burned area data or estimated by the fire

416 submodule (described below). Following Hurtt et al., 2002, fire risk is controlled by fuel and ignition rate, thereby

417  $\lambda_{fire}(a, t)$  is given by:

$$\lambda_{fire}(a, t) = B_{fuel}(a, t)f_{ignition}(a, t) \quad \text{Eq. S10.9}$$

$$B_{fuel}(a, t) = \int_0^\infty [B_l(\mathbf{z}, \mathbf{x}, a, t) + f_{agb}B_{sw}(\mathbf{z}, \mathbf{x}, a, t) + f_{agb}B_s(\mathbf{z}, \mathbf{x}, a, t)]n_i(\mathbf{z}, \mathbf{x}, a, t)d\mathbf{z} \quad \text{Eq. S10.10}$$

$$\lambda_{fire}(a, t) = \begin{cases} \left(\frac{\bar{D}}{30000}\right)^{10}, & P(a, t) < 100 \text{ mm month}^{-1} \\ 0.0, & \text{otherwise.} \end{cases} \quad \text{Eq. S10.11}$$

418 where  $B_{fuel}(a, t)$  is total aboveground carbon as fuel,  $f_{agb}$  is aboveground ratio of structural biomass  $B_s$ , which is

419 set as 0.8.  $\bar{D}$  is annual average drought index, calculated from rolling monthly estimates of the number of days

420 precipitation is below potential evapotranspiration rate.

421

422

423 **S11. Land use submodule**

424 The land use submodule describes the demographic dynamics of patches and cohorts by tracking the sub-grid  
 425 heterogeneity associated with different land use types and transitions. A wide range of land use activities are  
 426 accounted for including deforestation, reforestation, shifting cultivation, and wood harvest. In this submodule, land  
 427 use activities can alter the demography of patches and cohorts. For example, deforestation for cropland results in an  
 428 area decrease of forest patches and area increase of new cropland patches, and correspondingly resets the age of  
 429 affected patches and cohorts. In addition, land use activities alter carbon dynamics, including redistribution of  
 430 carbon among plant, soil, and wood timber product pools, and legacy effects on the carbon balance such as elevated  
 431 heterotrophic respiration from dead plants and enhanced carbon sequestration from plant regrowth. Currently, the  
 432 submodule is structured for use with standard land use forcing from CMIP5 and CMIP6 (i.e., the Land Use  
 433 Harmonization 1 (LUH1) and 2 (LUH2) datasets) (Hurtt et al., 2011, 2019, 2020). These datasets provide historical  
 434 gridded land use fractions and transitions between land use types on an annual basis.

435  
 436 Four land use types are characterized: primary land, secondary land, cropland, and pasture. Patches are tagged with a  
 437 particular land use type (i.e., primary (v), secondary (s), cropland (c), and pasture (p)), and labelled with the  
 438 corresponding subscript of  $p_i(a, t)$  in the Eq. 1 (the core PDE equation for patch dynamic). Transition types among  
 439 the four land use types are listed in Table. S10.1, along with their corresponding input variables in LUH1 and  
 440 LUH2. In this table,  $\lambda_{v,c}$ ,  $\lambda_{v,p}$ ,  $\lambda_{s,c}$  and  $\lambda_{s,p}$  represent deforestation,  $\lambda_{v,s}$  and  $\lambda_{s,s}$  represent wood harvest,  $\lambda_{c,s}$  and  $\lambda_{p,s}$   
 441 represent reforestation. For each grid cell, patch area is subject to:

$$\int_0^{\infty} p_i(a, t) da = LU_i(t) \quad (i = v, s, c \text{ and } p) \quad \text{Eq. S11.1}$$

442 where  $LU_i(t)$  is the area of the land use type  $i$  at time  $t$ , specified by the external land use change dataset (e.g.,  
 443 LUH1 or LUH2).

444  
 445 Land use transitions drive patch demographic changes by reducing the area and land-use proportion of existing  
 446 patches, which is described as:

$$\frac{\partial}{\partial t} p_i(a, t) = -\frac{\partial}{\partial a} p_i(a, t) - \lambda_i(a, t) p_i(a, t) - \sum_j \lambda_{j,i}(a, t) p_i(a, t) \quad \text{Eq. S11.2}$$

447 The above equation has been described in section 2.1, governing patch dynamics in terms of ageing and disturbance  
 448 due to both natural and anthropogenic land use change. The last term on the right-hand side of the equation  
 449 represents the patch fraction  $p_i(a, t)$  that decreases due to a land use transition from current type  $i$  to new type  $j$ .  
 450 Along with this fractional decrease for all involved patches, a new patch with land use type  $j$  will be formed. The  
 451 area, carbon, nitrogen, and water boundary conditions for this new patch are represented as:

$$p_j(0, t) = \sum_i \int_0^{\infty} \lambda_{j,i}(a, t) p_i(a, t) da \quad (i, j = v, s, c \text{ and } p) \quad \text{Eq. S11.3}$$

$$PL_j(0, t) = \sum_i PL_i(0, t) \frac{\int_0^\infty \lambda_{j,i}(a, t) p_i(a, t) da}{p_j(0, t)} \quad (i, j = v, s, c \text{ and } p) \quad \text{Eq. S11.4}$$

452 Where  $PL$  represents each pool of soil carbon, nitrogen, and water. The above two equations show that the new  
 453 patch inherits pools from the source patches proportionally.

454

455 Depending on the specific transition type, land use transitions may also involve plant removal (Table S10.1). Plant  
 456 removal will clear native plants and distribute associated carbon to either the wood product or soil litter pools. The  
 457 carbon from plant removal is partitioned between carbon pools as follows:

$$\begin{aligned} C_{res,i}(t) & \quad \text{Eq. S11.5} \\ &= \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) \\ &+ B_s(\mathbf{z}, \mathbf{x}, a, t)] n_i(\mathbf{z}, \mathbf{x}, a, t) p_i(a, t) \lambda_{i,j}(a, t) \zeta_{res}(\mathbf{x}, i) d\mathbf{z} da \quad (i, j = v, s, c \text{ and } p) \end{aligned}$$

$$\begin{aligned} \Delta C_{wood,1yr}(t) &= \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) \\ &+ B_s(\mathbf{z}, \mathbf{x}, a, t)] n_i(\mathbf{z}, \mathbf{x}, a, t) p_i(a, t) \lambda_{i,j}(a, t) [1 \\ &- \zeta_{res}(\mathbf{x}, i, j)] \eta_{1yr}(\mathbf{x}, i, j) d\mathbf{z} da \quad (i, j = v, s, c \text{ and } p) \end{aligned} \quad \text{Eq. S11.6}$$

$$\begin{aligned} \Delta C_{wood,10yr}(t) &= \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) \\ &+ B_s(\mathbf{z}, \mathbf{x}, a, t)] n_i(\mathbf{z}, \mathbf{x}, a, t) p_i(a, t) \lambda_{i,j}(a, t) [1 \\ &- \zeta_{res}(\mathbf{x}, i, j)] \eta_{10yr}(\mathbf{x}, i, j) d\mathbf{z} da \quad (i, j = v, s, c \text{ and } p) \end{aligned} \quad \text{Eq. S11.7}$$

$$\begin{aligned} \Delta C_{wood,100yr}(t) &= \int_0^\infty \int_0^\infty [B_a(\mathbf{z}, \mathbf{x}, a, t) \\ &+ B_s(\mathbf{z}, \mathbf{x}, a, t)] n_i(\mathbf{z}, \mathbf{x}, a, t) p_i(a, t) \lambda_{i,j}(a, t) [1 \\ &- \zeta_{res}(\mathbf{x}, i, j)] \eta_{100yr}(\mathbf{x}, i, j) d\mathbf{z} da \quad (i, j = v, s, c \text{ and } p) \end{aligned} \quad \text{Eq. S11.8}$$

458 Where  $C_{res,i}(t)$  is removed carbon that is allocated to soil litter pools.  $\Delta C_{wood,1yr}(t)$ ,  $\Delta C_{wood,10yr}(t)$  and  
 459  $\Delta C_{wood,100yr}(t)$  are removed carbon that is allocated to wood product pools with decay rates of 1-year, 10-year and  
 460 100-year, respectively. The coefficient  $\zeta_{res}(\mathbf{x}, i, j)$  is the carbon fraction left on-site;  $\eta_{1yr}(\mathbf{x}, i, j)$ ,  $\eta_{10yr}(\mathbf{x}, i, j)$  and  
 461  $\eta_{100yr}(\mathbf{x}, i, j)$  are the relative fractions entering each of the three wood product pools. The four coefficients are  
 462 differentiated among PFTs and between primary or secondary land (Table S10.2), the parameterization is based on  
 463 Hansis et al. 2015.

464

465 In addition to patch dynamics arising from land use transitions, cropland patches are routinely harvested and planted  
 466 on an annual basis, with planting and harvesting dates specified by an external crop calendar (Sacks et al. 2010).

467 Crop harvesting only leaves a limited number of plants in each patch to ensure reproduction in the following years,

468 removing all other plants. For pasture patches, grazing is routinely implemented to similarly remove a fraction of  
 469 plants from each pasture patch. The removed carbon from harvesting and grazing are given by:

$$C_{rem,c}(t) = \int_0^{\infty} \int_0^{\infty} [B_a(\mathbf{z}, \mathbf{x}, a, t) + B_s(\mathbf{z}, \mathbf{x}, a, t)][n_c(\mathbf{z}, \mathbf{x}, a, t) - n_{c,min}] dz da \quad \text{Eq. S11.9}$$

$$C_{rem,p}(t) = \int_0^{\infty} \int_0^{\infty} [B_a(\mathbf{z}, \mathbf{x}, a, t) + B_s(\mathbf{z}, \mathbf{x}, a, t)]n_p(\mathbf{z}, \mathbf{x}, a, t)\lambda_{graz\_inten} dz da \quad \text{Eq. S11.10}$$

470 Where  $n_{c,min}$  is the minimum density of crop plants that are retained post-harvest,  $\lambda_{graz\_inten}$  is the grazing  
 471 intensity which specifies the fraction of plants to be removed due to grazing.

472  
 473 The removed carbon is distributed to the product pools and soil carbon pool, the partitioning of which is given by:

$$C_{rem,c}(t) = \zeta_{res,c}C_{rem,c}(t) + (1 - \zeta_{res,c})C_{rem,c}(t) \quad \text{Eq. S11.11}$$

$$C_{rem,p}(t) = \zeta_{res,p}C_{rem,p}(t) + (1 - \zeta_{res,p})C_{rem,p}(t) \quad \text{Eq. S11.12}$$

474 In above two equations, the first term on the right-hand side of the equation represents on-site plant residuals on  
 475 cropland or pasture, respectively, these residuals will be loaded into soil litter pools. The second term represents the  
 476 removed carbon allocated to the product pools of harvested crop and grazed grass.  $\zeta_{res,c}$  and  $\zeta_{res,p}$  are the on-site  
 477 fraction coefficients, set at 0.5 for cropland and 0.1 for pasture.

478  
 479 Table S11.1. Land use transition types and their corresponding input variables from LUH1 and LUH2. Note *crops*  
 480 include C3 annual crops (c3ann), C4 annual crops (c4ann), C3 perennial crops (c3per), C4 perennial crops (c4per),  
 481 and C3 nitrogen-fixing crops (c3nfx). All transitions represent clearing type except primary land harvesting ( $\lambda_{v,s}$ )  
 482 and secondary land harvesting ( $\lambda_{s,s}$ ). Clearing and harvesting types have different parameterization for plant  
 483 removal (see Table S11.2).

Land use transition	LUH1	LUH2	Plant removal
$\lambda_{v,s}$	<i>gflvh, gflvh2</i>	<i>primf_harv, primn_harv</i>	Y
$\lambda_{v,c}$	<i>gflvc</i>	<i>primf_to_crops, primn_to_crops</i>	Y
$\lambda_{v,p}$	<i>gflvp</i>	<i>primf_to_pastr, primn_to_pastr</i> <i>primf_to_range, primn_to_range</i>	Y
$\lambda_{s,s}$	<i>gfsh1, gfsh2, gfsh3</i>	<i>secyf_harv, secmf_harv, secnf_harv</i>	Y
$\lambda_{s,c}$	<i>gfsc</i>	<i>secdf_to_crops, secdn_to_crops</i>	Y
$\lambda_{s,p}$	<i>gfisp</i>	<i>secdf_to_pastr, secdn_to_pastr</i> <i>secdn_to_range, secdn_to_range</i>	Y
$\lambda_{c,s}$	<i>gfics</i>	<i>crops_to_secdf, crops_to_secdn</i>	N
$\lambda_{c,p}$	<i>gficp</i>	<i>crops_to_pastr, crops_to_range</i>	N
$\lambda_{p,s}$	<i>gfips</i>	<i>pastr_to_secdf, pastr_to_secdn</i> <i>range_to_secdf, range_to_secdn</i>	N
$\lambda_{p,c}$	<i>gfipc</i>	<i>pastr_to_crops, range_to_crops</i>	Y

484  
 485 As Eq. S11.6, S11.7, S11.8, S11.11, and S11.12 show, carbon that is partially removed during land use transitions  
 486 will be allocated to the respective product (e.g., wood, crop, or grass). These pools decay with different rates, for



487 example, crop and grass pools are assumed to decay immediately, and are lost to the atmosphere as land use  
 488 emissions. However, wood product pools decay slowly over time with a rate following an exponential curve:

$$\frac{dC_{wood,nyr}(a,t)}{dt} = \Delta C_{wood,nyr}(t) + C_{wood,nyr}(a,t)e^{-\tau_{nyr}dt} \quad \text{Eq. S11.13}$$

489  
 490 Where  $C_{wood,nyr}$  is the  $nyr$  product pool ( $nyr=1yr, 10yr, \text{ or } 100yr$ ),  $\Delta C_{wood,nyr}(t)$  is newly loaded carbon due to  
 491 land use transitions,  $\tau_{nyr}$  is the coefficient governing the decay rate. This rate is currently set at -1.873, 0.187 and  
 492 0.018 for the three wood pools ( $C_{wood,1yr}$ ,  $C_{wood,10yr}$  and  $C_{wood,100yr}$ ) respectively, such that three pools reduce to  
 493 15% of their respective size within 1 year, 10 years, or 100 years. Decayed carbon from all of three wood product  
 494 pools contribute to land use emissions.

495  
 496 Table S11.2. Parameters for land use transitions involved in plant removals (i.e., Eq. S11.5-8)

Parameters	C4ShG	C3ShG	EaSBT, MiSBT, LaSBT		NSP, LaSC
			TRO	NTRO	
Harvesting on primary land					
$\eta_{1yr}(x, v, s)$	1.0	1.0	0.90	0.40	0.40
$\eta_{10yr}(x, v, s)$	0.0	0.0	0.04	0.24	0.24
$\eta_{100yr}(x, v, s)$	0.0	0.0	0.06	0.36	0.36
$\zeta_{res}(x, v, s)$	0.860	0.780	0.825	0.795	0.870
Harvesting on secondary land					
$\eta_{1yr}(x, s, s)$	1.0	1.0	0.90	0.40	0.40
$\eta_{10yr}(x, s, s)$	0.0	0.0	0.04	0.24	0.24
$\eta_{100yr}(x, s, s)$	0.0	0.0	0.06	0.36	0.36
$\zeta_{res}(x, s, s)$	0.810	0.700	0.750	0.725	0.820
Clearing					
$\eta_{1yr}(x, i, j)$	1.0	1.0	0.59	0.59	0.59
$\eta_{10yr}(x, i, j)$	0.0	0.0	0.41	0.31	0.31
$\eta_{100yr}(x, i, j)$	0.0	0.0	0.00	0.10	0.10
$\zeta_{res}(x, i, j)$	0.50	0.50	0.33	0.33	0.33

497  
 498  
 499

500 **Reference**

- 501
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