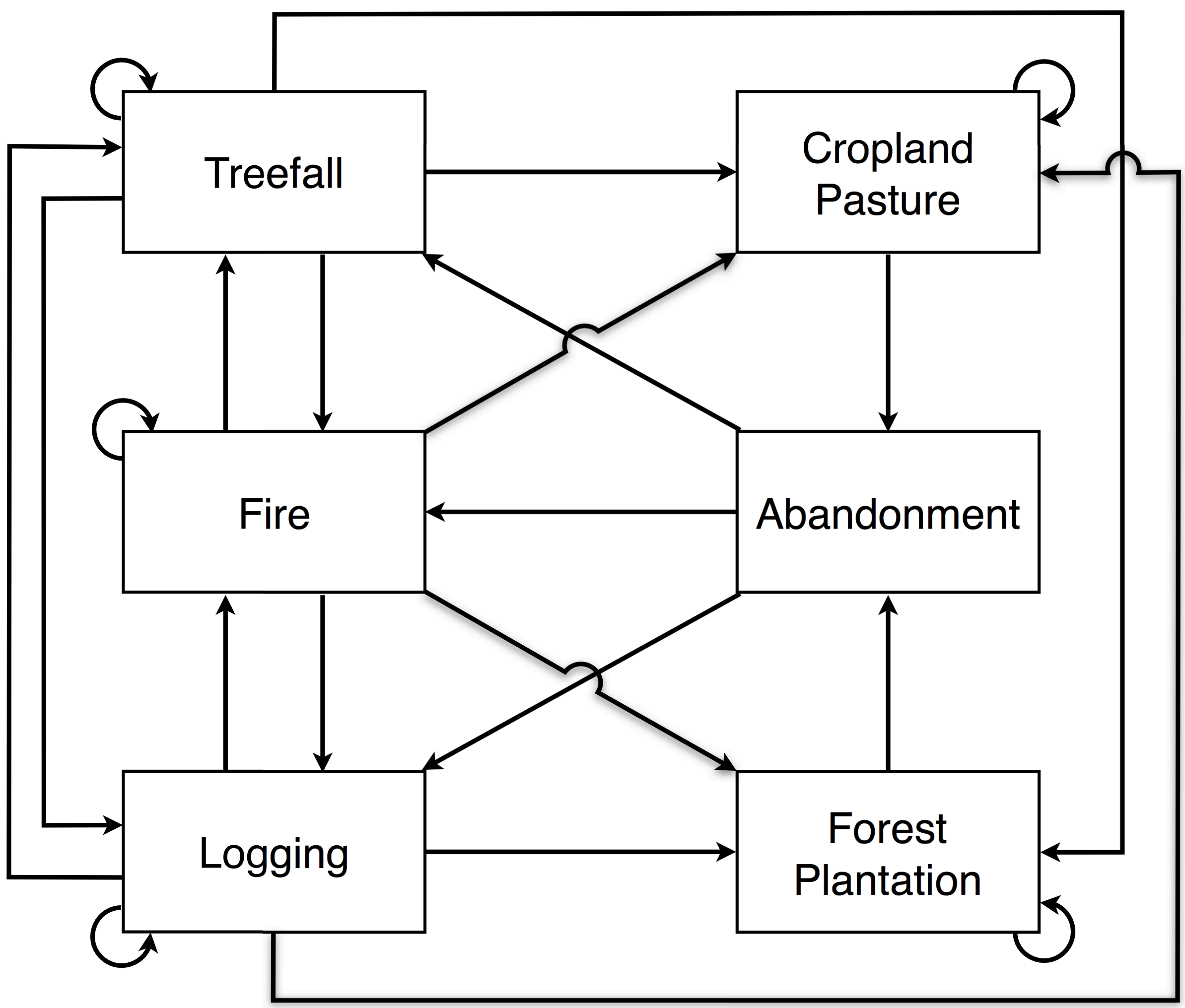

Figure S1: Schematics of disturbance types that generate new patches in ED-2.2. Patches are classified according to the last disturbance type (boxes), and new disturbances that create new patches are indicated by arrows (the arrow head points to the new disturbance type). The absence of arrows between some disturbance patches (e.g. from cropland to tree fall) indicate that such transition is not allowed. Arrows pointing to the same disturbance type indicate generation of new patches without change in the disturbance type.

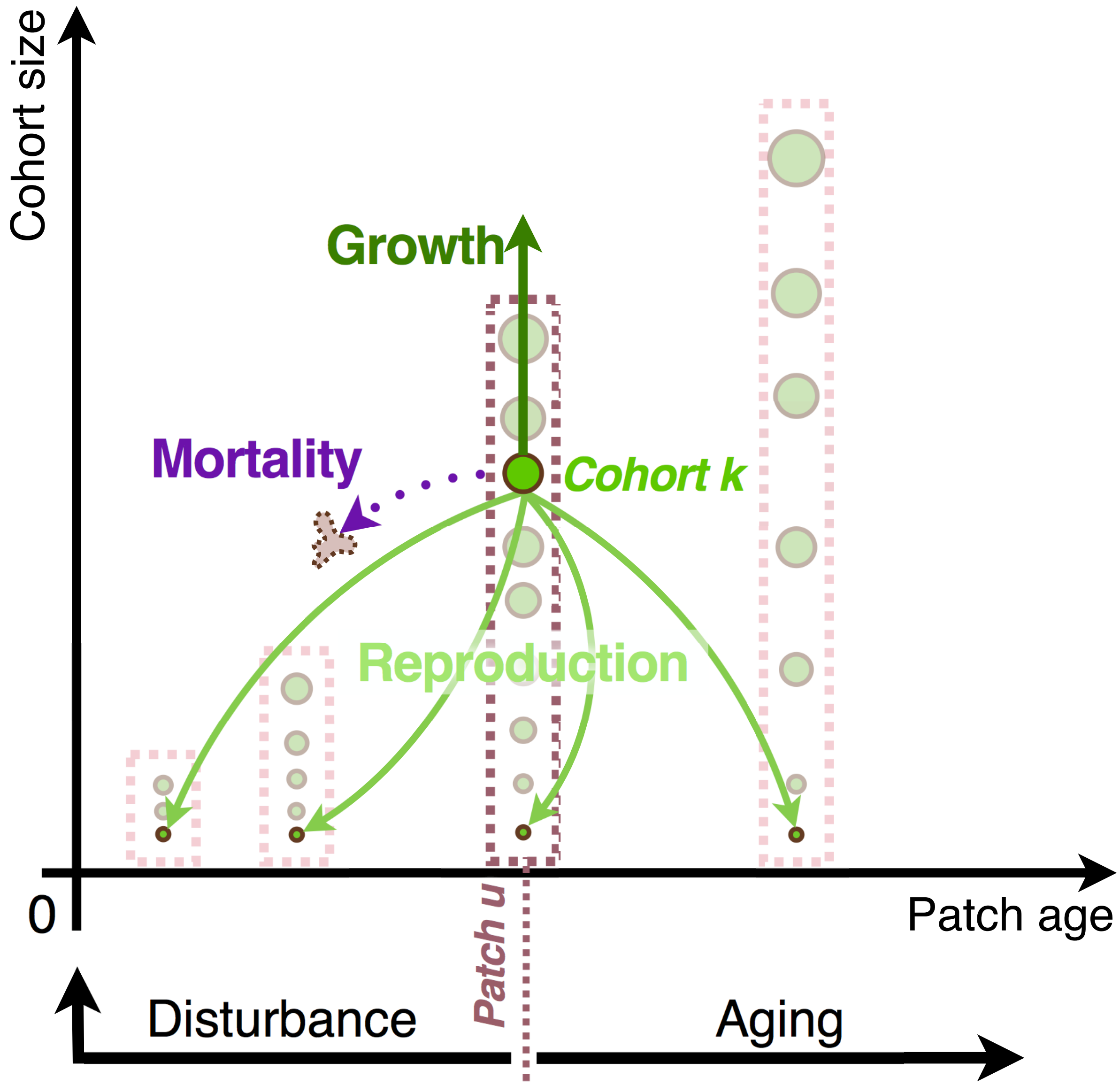

Figure S2: Schematics of ecosystem dynamics in ED-2.2, based on Fig. 5 of Moorcroft et al. (2001). The diagram shows a simplified case in which only of plant functional type and one disturbance type exist. Each dashed box corresponds to one patch, and each circle correspond to one cohort. Changes in the ecosystem structure are represented by arrows: grey arrows are associated with cohort dynamics, and black arrows are associated with patch dynamics. Every cohort time step, cohorts can grow in size, some of the cohort population is lost through mortality, and new cohorts are generated from reproduction. Every patch time step, patch age is increased linearly due to age, and a fraction of each patch is lost through disturbance, which resets patch age.

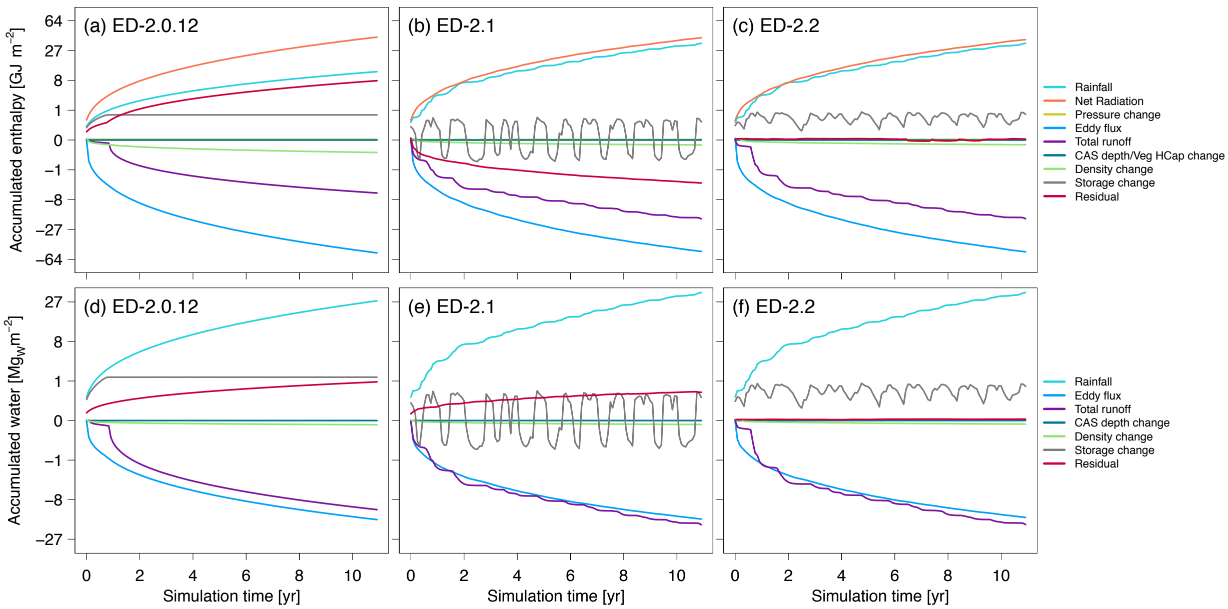

Figure S3: Comparison of budget closure for (a-c) enthalpy and (d-f) water between three different ED-2 versions: (a,d) ED-2.0.12 (`https://github.com/EDmodel/ED2/releases/tag/rev-12`), the first stable version of ED-2.0 (Medvigy et al., 2009) using the current model code structure; (b,e) ED-2.1 (`https://github.com/EDmodel/ED2/releases/tag/rev-64`); (c,f) ED-2.2. Simulations were carried out for a single-patch simulation at GYF for 11 years, without vegetation dynamics (earlier releases did not account for changes in energy and water when vegetation dynamics was active). Terms are presented as the cumulative contribution to the change storage. Total storage is the combination of canopy air space, cohorts, temporary surface water and soil layers. Positive (negative) values mean accumulation (loss) by the combined storage pool over the time. Pressure change accounts for changes in enthalpy when pressure from the meteorological forcing is updated, and density change accounts for changes in mass to ensure the ideal gas law. Canopy air space (CAS) change and vegetation heat capacity (Veg Hcap) change reflect the addition/subtraction of carbon, water, and enthalpy due to the vegetation dynamics modifying the canopy air space depth and the total heat capacity of the vegetation due to biomass accumulation or loss. Storage change is the net gain or loss of total storage, and residual corresponds to the deviation from the perfect closure. Note that we present the *y* axis in cube root scale to improve visualization of the smaller terms.

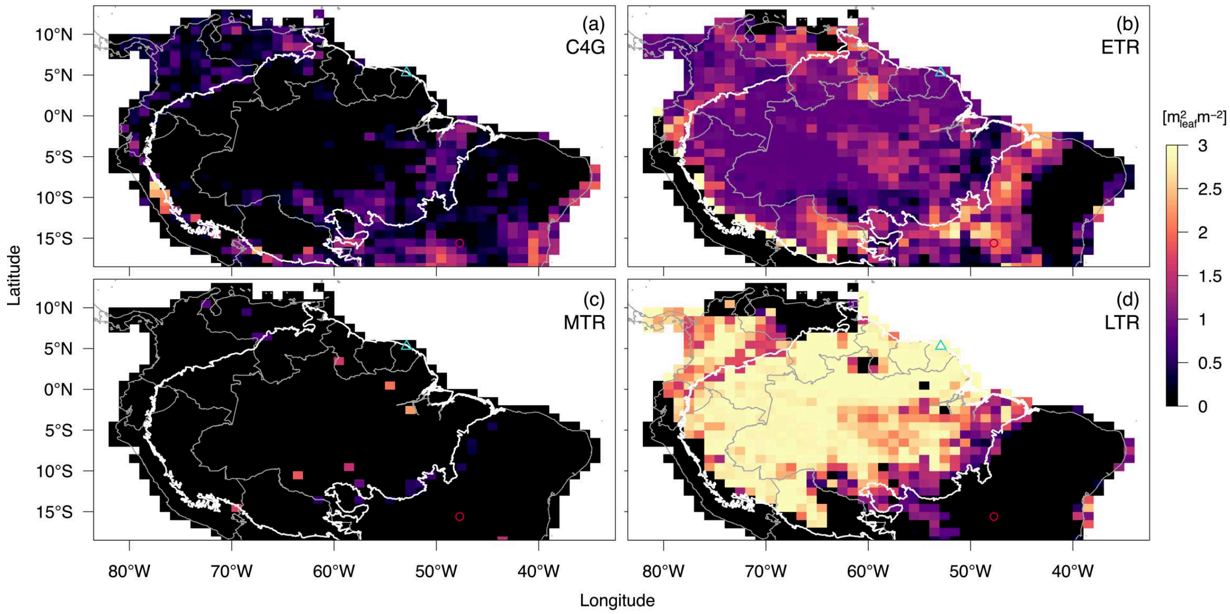

Figure S4: Simulated distribution of PFT-dependent leaf area index across tropical South America: (a) C_4 grasses (C4G); (b) Early-successional, tropical trees (ETR); (c) mid-successional, tropical trees (MTR); (d) late-successional, tropical trees (LTR). Maps were obtained from the final state of a 500-year simulation (1500–2000), initialized with near-bare ground conditions, active fires, and with prescribed land use changes between 1900 and 2000. Points indicate the location of the example sites (Fig. 8): (blue triangle) Paracou (GYF), a tropical forest site; (red circle) Brasília (BSB), a woody savanna site. White contour is the domain of the Amazon biome, and grey contours are the political borders.

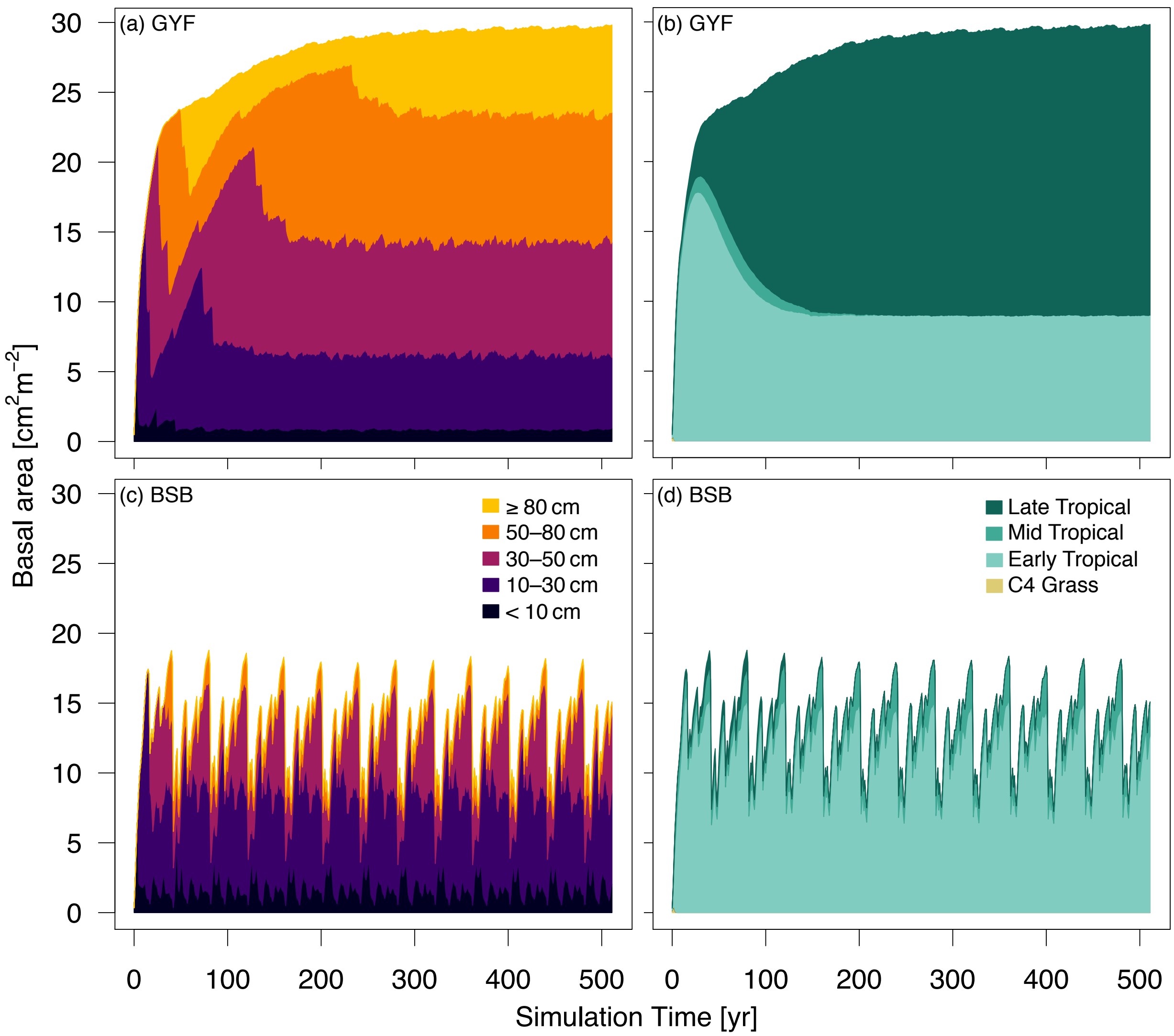

Figure S5: Simulated time series of basal area for near-bare ground simulations for (a,b) Paracou (GYF, tropical forest) and (c,d) Brasília (BSB, woody savanna), using local meteorological forcing and active fires, colored by the relative contribution of (a,c) plants of different sizes and (b,d) plants of different functional groups. See Fig. S4 for the location of both example sites.

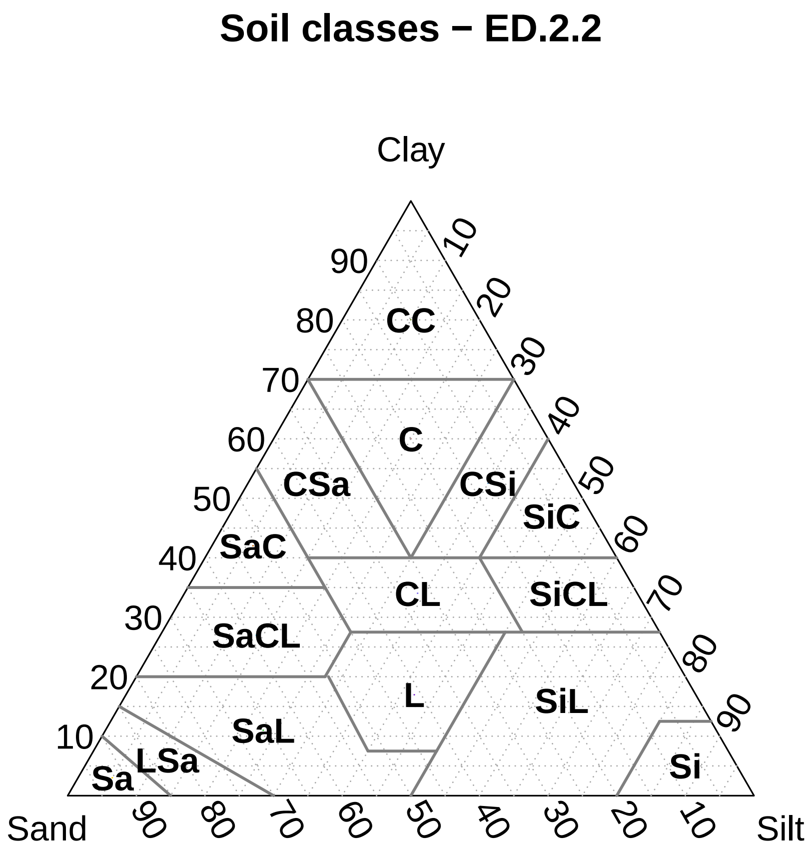

Figure S6: Barycentric diagram of volumetric percentage of soil particle sizes (sand, silt, and clay) along with the canonical soil texture classes in ED-2.2. Classes are: Sa – sand, LSa – loamy sand, SaL – sandy loam, SiL – silty loam, L – loam, SaCL – sandy clay loam, SiCL – silty clay loam, CL – clayey loam, SaC – sandy clay, SiC – silty clay, C – clay, Si – silt, CC – heavy clay, CSa – clayey sand, and CSi – clayey silt.

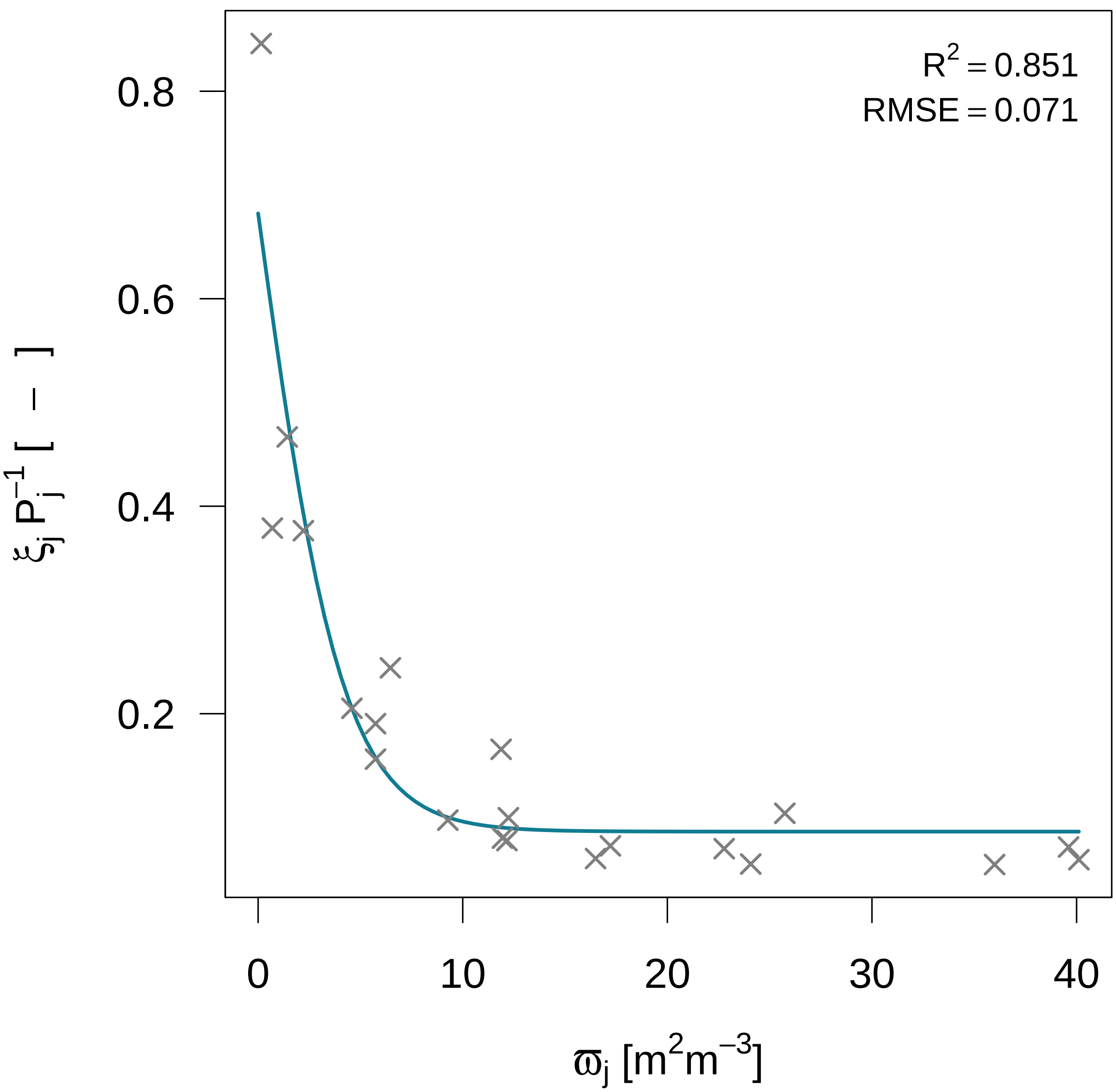

Figure S7: Fitted curve (Eq. S120) relating the effective drag coefficient ($\xi j/\mathcal{P}_j$) with plant area density (ϖ_j). Data points for fitting were extracted from Figure 3a of Wohlfahrt and Cernusca (2002) using a digitizer tool. Adjusted R^2 and the root mean square error (RMSE) are shown in the top right.

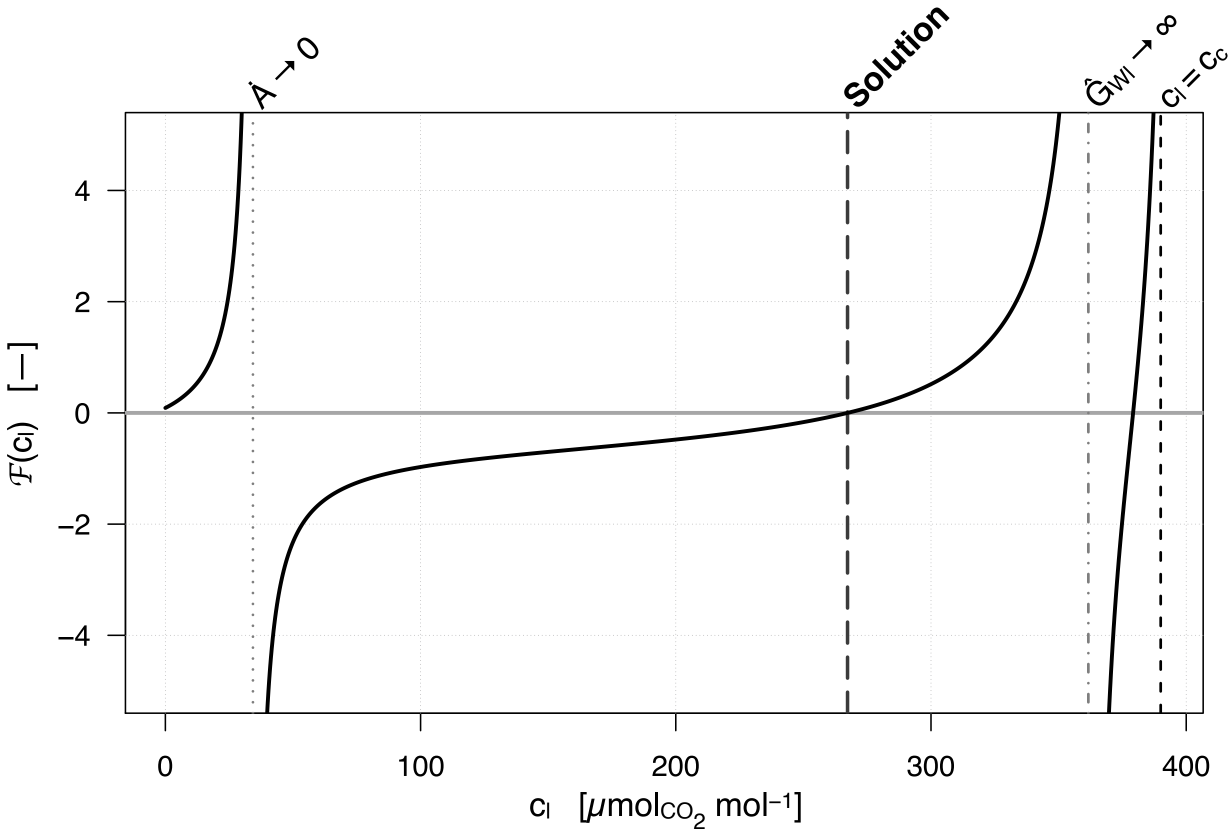

Figure S8: Example for the function $\mathcal{F}(c_{l_k})$ curve for the RuBP-saturated case for a mid-successional, tropical broadleaf tree when $\dot{Q}_{\mathrm{PAR}:a,l_k} = 100\,\mathrm{W\,m^{-2}}$, $T_{t_k} = T_c = 301.15\,\mathrm{K}$, $w_c = 0.017\,\mathrm{kg_W\,kg_{Air}^{-1}}$, $u_{t_k} = 0.25\,\mathrm{m\,s^{-1}}$, and $c_c = 390\,\mu\mathrm{mol_C\,mol_{Air}^{-1}}$. Vertical lines shows the solution and the singularities within the plausible range.

Table S1: List of subscripts used in the manuscript. Fluxes are denoted by a dotted letter, and two subscripts separated with a comma: $\dot{X}_{m,n}$. This means positive (negative) flux going from thermodynamic system m (n) to thermodynamic system n (m). N_T is the total number of cohorts, N_G is the total number of soil (ground) layers, N_S is the total number of temporary surface water/snowpack layers, and N_C is the total number of canopy air space layers, currently only used to obtain properties related to canopy conductance.

Subscript	Description
X_3	Property at the water's triple point ($T_3 = 273.16$ K)
X_a	Air above canopy, from the meteorological forcing
X_{b_k}	Branch wood of cohort k ($k \in \{1,2,\ldots,N_T\}$)
$X_{\mathbf{C}}$	Size vector (leaves, fine roots, sapwood, heartwood, and non-structural storage)
X_C	Carbon component
X_c	Canopy air space (single layer)
X_{c_j}	Canopy air space, layer j ($j \in \{1,2,\ldots,N_C\}$)
X_d	Non-water component of thermodynamic system
X_{e_j}	Necromass pools: e_1, metabolic litter (fast); e_2, structural debris (intermediate); e_3, humified/dissolved (slow)
X_f	Plant functional type
X_{Fc}	Soil property at field capacity
X_{Fr}	Soil property at critical moisture for fire ignition
X_{g_j}	Soil (ground), layer j ($j \in \{1,2,\ldots,N_G\}$)
X_{h_k}	Structural (heartwood) of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_i	Ice
$X_{i\ell}$	Ice-liquid phase transition
X_{iv}	Ice-vapor phase transition
X_j	Soil layer j ($j \in \{1,2,\ldots,N_G\}$), for variables that are only defined for soils
X_k	Cohort k ($k \in \{1,2,\ldots,N_T\}$), for variables that are only defined for cohorts
X_ℓ	Liquid water
$X_{\ell v}$	Liquid-vapor phase transition
X_{l_k}	Leaves of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{Ld}	Soil property at critical moisture for leaf shedding (drought-deciduous phenology)
X_m	Spectral band: $m = 1$, PAR; $m = 2$, NIR; $m = 3$, TIR
X_{n_k}	Non-structural carbon storage (starch, sugars) of cohort k
X_o	Runoff (drainage)
X_p	Property at constant pressure
X_{Po}	Soil property at soil porosity (water saturation)
X_q	Disturbance type
X_{r_k}	Roots of cohort k
X_{Re}	Soil property at residual soil moisture
X_{s_j}	Temporary surface water/snowpack, layer j ($j \in \{1,2,\ldots,N_S\}$)
X_{t_k}	Cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_U	Property associated with momentum (forced convection)
X_u	Patch u ($u \in \{1,2,\ldots,N_P\}$)
X_v	Water vapor
X_w	Water component of thermodynamic system (any phase)

Table S1: (Continued)

Subscript	Description
X_{Wp}	Soil property at permanent wilting point
X_x	West-East direction
$X_{\mathbf{x}}$	Horizontal direction
X_y	South-north direction
X_z	Vertical direction
X_{α_k}	Total living tissues (leaves, fine roots, sapwood) of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{β_k}	Branch boundary layer of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{Δ_k}	Carbon balance of cohort k ($k \in \{1,2,\ldots,N_T\}$)Q
X_{Θ}	Property associated with buoyancy (free convection)
X_{κ}	Soil textural component: $\kappa = 0$, water; $\kappa = 1$, sand; $\kappa = 2$, silt; $\kappa = 3$, clay
X_{λ_k}	Leaf boundary layer of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{ϱ_k}	Reproductive tissues (seeds, fruits, flowers, cones) of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{σ_k}	Sapwood of cohort k ($k \in \{1,2,\ldots,N_T\}$)
X_{∞}	Fluxes that depend on air above layer a, such as radiation and rainfall
$X_{\varnothing}$	Bare ground equivalent
$X_{\circledast}$	Pure, fresh snow

Table S2: List of variables used in this manuscript. For variables used in various thermodynamic systems, the subscript is omitted (see Table S1 for a comprehensive list of subscripts). Variable dimensions are shown in standard units for reference. Units with subscript are specific to a single substance: $\mathrm{kg_W}$ means kilograms of water, and $\mathrm{kg_C}$ means kilograms of carbon, and $\mathrm{kg_D}$ means kilogram of non-water material.

Variable	Description	Units
A	Site area	-
$\dot{A}$	Net leaf-level CO_2 uptake rate	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\mathcal{A}$	Mean leaf/branch inclination relative to horizontal plane	rad
a	Patch age since last disturbance	s
B	Soil carbon decay rates under optimal conditions	$\mathrm{s^{-1}}$
$\mathcal{B}_C$	Carbon to oven-dry biomass ratio	$\mathrm{kg_C\,kg_{Bio}^{-1}}$
$\mathcal{B}_W$	Water to oven-dry biomass ratio	$\mathrm{kg_W\,kg_{Bio}^{-1}}$
b	Slope of the logarithm of the water retention curve	-
BA	Basal area	$\mathrm{cm^2}$
C	Carbon mass (area-based, extensive)	$\mathrm{kg_C\,m^{-2}}$
$\mathbf{C}$	Size (carbon mass) vector	$\mathrm{kg_C\,plant^{-1}}$
$\mathcal{C}$	Empirical coefficients for determining biomass of individual tissues	-
$C^{\bullet}$	Expected carbon mass given size, PFT, and demographic density	$\mathrm{kg_C\,m^{-2}}$
$C^{\circledcirc}$	Carbon mass needed to bring tissue to allometry given size and PFT	$\mathrm{kg_C\,m^{-2}}$
$\dot{C}$	Carbon flux	$\mathrm{kg_C\,m^{-2}\,s^{-1}}$
$\dot{C}^{\star}$	Carbon flux to necromass pools due to mortality	$\mathrm{kg_C\,m^{-2}\,s^{-1}}$
c	Carbon mixing ratio (intensive)	$\mathrm{mol_C\,mol^{-1}}$
D	"Dry material" mass (area-based, extensive)	$\mathrm{kg_D\,m^{-2}}$
$\mathcal{D}$	"Dry material" mass (volume-based, extensive)	$\mathrm{kg_D\,m^{-3}}$
d	Specific mass of "dry material" (intensive)	$\mathrm{kg_D\,kg^{-1}}$
DBH	Diameter at breast height	cm
$Đ$	Auxiliary variable for solution of canopy radiation transfer	-
$\eth$	Sub-surface drainage impediment parameter	-
E	Average projection of leaves and branches onto the horizontal	-
$\dot{E}$	Leaf-level transpiration rate	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\mathcal{E}$	Penalty reduction function for extreme temperatures and soil moistures	-
Ein	Average photon specific energy in the PAR band	$\mathrm{J\,mol^{-1}}$
e_l	Leaf elongation factor given environmental constrains	-
$\mathcal{F}$	Dimensionless function of intercellular carbon dioxide	-
f_{AG}	Fraction of woody biomass that is above ground	-
f_{Clump}	Clumping factor	-
f_{Gl}	Ratio between stomatal conductance of CO_2 and water	-
$f_{G\lambda}$	Ratio between leaf boundary layer conductance of CO_2 and water	-
f_h	Fraction of the decay of soil carbon pools that are respired	-
f_{LD}	Fraction of carbon reabsorption before leaf shedding	-
f_{lw}	Down-regulation factor for photosynthesis due to soil moisture limitation	-
f_R	Ratio between day respiration and maximum carboxylation	-
f_r	Ratio between fine root and leaf biomass on allometry given size and PFT	-
f_{TSW}	Fraction of ground covered by water or snow	-
$f_{\mathcal{V}}$	Volumetric fraction	-

Table S2: (Continued)

Variable	Description	Units
f_δ	Fraction of reproduction that is randomly dispersed	–
f_σ	Scaling factor between height, sapwood, and leaf biomass on allometry	$\mathrm{m^{-1}}$
G	Conductance (rate form)	$\mathrm{m\,s^{-1}}$
$\hat{G}$	Conductance (flux form)	$\mathrm{kg\,m^{-2}\,s^{-1}}$ or $\mathrm{mol\,m^{-2}\,s^{-1}}$
g	Gravity acceleration	$\mathrm{m\,s^{-2}}$
$\mathbf{g}$	Net growth rate	$\mathrm{kg_C\,plant^{-1}\,s^{-1}}$
Gr	Grashof number	–
H	Enthalpy (area-based, extensive)	$\mathrm{J\,m^{-2}}$
$\dot{H}$	Enthalpy flux associated with mass flux	$\mathrm{W\,m^{-2}}$
h	Specific enthalpy (intensive)	$\mathrm{J\,kg^{-1}}$
$\tilde{h}$	Specific enthalpy at reference height	$\mathrm{J\,kg^{-1}}$
$\mathcal{I}$	Fire intensity parameter	$\mathrm{s^{-1}}$
i	Fraction of water in solid phase (ice)	–
K	Eddy diffusivity	$\mathrm{m^2\,s^{-1}}$
$\mathcal{K}_\mathrm{C}$	Michaelis constant for carboxylation	$\mathrm{mol_C\,mol^{-1}}$
$\mathcal{K}_\mathrm{ME}$	Effective Michaelis constant	$\mathrm{mol_C\,mol^{-1}}$
$\mathcal{K}_\mathrm{O}$	Michaelis constant for oxygenation	$\mathrm{mol_{O_2}\,mol^{-1}}$
k_PEP	Slope of CO_2-limited carboxylation rate	$\mathrm{mol\,mol_C^{-1}}$
$\mathcal{L}$	Obukhov length scale	m
l	Specific latent heat	$\mathrm{J\,kg^{-1}\,K^{-1}}$
$l_{i\ell 3}$	Specific latent heat of fusion at triple point temperature	$\mathrm{J\,kg^{-1}\,K^{-1}}$
l_{iv3}	Specific latent heat of sublimation at triple point temperature	$\mathrm{J\,kg^{-1}\,K^{-1}}$
ℓ	Fraction of water in liquid phase	–
$\pounds$	Fraction of living tissues that are lignified	–
M	Slope of stomatal conductance function	–
$\mathcal{M}$	Molar mass	$\mathrm{kg\,mol^{-1}}$
MCWD	Maximum cumulative water deficit	mm
m	Mortality rate	$\mathrm{s^{-1}}$
n	Cohort demographic density	$\mathrm{plant\,m^{-2}}$
N_C	Number of canopy air space layers	–
N_F	Number of plant functional types	–
N_G	Number of soil layers	–
N_P	Number of patches	–
N_Q	Number of disturbance types	–
N_S	Actual number of temporary surface water layers	–
N_S^max	Maximum number of temporary surface water layers	–
N_T	Number of cohorts	–
$N_{T(\mathrm{canopy})}$	Number of canopy cohorts	–
Nu	Nusselt number	–
$\mathcal{O}$	Open canopy fraction	–
o	Oxygen mixing ratio	$\mathrm{mol_{O_2}\,mol^{-1}}$
$\mathcal{P}$	Sheltering factor for momentum	–
p	Atmospheric pressure	Pa
$p_{vi}^{\equiv}$	Saturation pressure: vapor-ice	Pa
$p_{v\ell}^{\equiv}$	Saturation pressure: vapor-liquid	Pa

Table S2: (Continued)

Variable	Description	Units
Pr	Prandtl number	–
$\dot{Q}$	Heat flux (no mass exchange involved)	$\mathrm{W\,m^{-2}}$
$\dot{Q}^{\odot}$	Downward direct irradiance	$\mathrm{W\,m^{-2}}$
$\dot{Q}^{\Downarrow}$	Downward hemispheric diffuse irradiance	$\mathrm{W\,m^{-2}}$
$\dot{Q}^{\Uparrow}$	Upward hemispheric diffuse irradiance	$\mathrm{W\,m^{-2}}$
$\dot{Q}^{\blacklozenge}$	Irradiance emitted by black body	$\mathrm{W\,m^{-2}}$
$\mathcal{Q}_{10}$	Temperature coefficient for temperature-response function	–
$\dot{q}^{\mathrm{PAR}}$	Photon flux absorbed by leaves	$\mathrm{W\,m_{Leaf}^{-2}}$
q	Specific heat (intensive)	$\mathrm{J\,kg^{-1}}$
$q^{(\mathrm{OD})}$	Specific heat of oven-dry tissue (intensive)	$\mathrm{J\,kg^{-1}}$
q_p	Specific heat at constant pressure (intensive)	$\mathrm{J\,kg^{-1}}$
$\dot{R}$	Leaf-level dark respiration rate	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\mathcal{R}$	Gas constant for typical air	$\mathrm{J\,mol^{-1}\,K^{-1}}$
r	Decay rate associated with root respiration	$\mathrm{s^{-1}}$
Re	Reynolds number	–
Ri_B	Bulk Richardson number	–
S	Elements of the flux matrix for solving the canopy radiation transfer model	–
$\mathbf{S}$	Flux matrix for solving the canopy radiation transfer model	–
$\mathcal{S}$	Above-canopy velocity variance to momentum flux ratio	–
SLA	Specific leaf area	$\mathrm{m_{Leaf}^{2}\,kg_C^{-1}}$
s_g	Soil wetness function for ground evaporation	–
s_l	Soil wetness function for drought-deciduous phenology	–
$ß$	Joint eddy mixing length scale (shear- and wake-driven turbulence)	–
T	Temperature	K
T_3	Temperature of water triple point	K
$T_{\ell 0}$	Zero-energy temperature of supercooled liquid water	K
T_{v0}	Zero-energy temperature of supercooled water vapor	K
$T_{\mathcal{V}}$	Virtual temperature	K
$\mathcal{T}$	Temperature coefficient function ($\mathcal{Q}_{10}$ function)	–
$\mathcal{T}'$	Penalty reduction function for extreme temperatures	–
t	Time	s
t_{Runoff}	Runoff decay time	s
TKE	(Specific) Turbulent kinetic energy	$\mathrm{m^2\,s^{-2}}$
Þ	Auxiliary variable for solution of canopy radiation transfer	–
þ	Number of leaf sides with stomata	–
$\dot{U}$	Momentum flux	$\mathrm{kg\,m^{-1}\,s^{-2}}$
$u_{\mathbf{x}}$	Horizontal wind speed	$\mathrm{m\,s^{-1}}$
u_z	Vertical wind velocity	$\mathrm{m\,s^{-1}}$
$u^{\star}$	Friction velocity	$\mathrm{m\,s^{-1}}$
$\dot{V}_C$	Leaf-level carboxylation rates	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\dot{V}_C^{\mathrm{RuBP}}$	RuBP-saturated carboxylation rates	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\dot{V}_C^{\mathrm{CO_2}}$	CO_2-limited carboxylation rate	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\dot{V}_C^{\mathrm{PAR}}$	Light-limited carboxylation rate	$\mathrm{mol_C\,m_{Leaf}^{-2}\,s^{-1}}$
$\dot{V}_O$	Leaf-level oxygenation (photorespiration) rate	$\mathrm{mol_{O_2}\,m_{Leaf}^{-2}\,s^{-1}}$
$\mathcal{V}$	Volume	$\mathrm{m^3}$
v	Fraction of water in gas phase (water vapor)	–

Table S2: (Continued)

Variable	Description	Units
W	Water mass (area-based, extensive)	$\mathrm{kg_W\,m^{-2}}$
$\dot{W}$	Water flux	$\mathrm{kg_W\,m^{-2}\,s^{-1}}$
$\mathcal{W}$	Water mass (volume-based, extensive)	$\mathrm{kg_W\,m^{-3}}$
w	Specific humidity (intensive)	$\mathrm{kg_W\,kg^{-1}}$
$w^{\equiv}$	Saturation specific humidity (intensive)	$\mathrm{kg_W\,kg^{-1}}$
$\hat{w}_{\mathrm{max}}$	Cohort water holding capacity of rainfall interception, dew and frost	$\mathrm{kg_W\,m^{-2}_{Leaf+Wood}}$
X	Crown area index	$\mathrm{m^2_{Crown}\,m^{-2}}$
$x^{\star}$	Characteristic dimension for boundary-layer generating obstacle	m
Y	Auxiliary functions, used only in the sections where they are described	–
$\mathcal{Y}$	Boolean variable controlling fire ignition	–
y	Auxiliary constants, used only in the sections where they are described	–
Z	Zenith distance	rad
z	Height ($z > 0$) or depth ($z < 0$)	m
$z^{\star}$	Height above displacement height	m
z^{-}	Height of crown base	m
z_0	Roughness length	m
z_d	Displacement height	m
α	Probability distribution of gap ages	–
β	Backscattering coefficient, diffuse irradiance	–
$\beta^{\odot}$	Backscattering coefficient, direct irradiance	–
Γ	CO_2 compensation point	$\mathrm{mol_C\,mol^{-1}}$
γ	Growth rate	$\mathrm{s^{-1}}$
Δt	Time step	s
Δw	Stomatal conductance control on severe leaf-level water vapor deficit	$\mathrm{kg_W\,kg^{-1}}$
Δz	Layer thickness	m
δ_{ij}	Kronecker delta (1 if $i = j$, 0 otherwise)	–
ϵ	Quantum yield	–
ε	Thermal dilatation coefficient	$\mathrm{K^{-1}}$
F	Coefficients for generic function of CO_2 uptake rate (Table S8)	–
ζ	Dimensionless Obukhov length	–
ζ_0	Dimensionless roughness length	–
η	Thermal diffusivity of air	$\mathrm{m^2\,s^{-1}}$
θ	Potential temperature	K
$\theta_{\mathcal{V}}$	Virtual potential temperature	K
$\theta^{\star}_{\mathcal{V}}$	Characteristic scale: Virtual potential temperature	K
ϑ	Volumetric soil moisture	$\mathrm{m^3_W\,m^{-3}}$
ι_U	Turbulence intensity	–
κ	von Kármán constant	–
$\varkappa$	Auxiliary variable for solution of canopy radiation transfer	–
Λ	Leaf area index	$\mathrm{m^2_{Leaf}\,m^{-2}}$
λ	Disturbance rate	$\mathrm{s^{-1}}$
μ	Inverse of optical depth per unit of plant area index	$\mathrm{m^2_{Plant}\,m^{-2}}$
$\mu^{\odot}$	Same as above, specific for direct radiation	$\mathrm{m^2_{Plant}\,m^{-2}}$
$\overline{\mu}$	Same as above, specific for diffuse radiation	$\mathrm{m^2_{Plant}\,m^{-2}}$
ν	Kinematic viscosity	$\mathrm{m^2\,s^{-1}}$
Ξ	Cumulative cohort drag area per unit ground area	$\mathrm{m^2_{Plant}\,m^{-2}}$

Table S2: (Continued)

Variable	Description	Units
ξ	Drag coefficient	–
Π	Total plant area index	$m^2_{Plant}\,m^{-2}$
$\tilde{\Pi}$	Clump-corrected, effective total plant area index	$m^2_{Plant}\,m^{-2}$
ϖ	Plant area density	$m^2_{Plant}\,m^{-3}$
ρ	Density	$kg\,m^{-3}$
ϱ	Recruitment rate	s^{-1}
$\hat{\sigma}$	Survivorship fraction following disturbance	–
σ_{SB}	Stefan-Boltzmann constant	$W\,m^{-2}\,K^{-4}$
σ_u	Standard deviation of wind speed	$m\,s^{-1}$
ς	Scattering coefficient, diffuse irradiance	–
$\varsigma^{\odot}$	Scattering coefficient, direct irradiance	–
ς_R	Reflectance coefficient	–
ς_T	Transmittance coefficient	–
τ	Turnover rate (active tissues or non-structural carbon)	s^{-1}
Υ_Q	Thermal conductivity	$W\,m^{-1}\,K^{-1}$
Υ_Ψ	Hydraulic conductivity	$m\,s^{-1}$
ϕ	Oxygenase:Carboxylase ratio	$mol_{O_2}\,molC^{-1}$
φ_U	Dimensionless stability function of momentum (eddy flux)	–
φ_Θ	Dimensionless stability function of heat (eddy flux)	–
χ	Mean orientation factor	–
Ψ	Soil matric potential	m
ψ_U	Dimensionless flux profile function of momentum (eddy flux)	–
ψ_Θ	Dimensionless flux profile function of heat (eddy flux)	–
Ω	Branch wood area index	$m^2_{Wood}\,m^{-2}$
ω	Leaf shedding rate	s^{-1}

Table S3: List of universal (physical) constants used in ED-2.2. For parameters that can be constrained and optimized, refer to Tables S4 (global) and S5 (PFT-dependent).

Symbol	Value	Description
Ein	$2.17 \cdot 10^{-5}\ \mathrm{J\,mol^{-1}}$	Average photon specific energy in the PAR band
g	$9.807\ \mathrm{m\,s^{-2}}$	Gravity acceleration
$\mathcal{M}_C$	$1.201 \cdot 10^{-2}\ \mathrm{kg\,mol^{-1}}$	Molar mass of carbon
$\mathcal{M}_d$	$2.897 \cdot 10^{-2}\ \mathrm{kg\,mol^{-1}}$	Molar mass of dry air
$\mathcal{M}_w$	$1.802 \cdot 10^{-2}\ \mathrm{kg\,mol^{-1}}$	Molar mass of water
$l_{i\ell 3}$	$3.34 \cdot 10^{5}\ \mathrm{J\,kg^{-1}}$	Specific latent heat of melting at the water triple point
l_{iv3}	$l_{i\ell 3} + l_{\ell v3}$	Specific latent heat of sublimation at the water triple point
$l_{\ell v3}$	$2.50 \cdot 10^{6}\ \mathrm{J\,kg^{-1}}$	Specific latent heat of vaporization at the water triple point
$o_{\oplus}$	$0.209\ \mathrm{mol_{O_2}\,mol^{-1}}$	Reference oxygen mixing ratio
p_0	$10^{5}\ \mathrm{Pa}$	Reference pressure for potential temperature
q_i	$2093\ \mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of ice
q_ℓ	$4186\ \mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of liquid water
q_{pd}	$1005\ \mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of dry air at constant pressure
q_{pv}	$1859\ \mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of water vapor at constant pressure
$\mathcal{R}$	$8.315\ \mathrm{J\,mol^{-1}\,K^{-1}}$	Ideal gas constant
T_0	$273.15\ \mathrm{K}$	Zero degrees Celsius
T_3	$273.16\ \mathrm{K}$	Water triple point
κ	0.40	von Kármán constant
ρ_ℓ	$1000\ \mathrm{kg\,m^{-3}}$	Density of liquid water
$\rho_{\circledast}$	$100\ \mathrm{kg\,m^{-3}}$	Density of fresh snow
σ_{SB}	$5.67 \cdot 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$	Stefan-Boltzmann constant
$\Upsilon_{\mathrm{Q}_\ell}$	$0.57\ \mathrm{W\,m^{-1}\,K^{-1}}$	Thermal conductivity of liquid water

Table S4: List of default values for global parameters used in ED-2.2. Soil carbon parameters $x_{\mathbf{e}}$ are shown as vectors $(x_{e_1};x_{e_2};x_{e_3})$ corresponding to the fast, intermediate, and slow pools, respectively. Optical parameters are shown as vectors $(x_{\mathrm{PAR}};x_{\mathrm{NIR}};x_{\mathrm{TIR}})$ corresponding to the photosynthetically active (PAR), near infrared and thermal infrared bands, respectively. For default PFT-specific parameters, refer to Table S5; physical constants are listed in Table S3.

Symbol	Value	Description
$B_{\mathbf{e}}$	$(11.0;4.5;0.2)\ \mathrm{yr}^{-1}$	Optimal decay rates of soil carbon pools
$\mathcal{B}_C$	$0.5\ \mathrm{kg_C\,kg_{Bio}^{-1}}$	Carbon:oven-dry-biomass ratio
e_{Cold}	0.24	Decay parameter for decomposition at cold temperatures
e_{Dry}	0.60	Decay parameter for decomposition at dry conditions
e_{Hot}	12.0	Decay parameter for decomposition at hot temperatures
e_{Wet}	36.0	Decay parameter for decomposition at wet conditions
f_{Gl}	1.6	Water:CO_2 diffusivity ratio
$f_{G\lambda}$	1.4	Water:CO_2 leaf-boundary-layer conductance ratio
$f_{h\mathbf{e}}$	$(1.0;0.3;1.0)$	Fraction of decay due to heterotrophic respiration
f_{LD}	0.5	Fraction of carbon retained by plants when shedding leaves
$\mathcal{I}$	$0.5\ \mathrm{yr}^{-1}$	Fire intensity parameter
$\mathcal{K}_{C_{15}}$	$214.2\ \mu\mathrm{mol_{CO_2}\,mol^{-1}}$	Michaelis constant for carboxylation at 15 °C
$\mathcal{K}_{O_{15}}$	$0.2725\ \mathrm{mol_{O_2}\,mol^{-1}}$	Michaelis constant for oxygenation at 15 °C
k_{PEP}	$17949\ \mathrm{mol_{Air}\,mol_{CO_2}^{-1}}$	Initial slope for the PEP carboxylase (C_4 photosynthesis)
Pr	0.74	Prandtl number
$\mathcal{Q}_{10}\,(\mathcal{K}_C)$	2.1	Temperature factor for Michaelis constant (carboxylation)
$\mathcal{Q}_{10}\,(\mathcal{K}_O)$	1.2	Temperature factor for Michaelis constant (oxygenation)
$\mathcal{Q}_{10}\,(\phi)$	0.57	Temperature factor for carboxylase:oxygenase ratio
$T_{g\mathrm{Cold}}$	291.15 K	Temperature threshold for decomposition at cold temperatures
$T_{g\mathrm{Hot}}$	318.15 K	Temperature threshold for decomposition at hot temperatures
t_{Runoff}	3600 s	E-folding Decay time for surface runoff
$\hat{w}_{\max}$	$0.11\ \mathrm{kg_W\,m_{Leaf+Wood}^{2}}$	Water holding capacity
$z_{0\varnothing}$	0.01 m	Roughness length of bare soil
z_{Fr}	-0.50 m	Soil depth used to evaluate fuel dryness
λ_{TF}	$0.014\ \mathrm{yr}^{-1}$	Tree fall disturbance rate
$\vartheta'_{\mathrm{Dry}}$	0.48	Relative moisture threshold for decomposition at dry conditions
$\vartheta'_{\mathrm{Wet}}$	0.98	Relative moisture threshold for decomposition at wet conditions
$\overline{\mu}_s$	0.05 m	Inverse of the optical depth of temporary surface water
ς_{3g}	0.02	Scattering coefficients (thermal infrared) for bare soil
$\varsigma_{R_s}^{\circledast}$	$(0.518;0.435;0.030)$	Reflectance coefficients (thermal infrared) for pure snow
ϕ_{15}	4561	Carboxylase:oxygenase ratio at 15 °C
$\tilde{\psi}_0$	0.190	Flux profile function of momentum at roughness height

Table S5: List of default parameters that depend on plant functional type (PFT) used in ED-2.2 and described in the text. The PFTs are C_4 tropical grass (C4G), C_3 tropical grass (C3G); early successional tropical tree (ETR); mid-successional tropical tree (MTR); late-successional tropical tree (LTR). Spectral-dependent parameters x are provided as vectors $(x_{\mathrm{PAR}};x_{\mathrm{NIR}};x_{\mathrm{TIR}})$, corresponding to the visible (photosynthetically active), nearinfrared, and thermal infrared, respectively. The default parameters for temperate PFTs are the same as Medvigy et al. (2009). The values of constants and default global parameters are shown in Table S3.

Symbol	PFT-specific value					Units	Description
	C4G	C3G	ETR	MTR	LTR		
$\mathcal{B}_{Wl}$	0.7	0.7	0.7	0.7	0.7	-	Water:oven-dry-biomass ratio for leaves
$\mathcal{B}_{Wb}$	1.85	1.85	1.85	1.85	1.85	-	Water:oven-dry-biomass ratio for wood
$\mathcal{C}_{0l}$	0.158	0.158	0.418	0.560	0.701	-	Scaling coefficient for leaf biomass allometry
$\mathcal{C}_{1l}$	0.975	0.975	0.975	0.975	0.975	-	Exponent coefficient for leaf biomass allometry
$\mathcal{C}_{0h}$	0.0627	0.0627	0.166	0.222	0.282	-	Scaling coefficient for heartwood biomass allometry (sub-canopy)
$\mathcal{C}_{1h}$	2.432	2.432	2.432	2.432	2.432	-	Exponent coefficient for heartwood biomass allometry (sub-canopy)
$\mathcal{C}_{2h}$	0.0647	0.0647	0.172	0.230	0.291	-	Scaling coefficient for heartwood biomass allometry (canopy)
$\mathcal{C}_{3h}$	2.426	2.426	2.426	2.426	2.426	-	Exponent coefficient for heartwood biomass allometry (canopy)
f_{AG}	0.70	0.70	0.70	0.70	0.70	-	Fraction of above-ground biomass
f_{Cold}	0.40	0.40	0.40	0.40	0.40	-	Decay parameter to down-regulate metabolism at cold temperatures
f_{Clump}	1.00	1.00	0.80	0.80	0.80	-	Clumping index
f_{Hot}	0.40	0.40	0.40	0.40	0.40	-	Decay parameter to down-regulate metabolism at hot temperatures
f_n	0.00	0.00	0.10	0.10	0.10	-	Fraction of carbon storage retained in storage pool
f_r	1.00	1.00	1.00	1.00	1.00	-	Fine-root:leaf biomass ratio
f_R	0.035	0.015	0.015	0.015	0.015	-	Respiration:carboxylation ratio
f_ϱ	1.0	1.0	0.30	0.30	0.30	-	Fraction of carbon allocation to reproduction at maturity
f_σ	3900	3900	3900	3900	3900	$m^3\,kg_C^{-1}$	Sapwood:leaf biomass scaling factor
$\hat{G}_{lw}^{\varnothing}$	0.1	0.1	0.1	0.1	0.1	$\mathrm{mol\,m^{-2}\,s^{-1}}$	Residual conductance (closed stomata)
$\hat{G}_r$	900	900	600	600	600	$\mathrm{m^2\,kg_C^{-1}\,yr^{-1}}$	Scaling factor for fine root conductance
$£_h$	1.0	1.0	1.0	1.0	1.0	-	Fraction of lignified tissues (sapwood and hardwood)

Table S5: (Continued)

Symbol	PFT-specific value					Units	Description
	C4G	C3G	ETR	MTR	LTR		
$\pounds_l$	0.0	0.0	0.0	0.0	0.0	-	Fraction of lignified tissues (leaves and fine roots)
M	7.2	9.0	9.0	9.0	9.0	-	Slope factor for stomatal conductance
m_ϱ	0.95	0.95	0.95	0.95	0.95	mo^{-1}	Loss rate of reproductive tissues
$\mathcal{Q}_{10}(\dot{V}_C)$	2.40	2.40	2.40	2.40	2.40	-	Temperature dependence factor for carboxylation rate
$\mathcal{Q}_{10}(r_r)$	2.40	2.40	2.40	2.40	2.40	-	Temperature dependence factor for fine root respiration
$q_l^{(\mathrm{OD})}$	3218	3218	3218	3218	3218	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of oven-dry leaf biomass
$q_b^{(\mathrm{OD})}$	1217	1217	1217	1217	1217	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat of oven-dry wood biomass
$r_{r_{15}}$	0.246	0.246	0.246	0.246	0.246	$\mathrm{s^{-1}}$	Fine-root respiration rate at 15 °C
SLA	22.70	22.70	16.02	11.65	9.66	$\mathrm{m^2\,kg_C^{-1}}$	Specific leaf area
T_{Cold}	288.15	283.15	283.15	283.15	283.15	K	Cold temperature threshold for metabolic activity
T_F	275.65	275.65	275.65	275.65	275.65	K	Temperature threshold for plant hardiness to frost
T_{Hot}	318.15	318.15	318.15	318.15	318.15	K	Hot temperature threshold for metabolic activity
$\flat$	1	1	1	1	1	-	Number of sides of leaf with stomata
$\dot{V}_{C_{15}}^{\max}$	12.5	18.75	18.75	12.5	6.25	$\mu\mathrm{mol_C\,m^{-2}\,s^{-1}}$	Maximum carboxylation rate at 15 °C
$x_\beta^\star$	0.05	0.05	0.05	0.05	0.05	m	Typical obstacle size for branches and twigs
$x_\lambda^\star$	0.05	0.05	0.10	0.10	0.10	m	Typical leaf width
z_t^{Repro}	1.5	1.5	18.0	18.0	18.0	m	Plant height at reproductive maturity
$\Delta q_b^{\mathrm{Bond}}$	63.10	63.10	63.10	63.10	63.10	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat associated with bonding between wood and water
Δw	0.016	0.016	0.016	0.016	0.016	$\mathrm{mol_W\,mol^{-1}}$	Leaf water deficit down-regulation parameter (stomatal conductance)
ϵ	0.055	0.080	0.080	0.080	0.080	-	Quantum yield
ρ_t	0.20	0.20	0.53	0.71	0.90	$\mathrm{g\,cm^{-3}}$	Wood density (values for grasses needed for mortality)
$\hat{\sigma}^{\mathrm{FR}}$	0.0	0.0	0.0	0.0	0.0	-	Survivorship to fire disturbance
$\hat{\sigma}^{\mathrm{TF}}(z_t < 10\ \mathrm{m})$	0.25	0.25	0.10	0.10	0.10	-	Survivorship of small trees to tree fall disturbance
$\hat{\sigma}^{\mathrm{TF}}(z_t \geq 10\ \mathrm{m})$	0.0	0.0	0.0	0.0	0.0	-	Survivorship of large trees to tree fall disturbance
$\varsigma_R^{\mathrm{Leaf}}$	(0.100;0.400,0.040)			(0.100;0.400;0.050)		-	Leaf reflectance
$\varsigma_R^{\mathrm{Wood}}$	(0.160;0.250;0.040)			(0.110;0.250;0.100)		-	Wood reflectance
$\varsigma_T^{\mathrm{Leaf}}$	(0.050;0.200;0.000)			(0.050;0.200;0.000)		-	Leaf transmittance
$\varsigma_T^{\mathrm{Wood}}$	(0.028;0.248;0.000)			(0.001;0.001;0.000)		-	Wood transmittance

Table S5: (Continued)

Symbol	PFT-specific value					Units	Description
	C4G	C3G	ETR	MTR	LTR		
τ_l	2.0	2.0	1.0	0.50	0.33	yr^{-1}	Leaf turnover rate
τ_n	0.333	0.333	0.167	0.167	0.167	yr^{-1}	Storage turnover rate
τ_r	2.0	2.0	1.0	0.50	0.33	yr^{-1}	Fine-root turnover rate
τ_Δ	0.333	0.333	0.333	0.333	0.333	dy^{-1}	Growth respiration factor
χ	0.00	0.00	0.10	0.10	0.10	-	Mean orientation factor

Table S6: List of soil component properties (air, sand, silt, and clay), used to derive most soil-texture dependent properties. Most parameters are based on Monteith and Unsworth (2008); values for silt were unavailable and assumed to be intermediate between sand and clay. The volumetric fractions of the default soil texture types in ED-2.2 are listed in Table S7.

Symbol	Soil components				Units	Description
	Air	Sand	Silt	Clay		
q	1010	800	850	900	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Specific heat
ρ	1.200	2660	2655	2650	$\mathrm{kg\,m^{-3}}$	Bulk density
Υ_{Q}	0.025	8.80	5.87	2.92	$\mathrm{W\,m^{-1}\,K^{-1}}$	Thermal conductivity

Table S7: List of volumetric fractions of sand, silt, and clay ($f_{\mathcal{V}}$) for the default soil texture types in ED-2.2 (Fig. S6). Component-specific properties of soils are listed in Table S6.

Class	Description	Volumetric fractions		
		Sand	Silt	Clay
Sa	Sand	0.920	0.050	0.030
LSa	Loamy sand	0.825	0.115	0.060
SaL	Sandy loam	0.660	0.230	0.110
SiL	Silt loam	0.200	0.640	0.160
L	Loam	0.410	0.420	0.170
SaCL	Sandy clay loam	0.590	0.140	0.270
SiCL	Silty clay loam	0.100	0.560	0.340
CL	Clayey loam	0.320	0.340	0.340
SaC	Sandy clay	0.520	0.060	0.420
SiC	Silty clay	0.060	0.470	0.470
C	Clay	0.200	0.200	0.600
Si	Silt	0.075	0.875	0.050
CC	Heavy clay	0.100	0.100	0.800
CSa	Clayey sand	0.375	0.100	0.525
CSi	Clayey silt	0.125	0.350	0.525

Table S8: Coefficients used in Eq. (S176) for each limitation and photosynthetic path. The special case in which the stomata are closed is also shown for reference.

Case	C_3 photosynthesis				C_4 photosynthesis			
	F^A	F^B	F^C	F^D	F^A	F^B	F^C	F^D
Closed stomata	0	0	0	1	0	0	0	1
RuBP-saturated	$\dot{V}_{C_k}^{\max}$	$-\dot{V}_{C_k}^{\max}\,\Gamma_k$	1	$\mathcal{K}_{\mathrm{ME}_k}$	0	$\dot{V}_{C_k}^{\max}$	0	1
CO_2-limited	$\dot{V}_{C_k}^{\max}$	$-\dot{V}_{C_k}^{\max}\,\Gamma_k$	1	$\mathcal{K}_{\mathrm{ME}_k}$	$k_{\mathrm{PEP}}\,\dot{V}_{C_k}^{\max}$	0	0	1
Light-limited	$\epsilon_k\ \dot{q}_k$	$-\ \epsilon_k\ \dot{q}_k\,\Gamma_k$	1	$2\,\Gamma_k$	0	$\epsilon_k\ \dot{q}_k$	0	1

S1 Boundary conditions for the ecosystem dynamics equations

The boundary conditions for Eq. (2) and (3) are:

$$\underbrace{n_{fq}\left(\mathbf{C}_{f0},a,t\right)}_{\text{Recruit}} = \frac{1}{\mathbf{g}_{f0}\cdot\mathbf{1}}\left\{\underbrace{\int_{\mathbf{C_{f_0}}}^{\infty}\left(1-f_{\delta_f}\right)\,\varrho_f\,\,n_{fq}\mathrm{d}\mathbf{C}}_{\text{Local recruitment}}+\underbrace{\sum_{q'=1}^{N_Q}\left[\int_{\mathbf{C_{f_0}}}^{\infty}\int_0^{\infty} f_{\delta_f}\,\,\varrho_f\,\,n_{FQ'X'Y}\,\alpha_{fq'}\,\mathrm{d}a\,\mathrm{d}\mathbf{C}\right]}_{\text{Non-local, random dispersal}}\right\}, \tag{S1}$$

$$\underbrace{n_{fq}\left(\mathbf{C}_f,0,t\right)}_{\text{Population at new gap}} = \underbrace{\sum_{q'=1}^{N_Q}\left[\int_0^{\infty}\hat{\sigma}_{fq'}\,n_{fq'}\,\alpha_{q'}\,\mathrm{d}a\right]}_{\text{Disturbance Survivors}}, \tag{S2}$$

$$\underbrace{\alpha_q\left(0,t\right)}_{\text{Probability of new gap}} = \underbrace{\sum_{q'=1}^{N_Q}\lambda_{q'q}\,\alpha_{q'}\mathrm{d}a}_{\text{Disturbance rates}}, \tag{S3}$$

where $\mathbf{C}_{f0}$ is the size of the smallest individual of PFT f; $\mathbf{g}_{f0}$ is the growth rate for individuals of PFT f with size $\mathbf{C}_{f0}$; $\mathbf{1}$ is the unity vector for size; ϱ_f is the recruitment rate, which may depend on the PFT, size, and carbon balance; f_{δ_f} is the fraction of recruits of PFT f that are randomly dispersed instead of locally recruited; and $\hat{\sigma}_{fq}$ is size-dependent survivorship probability for a PFT f following a disturbance of type q (for a complete list of subscripts and variable meanings, refer to Tables S1 and S2). Both $\mathbf{g}_f$ and m_f are functions of the plant size and the individual's carbon balance. The individual's carbon balance depends on the environment perceived by each individual; in turn, the environment perceived by each individual is modulated by both the plant community living in the same gap and the general landscape environment. Likewise, the disturbance rates may be affected by the local plant community in the gap and the regional landscape environment.

S2 Long-term carbon dynamics and relation with carbon balance

S2.1 Leaf phenology

Leaf shedding rates (ω_{l_k}) depend on the cohort's life strategy (evergreen or deciduous). In case of deciduous trees, the rates are modulated by the difference between the fully-flushed leaf biomass given size ($C^\bullet$, Supplement S16) and the maximum leaf biomass given environmental constrains, expressed through the leaf elongation factor (e_{l_k}). For cold-deciduous cohorts, e_{l_k} is determined either from a prognostic model (Botta et al., 2000; Albani et al., 2006) or prescribed from MODIS-based estimates or from ground observations (Medvigy et al., 2009). For drought-deciduous cohorts, it is determined by the following parameterization:

$$e_{l_k} = \begin{cases} 1 & \text{, if } s_{l_k} \geq 1 \\ s_{l_k} & \text{, if } 0.05 \leq s_{l_k} < 1 \\ 0 & \text{, if } s_{l_k} < 0.05 \end{cases} , \tag{S4}$$

$$s_{l_k} = \frac{1}{|z_{r_k}|\,\Delta t_{\mathrm{El}}} \int_{t'-\Delta_{\mathrm{Phen}}}^{t'} \left(\sum_{j=j(z_{r_k})}^{N_G} \left\{ \frac{\max\left[0, \Psi_{g_j}(t') + \frac{1}{2}\left(z_{g_j} + z_{g_{j+1}}\right) - \Psi_{\mathrm{Wp}}\right]}{\Psi_{\mathrm{Ld}} - \Psi_{\mathrm{Wp}}} \right\} \right) \mathrm{d}t, \tag{S5}$$

where z_{r_k} is the rooting depth of cohort k (Supplement S16), Δt_{El} is the time scale for changes in phenology (assumed 10 days), $j(z_{r_k})$ is the soil layer containing the deepest roots of cohort k, Ψ_{g_j} is the soil matric potential at soil layer j, Ψ_{Ld} is the soil matric potential below which plants start shedding leaves (assumed -1.2 MPa), Ψ_{Wp} is the soil matric potential at the wilting point, and z_{g_j} is the depth of soil layer j, ($z_{g_{N_G+1}} \equiv 0$). Leaf shedding occurs whenever soil is drier than the threshold defined by Ψ_{Ld} and drought conditions are deteriorating:

$$\omega_{l_k} = \frac{1}{\Delta t_{\mathrm{Phen}}} \max\left[0, \frac{C_{l_k}}{C^\bullet_{l_k}} - f_{\mathrm{El}}\right]. \tag{S6}$$

In addition to the cold-deciduous and drought-deciduous strategies, leaf phenology of tropical trees can also be represented by an empirical model that is driven by the seasonality of light availability (Kim et al., 2012); this approach, however, was not used in the model evaluation because the empirical model requires site-specific parameters to describe the seasonality of leaf flushing and leaf shedding, and this approach has been tested in only one site so far.

S2.2 Carbon allocation to living tissues and non-structural carbon

The accumulated carbon balance (C_{Δ_k}, Eq. 25) over the phenology time step Δt_{Phen} is used to update the non-structural carbon storage (C_{n_k}) as well as the changes in carbon stocks of living tissues (leaves: C_{l_k}; fine roots C_{r_k} and sapwood C_{σ_k}) due to carbon allocation, turnover losses, and phenology. Changes in living tissues and non-structural carbon are interdependent and described by the following system of equations (see also Medvigy et al., 2009; Kim et al., 2012):

$$\frac{\mathrm{d}C_{n_k}}{\mathrm{d}t} = \frac{1}{\Delta t_{\text{Phen}}}\left[\int_{t-\Delta t_{\text{Phen}}}^{t} \frac{\mathrm{d}C_{\Delta_k}}{\mathrm{d}t}\,\mathrm{d}t'\right] + \left(f_{\text{LD}}\,\omega_{l_k} - \gamma_{l_k}\right) C_{l_k} - \gamma_{r_k} C_{r_k} - \gamma_{\sigma_k} C_{\sigma_k} - \tau_{n_k} C_{n_k}, \qquad \text{(S7)}$$

$$\frac{\mathrm{d}C_{l_k}}{\mathrm{d}t} = \left(\gamma_{l_k} - \tau_{l_k} - \omega_{l_k}\right) C_{l_k}, \qquad \text{(S8)}$$

$$\frac{\mathrm{d}C_{r_k}}{\mathrm{d}t} = \left(\gamma_{r_k} - \tau_{r_k}\right) C_{r_k}, \qquad \text{(S9)}$$

$$\frac{\mathrm{d}C_{\sigma_k}}{\mathrm{d}t} = \gamma_{\sigma_k} C_{\sigma_k}, \qquad \text{(S10)}$$

where e_{l_k} is the elongation factor (Supplement S2.1); f_{LD} is the fraction of carbon retained from active leaf drop as storage, currently assumed to be 0.5; $(\gamma_{l_k};\gamma_{r_k};\gamma_{\sigma_k})$ are the growth rates of leaves, fine roots, and sapwood, respectively; $(\tau_{l_k};\tau_{r_k};\tau_{n_k})$ are the background turnover rates of leaves, fine roots, and non-structural carbon, and are typically assumed constant (Table S5; but see Kim et al., 2012); and ω_{l_k} is the phenology-driven leaf shedding rate (Supplement S2.1).

The allocation to living tissues depends on whether the plant carbon balance and environmental conditions are favorable for growing, and it is proportional to the amount of carbon needed by each pool to reach the expected carbon stock given size and environmental constrains (Supplement S16). First, let $\left(C_{l_k}^{\circledcirc};C_{r_k}^{\circledcirc};C_{\sigma_k}^{\circledcirc}\right)$ be the biomass increment needed to bring leaves, fine roots, and sapwood, respectively to the expected carbon stock given the plant size and PFT $\left(C_{l_k}^{\bullet};C_{r_k}^{\bullet};C_{\sigma_k}^{\bullet}\right)$:

$$C_{l_k}^{\circledcirc} = \max\left[0, e_{l_k} C_{l_k}^{\bullet} - C_{l_k}\left(1 - \tau_{l_k}\Delta t_{\text{Phen}}\right)\right], \qquad \text{(S11)}$$

$$C_{r_k}^{\circledcirc} = \max\left[0, C_{r_k}^{\bullet} - C_{r_k}\left(1 - \tau_{r_k}\Delta t_{\text{Phen}}\right)\right], \qquad \text{(S12)}$$

$$C_{\sigma_k}^{\circledcirc} = \max\left[0, C_{\sigma_k}^{\bullet} - C_{\sigma_k}\right], \qquad \text{(S13)}$$

$$C_{\alpha_k}^{\circledcirc} = C_{l_k}^{\circledcirc} + C_{r_k}^{\circledcirc} + C_{\sigma_k}^{\circledcirc}, \qquad \text{(S14)}$$

where $C_{\alpha_k}^{\circledcirc}$ is the biomass increment needed to bring all living tissues to expected biomass given size and PFT, and Δt_{Phen} is the phenology time step (Table 1). Growth rates of leaves (γ_{l_k}), fine roots (γ_{r_k}) and sapwood (γ_{σ_k}) are proportional to the amount needed by each tissue to be brought back to the expected biomass given size and PFT, but also constrained by the amount of non-structural carbon (C_{n_k}) available:

$$\gamma_{l_k} = \max\left\{0, \frac{1}{\Delta t_{\mathrm{Phen}}} \frac{e_{l_k} C^{\circledcirc}_{l_k}}{C^{\circledcirc}_{\alpha_k}} \min\left[C_{\alpha_k}, C_{n_k}\left(1-\tau_{n_k}\right)+C_{\Delta_k}\right]\right\}, \tag{S15}$$

$$\gamma_{r_k} = \max\left\{0, \frac{1}{\Delta t_{\mathrm{Phen}}} \frac{C^{\circledcirc}_{r_k}}{C^{\circledcirc}_{\alpha_k}} \min\left[C_{\alpha_k}, C_{n_k}\left(1-\tau_{n_k}\right)+C_{\Delta_k}\right]\right\}, \tag{S16}$$

$$\gamma_{\sigma_k} = \max\left\{0, \frac{1}{\Delta t_{\mathrm{Phen}}} \frac{C^{\circledcirc}_{\sigma_k}}{C^{\circledcirc}_{\alpha_k}} \min\left[C_{\alpha_k}, C_{n_k}\left(1-\tau_{n_k}\right)+C_{\Delta_k}\right]\right\}. \tag{S17}$$

When the cohorts are actively shedding leaves due to phenology, $(\gamma_{l_k}; \gamma_{r_k}; \gamma_{\sigma_k})$ are assumed to be zero. In case carbon balance is sufficiently negative to consume the entire non-structural carbon pool, carbon stocks of living tissues will be depleted and mortality rates will increase (Supplement S2.4).

S2.3 Carbon allocation to structural tissues and reproduction

Growth of structural (C_{h_k}) and reproductive (C_{ϱ_k}) tissues are calculated at the cohort dynamics time step (Δt_{CD}, Table 1), after the biomass of living tissues and phenology have been updated:

$$C_{h_k}(t) = C_{h_k}(t-\Delta t_{\mathrm{CD}}) + \gamma_{h_k} C_{n_k}(t)\,\Delta t_{\mathrm{CD}}, \tag{S18}$$

$$C_{\varrho_k}(t) = \varrho_{t_k}\, C_{n_k}(t), \tag{S19}$$

$$\gamma_{h_k} = \frac{1}{\Delta t_{\mathrm{CD}}} - \varrho_{t_k} - \gamma_{n_k}, \tag{S20}$$

$$\varrho_{t_k} = \frac{1}{\Delta t_{\mathrm{CD}}} \begin{cases} 0.0 & \text{, if } z_{t_k} < z^{\mathrm{Repro}}_{t_k} \text{ or } \omega_{l_k} > 0 \\ f_\varrho & \text{, otherwise} \end{cases}, \tag{S21}$$

$$\gamma_{n_k} = \frac{1}{\Delta t_{\mathrm{CD}}} \begin{cases} 1.0 & \text{, if } \omega_{l_k} > 0 \\ f_n & \text{, otherwise} \end{cases}, \tag{S22}$$

where z_{t_k} is the cohort height (Supplement S16); $z^{\mathrm{Repro}}_{t_k}$ is the minimum height for reproduction, currently defined as the maximum height for grasses and 18 m for tropical trees (based on Wright et al., 2005); f_ϱ is the fraction of carbon storage allocated for reproduction when trees are above minimum reproductive height, currently defined as 1.0 for grasses and 0.3 for tropical trees (Moorcroft et al., 2001); f_n is the fraction of carbon storage that is kept as storage, currently assumed to be 0 for grasses and 0.1 for tropical trees; and ω_{l_k} is the phenology-driven leaf shedding rate (Supplement S2.1). The total reproduction biomass C_{ϱ_k} is transferred either to the patches' seed bank or to the soil carbon pools. The fraction that is transferred to the soil carbon pools is defined in terms of a mortality factor (m_{ϱ_k}), by default equivalent to 95% in a month, which accounts for both the allocation to reproductive accessories (fruits, flowers, or cones), which are eventually lost, and the seedling mortality rate; the remainder $(1-m_{\varrho_k})$ is transferred to the seed bank. Carbon storage C_{n_k} is updated after carbon allocation to structural carbon and reproduction.

S2.4 Mortality rates

Following Moorcroft et al. (2001) and Albani et al. (2006), the individual-based mortality rate (m_{t_k}) of any cohort k is the sum of four terms:

$$m_{t_k} = \underbrace{m_{t_k}^{\mathrm{DI}}}_{\substack{\text{Aging}\\\text{(Density-Independent)}}} + \underbrace{m_{t_k}^{\mathrm{DD}}}_{\substack{\text{Carbon starvation}\\\text{(Density dependent)}}} + \underbrace{m_{t_k}^{\mathrm{CF}}}_{\text{Cold/Frost}} + \underbrace{m_{t_k}^{\mathrm{FR}}}_{\text{Fire}}. \tag{S23}$$

As in Moorcroft et al. (2001), density-independent mortality is the component attributable to aging of the cohort, and it depends both on the typical tree fall disturbance rate λ_{TF} (Table S4) and the cohort wood density:

$$m_{t_k}^{\mathrm{DI}} = \lambda_{\mathrm{TF}} \cdot \left[1 + 10.714 \cdot \left(1 - \frac{\rho_{t_k}}{\rho_{\mathrm{LTR}}}\right)\right], \tag{S24}$$

where ρ_{t_k} ($\mathrm{g\,cm^{-3}}$) is the wood density of cohort k (Table S5), and ρ_{LTR} is the wood density for late-successional, tropical broadleaf trees (Table S5).

Mortality due to cold or frost is also determined through a phenomenological parameterization that linearly increases mortality when the monthly mean canopy air space temperature $\overline{T}_c$ falls below a temperature threshold (Albani et al., 2006):

$$m_{t_k}^{\mathrm{CF}} = 3.0 \max\left[0, \min\left(1, 1 - \frac{\overline{T}_c - T_{F_k}}{5}\right)\right], \tag{S25}$$

where T_{F_k} is a cold temperature threshold that represents the plant hardiness to cold, currently assumed to be 275.65 K for all tropical plants.

Mortality due to fire in ED-2.2 follows the original implementation by Moorcroft et al. (2001), and assumes that while fire depends on local scale dryness, once it ignites, it can spread throughout the entire site. Unlike other mortality rates, here we take multiple patches into account (patches are denoted by subscript u). First, let $\lambda_{u,u_0}^{\mathrm{FR}}$ be the disturbance rate associated with fires affecting patch u (and creating patch u_0), defined as in Moorcroft et al. (2001):

$$\lambda_{u,u_0}^{\mathrm{FR}} = \mathcal{I} \sum_{u=1}^{N_P} \sum_{k=1}^{N_{T_u}} \left\{ \left[C_{ul_k} + f_{\mathrm{AG}_{uk}} \left(C_{u\sigma_k} + C_{uh_k} \right) \right] \mathcal{Y}_u \, \alpha_u \right\}, \tag{S26}$$

where N_P is the number of patches, N_{T_u} is the number of cohorts in patch u, $\mathcal{Y}_u$ is the binary ignition function, α_u is the relative area of patch u, and $\mathcal{I} = 0.5\ \mathrm{yr}^{-1}$ is a phenomenological parameter that controls fire intensity, and $f_{\mathrm{AG}_{uk}}$ is the fraction of the tissue that is above ground (Table S5).

The ignition switch is defined in terms of the dryness of the environment, following the original formulation by Moorcroft et al. (2001), which uses soil moisture to estimate dryness:

$$\mathcal{Y}_u = \begin{cases} 1 & \text{, if } \left(\frac{1}{z_{\mathrm{Fr}}} \int_{z_{\mathrm{Fr}}}^{0} \vartheta_g \, \mathrm{d}z \right) > \vartheta_{\mathrm{Fr}} \\ 0 & \text{, otherwise} \end{cases}, \tag{S27}$$

where z_{Fr} is the maximum soil depth to consider when assessing dryness and ϑ_{Fr} is the average soil moisture below which ignition occurs. Both z_{Fr} and ϑ_{Fr} are adjustable parameters; default values are $z_{\mathrm{Fr}} = -0.50$ m and $\vartheta_{\mathrm{Fr}} = \vartheta\left(\Psi_{\mathrm{Fr}}\right)$ ($\Psi_{\mathrm{Fr}} = -1.4$ MPa). Once the fire disturbance rate is determined, mortality rate can be determined from the definition of disturbance rate (c.f. Moorcroft et al., 2001):

$$m_{ut_k}^{\mathrm{FR}} = \ln \left[\frac{1}{\hat{\sigma}_{ut_k}^{\mathrm{FR}} + \left(1 - \hat{\sigma}_{ut_k}^{\mathrm{FR}}\right) \, \exp\left(-\lambda_{u,u_0}^{\mathrm{FR}} \, \Delta t_{\mathrm{PD}}\right)} \right], \tag{S28}$$

where $\hat{\sigma}_{ut_k}^{\mathrm{FR}}$ is the survivorship fraction of cohort t_k of patch u following fire disturbance; this value is currently assumed to be zero for all plants in ED-2.2.

Density-dependent mortality rate ($m_{t_k}^{\mathrm{DD}}$) is called so because it describes the limitations of carbon uptake due to competition with other trees to access shared resources such as light and water. Similarly to Moorcroft et al. (2001), the density-dependent mortality rate is parameterized with a logistic function:

$$m_{t_k}^{\mathrm{DD}}(t) = \frac{y_1}{1 + \exp\left[y_2 \left(\frac{\overline{C}_{\Delta_k}}{\overline{C}_{\Delta_k}^{\bullet}} - y_3 \right) \right]}, \tag{S29}$$

where $(y_1; y_2; y_3) = (5.0, 20.0, 0.2)$ are the default (but adjustable) parameters for tropical plants; $\overline{C}_{\Delta_k}$ is the average carbon balance of cohort k over a 12-month period ending at time t, and $\overline{C}_{\Delta_k}^{\bullet}$ is the average carbon balance the cohort would attain if it had no light or water limitation. The current implementation includes only light and moisture, although the idea can be extended to any limiting resource.

S3 Input fluxes for soil carbon pools

Soil carbon is represented by three pools characterized by their typical decay rates: the fast soil carbon (subscript e_1), is comprised by metabolic litter (non-lignified leaf and fine-root litter); the intermediate soil carbon (subscript e_2) represents the decaying structural tissues and lignified materials, and the slow soil carbon (e_3) represents the dissolved soil organic matter. Changes in soil carbon content of the three pools are described by the following ordinary differential equations:

$$\frac{\mathrm{d}\dot{C}_{e_1}}{\mathrm{d}t} = \dot{C}_{t_k,e_1} + \dot{C}^{\bigstar}_{t_k,e_1} - \dot{C}_{e_1,c} - \dot{C}_{e_1,e_3}, \tag{S30}$$

$$\frac{\mathrm{d}\dot{C}_{e_2}}{\mathrm{d}t} = \dot{C}_{t_k,e_2} + \dot{C}^{\bigstar}_{t_k,e_2} - \dot{C}_{e_2,c} - \dot{C}_{e_2,e_3}, \tag{S31}$$

$$\frac{\mathrm{d}\dot{C}_{e_3}}{\mathrm{d}t} = \dot{C}_{e_1,e_3} + \dot{C}_{e_2,e_3} - \dot{C}_{e_3,c}, \tag{S32}$$

where $(\dot{C}_{t_k,e_1};\dot{C}_{t_k,e_2})$ are the influxes from cohorts to fast and structural soil carbon that are due to maintenance and shedding of living tissues; $(\dot{C}^{\bigstar}_{t_k,e_1};\dot{C}^{\bigstar}_{t_k,e_2})$ are the influxes from cohorts to fast and structural soil carbon that are due to mortality; $(\dot{C}_{e_1,c};\dot{C}_{e_2,c};\dot{C}_{e_3,c})$ are the effluxes from all soil carbon pools through heterotrophic respiration; and $(\dot{C}_{e_1,e_3};\dot{C}_{e_2,e_3})$ are the decay fluxes that are transported from fast and structural carbon pools to the soil organic matter pool.

Heterotrophic respiration terms are discussed in Section 4.8. The transport terms between cohorts and the fast and the structural carbon pools are defined as:

$$\dot{C}_{t_k,e_1} = \left(1 - \pounds_{l_k}\right) \left[(1 - f_{\mathrm{LD}})\, \omega_{l_k} C_{l_k} + \tau_{l_k} C_{l_k} + \tau_{r_k} C_{r_k}\right], \tag{S33}$$

$$\dot{C}_{t_k,e_2} = \pounds_{l_k} \left(f_{\mathrm{LD}}\, \omega_{l_k} C_{l_k} + \tau_{l_k} C_{l_k} + \tau_{r_k} C_{r_k}\right), \tag{S34}$$

$$\dot{C}^{\bigstar}_{t_k,e_1} = m_{t_k} \left[\left(1 - \pounds_{l_k}\right) \left(C_{l_k} + C_{r_k}\right) + \left(1 - \pounds_{h_k}\right) \left(C_{\sigma_k} + C_{h_k}\right) + C_{n_k}\right] + m_{\varrho_k} C_{\varrho_k}, \tag{S35}$$

$$\dot{C}^{\bigstar}_{t_k,e_2} = m_{t_k} \left[\pounds_{l_k} \left(C_{l_k} + C_{r_k}\right) + \pounds_{h_k} \left(C_{\sigma_k} + C_{h_k}\right)\right], \tag{S36}$$

where $(\pounds_{l_k};\pounds_{h_k})$ are the fraction of soft — leaves and fine roots — and woody — sapwood and hardwood — tissues that are lignified, and $(\tau_{l_k};\tau_{r_k})$ are the leaf and fine root turnover rates (Table S5); f_{LD} is the fraction of carbon reabsorbed by cohorts when shedding leaves (Table S4); ω_{l_k} is the phenology-driven leaf shedding rate; m_{t_k} is the mortality rate (Supplement S2.4); and m_{ϱ_k} is the rate of loss associated with reproduction (reproductive accessories and seedling mortality; Supplement

S2.3).

The decay rates that are transported from fast and structural pools to dissolved soil carbon pools are also determined from the complementary fraction of decay functions, i.e. the fraction of decay that is not lost through heterotrophic respiration (see Section 4.8):

$$\dot{C}_{e_j,e_3} = \frac{1 - f_{he_j}}{f_{he_j}} \dot{C}_{e_j,c}, \tag{S37}$$

where the subscript e_j corresponds to either the fast (e_1) or the structural (e_2) soil carbon; f_{he_j} is the fraction of decay that is lost through respiration (Table S4); and $\dot{C}_{e_j,c}$ is the heterotrophic respiration flux from these soil carbon pools.

S4 Definition of enthalpy as a state function

Enthalpy is an extensive thermodynamic variable, therefore the total enthalpy of any thermodynamic system consisting of two or more materials is the sum of enthalpies of each material. Likewise, enthalpy must increase linearly with mass, therefore the total enthalpy of any material (H_x) is defined as $H_x = X \cdot h_x$, where X is the mass of this material and h_x is the specific enthalpy of this material.

For any material other than water (hereafter, dry material), h_d is defined as zero when the dry material temperature is 0 K; for water, the zero level is also at 0 K, with the additional condition that water is completely frozen. The specific enthalpy for dry material (h_d), ice (h_i), liquid water (h_ℓ) and water vapor (h_v) are defined as:

$$h_d(T) = \underbrace{q_d \cdot T}_{\text{Heating}} \tag{S38}$$

$$h_i(T) = \underbrace{q_i \cdot T}_{\text{Heating ice}} \tag{S39}$$

$$h_\ell(T) = \underbrace{h_i(T_{i\ell})}_{\text{Ice enthalpy at melting point}} + \underbrace{l_{i\ell}(T_{i\ell})}_{\text{Melting ice}} + \underbrace{q_\ell\,(T - T_{i\ell})}_{\text{Heating liquid}} \tag{S40}$$

$$h_v(T) = \underbrace{h_\ell(T_{\ell v})}_{\text{Liquid enthalpy at vaporization point}} + \underbrace{l_{\ell v}(T_{\ell v})}_{\text{Vaporization}} + \underbrace{q_{pv}\,(T - T_{\ell v})}_{\text{Heating vapor}} \tag{S41}$$

where q_d, q_i and q_ℓ are the specific heats for dry material, ice and liquid water, respectively; q_{pv} is the specific heat at constant pressure for water vapor; $T_{i\ell}$ and $T_{\ell v}$ are the temperatures where ice melted and liquid water vaporized; and $l_{i\ell}$ and $l_{\ell v}$ are the latent heat of melting and vaporization, respectively. Equation (S41) is still valid even when ice sublimates, because $l_{iv}(T) = l_{i\ell}(T) + l_{\ell v}(T)$ for any temperature T. By definition (e.g. Dufour and van Mieghem, 1975), the latent heat associated with phase change is the difference in enthalpy between the two phases at the temperature in which the phase change happens, therefore, we can determine the dependency of latent heat on temperature:

$$\left(\frac{\partial l_{\ell v}}{\partial T}\right)_p = \left(\frac{\partial h_v}{\partial T}\right)_p - \left(\frac{\partial h_\ell}{\partial T}\right)_p = q_{pv} - q_\ell, \tag{S42}$$

$$\left(\frac{\partial l_{i\ell}}{\partial T}\right)_p = \left(\frac{\partial h_\ell}{\partial T}\right)_p - \left(\frac{\partial h_i}{\partial T}\right)_p = q_\ell - q_i. \tag{S43}$$

If we further assume that the transition between ice and liquid phases can only occur at the water triple point (T_3), and that the latent heat of fusion $l_{i\ell 3} \equiv l_{i\ell}(T_3)$ and vaporization $l_{\ell v3} \equiv l_{\ell v}(T_3)$ are known (Table S3), we can combine Eq. (S38)-(S41) to obtain a generic state function for specific enthalpy h:

$$h = \frac{H}{D+W} = d\, q_d\, T + w\left[i\, q_i\, T + \ell\, q_\ell\, (T - T_{\ell 0}) + v\, q_{pv}\, (T - T_{v0})\right], \tag{S44}$$

$$d = \frac{D}{D+W}, \tag{S45}$$

$$w = \frac{W}{D+W}, \tag{S46}$$

$$T_{\ell 0} = T_3 - \frac{q_i\, T_3 + l_{i\ell 3}}{q_\ell}, \tag{S47}$$

$$T_{v0} = T_3 - \frac{q_i\, T_3 + l_{i\ell 3} + l_{\ell v3}}{q_{pv}}, \tag{S48}$$

where d and w are the specific mass of other materials and water, respectively, and i, ℓ, and v are fraction of ice, liquid water, and vapor, respectively. Importantly, (S44) does not contain any information about the temperature at which the phase changes had occurred, which is necessary because enthalpy must be a state function (i.e. path-independent).

Temperature T and phase fractions $(i;\ell;v)$ of any thermodynamic system are diagnosed from enthalpy. In the case of canopy air space, i, and ℓ are all assumed to be zero, and thus $v = 1$. The canopy air space temperature T_c is obtained by inverting Eq. S44 and using that $d = 1 - w$:

$$T_c = \frac{h_c + w\, q_{pv}\, T_{v0}}{(1-w)\, q_{pd} + w\, q_{pv}}. \tag{S49}$$

For other thermodynamic systems, v is assumed to be zero. To obtain the temperature and the liquid fraction, we eliminate i from Eq. (S44) by using that $i = 1 - \ell$, and define two critical values of specific enthalpy: h_{i3}, the enthalpy when the water is at the triple point temperature (T_3) but entirely frozen, and $h_{\ell 3}$, when water is entirely in liquid phase and still at triple point temperature:

$$h_{i3} = d\, q_d\, T_3 + w\, q_i\, T_3, \tag{S50}$$
$$h_{\ell 3} = h_{i3} + w\, l_{i\ell 3} = d\, q_d\, T_3 + w\, q_\ell\, (T_3 - T_{\ell 0})\,. \tag{S51}$$

Liquid water and ice can coexist when $T = T_3$, and this only occurs when $h_{i3} < h < h_{\ell 3}$. Therefore, we obtain T and ℓ by comparing the specific enthalpy with h_{i3} and $h_{\ell 3}$:

$$T = \begin{cases} \frac{h}{d\,q_d + w\,q_i} & \text{, if } h < h_{i3} \\ T_3 & \text{, if } h_{i3} \leq h \leq h_{\ell 3} \\ \frac{h + w\,q_\ell\,T_{\ell 0}}{d\,q_d + w\,q_\ell} & \text{, if } h > h_{\ell 3} \end{cases}, \tag{S52}$$

$$\ell = \begin{cases} 0 & \text{, if } h < h_{i3} \\ \frac{(h - h_{i3})\,l_{i\ell 3}}{w} & \text{, if } h_{i3} \leq h \leq h_{\ell 3} \\ 1 & \text{, if } h > h_{\ell 3} \end{cases}. \tag{S53}$$

S5 Specific heat capacity of the thermodynamic systems

From Eq. (S44), we must know the mass and specific heats of each material for each thermodynamic system. For water, specific heat depends on the phase: q_i (ice); q_ℓ (liquid); q_{pv} (vapor at constant pressure); values are shown in Table S3. The specific heats of dry materials are defined below.

S5.1 Soil

Soil water of layer j is normally expressed in terms of liquid-equivalent volumetric fraction (ϑ_{g_j}), thus the bulk density of water in the layer is simply $\mathcal{W}_{g_j} = \rho_\ell \vartheta_{g_j}$. Dry soil is a combination of sand, silt, clay, and air filling any pore space not filled by water, and its bulk density $\mathcal{D}_{g_j}$ for each layer is based on Monteith and Unsworth (2008, Section 15.3):

$$\mathcal{D}_{g_j} = \left[\sum_{\kappa=0}^{3} \rho_\kappa \mathcal{V}_{0\kappa}\left(z_{g_j}\right)\right], \tag{S54}$$
$$\mathcal{V}_{0\kappa}\left(z_{g_j}\right) = \begin{cases} \vartheta_{\mathrm{Po}} - \vartheta_{g_j} \approx \frac{\vartheta_{\mathrm{Re}} + \vartheta_{\mathrm{Po}}}{2} & \kappa = 0 \\ f_{\mathcal{V}_\kappa}\left(1 - \vartheta_{\mathrm{Po}}\right) & \kappa \neq 0 \end{cases}, \tag{S55}$$

where κ indices 0, 1, 2, 3 correspond to air, sand, silt, and clay, respectively; ρ_κ (Table S6) and $\mathcal{V}_{0\kappa}$ (Table S7) are the specific gravity and the reference volumetric fraction of each component, and z_{g_j} is the depth of soil layer j. The volumetric soil content depends on the following texture-dependent variables: $f_{\mathcal{V}_\kappa}$, the soil texture-dependent, volumetric fraction of each soil component excluding water and air; ϑ_{Po}, the total porosity or maximum soil moisture and ϑ_{Re} is the residual water content, defined in Supplement S7. In reality, the volumetric fraction of air is not constant and depends on soil moisture; nevertheless, the total air mass is three orders of magnitude less than the solid materials, thus the contribution of varying air in the pore space to changes in specific heat is negligible. To reduce the maximum error associated with this assumption, we use the volumetric fraction corresponding to halfway between the minimum and maximum soil moisture.

Specific heat of dry soil of layer j (q_{dg_j}) is also determined following Monteith and Unsworth (2008), as the weighted average of the specific heats of the four components (Table S6):

$$q_{dg_j} = \frac{\sum_{\kappa=0}^{3} (\rho_\kappa \mathcal{V}_{0\kappa} q_\kappa)}{\sum_{\kappa=0}^{3} (\rho_\kappa \mathcal{V}_{0\kappa})}. \tag{S56}$$

S5.2 Vegetation

In ED-2.2, vegetation biomass of the different tissues is usually expressed in $\mathrm{kg_C\,m^{-2}}$; for the energy budget, however, we must account for the total internal mass ($\mathrm{kg\,m^{-2}}$) because internal energy is also stored in non-carbon material, including the interstitial and intracellular water of leaves and above ground wood. Internal water is considered a plant functional trait that remains constant throughout the simulations, although it can be different for different plant functional types. The extensive mass of the vegetation tissue (D_{t_k}) for any cohort k is given by:

$$D_{t_k} = D_{l_k} + D_{b_k}, \tag{S57}$$

$$D_{l_k} = \frac{1}{\mathcal{B}_C} C_{l_k} \left(1 + \mathcal{B}_{Wl}\right), \text{ and} \tag{S58}$$

$$D_{b_k} = \frac{1}{\mathcal{B}_C} f_{\mathrm{AG}} C_{b_k} \left(1 + \mathcal{B}_{Wb}\right), \text{ and} \tag{S59}$$

where $\mathcal{B}_C = 2.0$ is the conversion from carbon to oven dry biomass, following Baccini et al. (2012); n_{t_k} is the demographic density of cohort k ($\mathrm{plant\,m^{-2}}$); C_{l_k} and C_{b_k} are the carbon biomass of leaves and wood for each cohort ($\mathrm{kg_C\,m^{-2}}$), respectively; D_{l_k} and D_{b_k} are the extensive internal mass leaves and wood, respectively; f_{AG} is the fraction of woody biomass that is above ground (assumed 0.7 for all tree PFTs); and $\mathcal{B}_{Wl} = 0.7$ (Forest Products Laboratory, 2010) and $\mathcal{B}_{Wb} = 1.85$ (Kursar et al., 2009) are the water to oven-dry mass ratios for leaves and wood.

The vegetation specific heat excluding intercepted water (q_{dt_k}) is based on the Gu et al. (2007) parameterization and determined by the weighted average of leaves and wood specific heats, which in turn are weighted averages of the specific heat of the oven-dry materials and water:

$$q_{dt_k} = \frac{1}{D_{t_k}} \left[D_{l_k} \frac{q_l^{(\mathrm{OD})} + \mathcal{B}_{Wl} q_\ell}{1 + \mathcal{B}_{Wl}} + D_{b_k} \left(\frac{q_b^{(\mathrm{OD})} + \mathcal{B}_{Wb} q_\ell}{1 + \mathcal{B}_{Wb}} + \Delta q_b^{\mathrm{Bond}} \right) \right] \tag{S60}$$

where $q_l^{(\mathrm{OD})}$ and $q_b^{(\mathrm{OD})}$ are the specific heats of oven-dry leaves and wood, respectively. The default values are taken from Forest Products Laboratory (2010) and Jones (2014) and assumed the same for all PFTs (Table S5); and $\Delta q_b^{\mathrm{Bond}}$ is a term included by Gu et al. (2007) and Forest Products Laboratory (2010) to represent the additional heat capacity associated with the bonding between wood and water (Table S5). Although $q_b^{(\mathrm{OD})}$ and $\Delta q_b^{\mathrm{Bond}}$ are both functions of temperature in Gu et al. (2007), we further simplified them to constants in ED-2.2, using their original equations at 15 °C (Table S5). In addition, using q_ℓ as the specific heat for water is equivalent to assuming that internal water does not freeze.

S5.3 Canopy air space

The specific heat at constant pressure of the canopy air space (q_{pc}) is determined similarly to the vegetation and soils, as the weighted average between dry air and water vapor:

$$q_{pc} = (1 - w_c)\, q_{pd} + w_c q_{pv}, \tag{S61}$$

where q_{pd} and q_{pv} are the specific heats of dry air and water vapor at constant pressure (Table S3).

S6 Canopy-Air-Space Pressure

Canopy-air-space pressure p_c is assumed to remain constant throughout the integration time step ($\Delta t_{\mathrm{Thermo}}$). At the end of the time step, the air pressure above canopy p_a is updated using the meteorological forcing, at which time p_c and h_c are also updated. To determine p_c, we combine three assumptions:

1. Both canopy air space and the air above are a mix of two perfect gases, dry air and water vapor (Dufour and van Mieghem, 1975):

$$p = \rho\,\mathcal{R}\left[\frac{1}{\mathcal{M}_d}(1-w) + \frac{1}{\mathcal{M}_w} w\right] T = \rho\,\frac{\mathcal{R}}{\mathcal{M}_d} T_{\mathcal{V}}, \tag{S62}$$

$$T_{\mathcal{V}} = T\left[1 - \left(1 - \frac{\mathcal{M}_d}{\mathcal{M}_w} w\right)\right], \tag{S63}$$

where $\mathcal{R}$ is the universal gas constant, and $\mathcal{M}_d$ and $\mathcal{M}_w$ are the molar masses of dry air and water (Table S3); and $T_{\mathcal{V}}$ is the virtual temperature, which is the temperature that pure dry air would be at if pressure and density were the same as the observed air:

2. p_c instantaneously changes when p_a is updated, and this update does not involve any exchange of mass or energy. This is equivalent to assuming that potential temperature of the canopy air space θ_c and air aloft θ_a do not change when pressure is updated, even if enthalpy and temperature change. Potential temperature, approximated to the potential temperature of dry air, is defined as:

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{\mathcal{R}}{\mathcal{M}_d\, q_{pd}}}, \tag{S64}$$

where p_0 is the reference pressure level and q_{pd} is the specific heat of dry air at constant pressure (Table S3).

3. The layer between canopy air space depth $\bar{z}_c$ and reference height of the air aloft z_a is in hydrostatic equilibrium:

$$\frac{\partial p}{\partial z} = -\rho\, g, \tag{S65}$$

where g is the gravity acceleration (Table S3).

Combining these three assumptions defining $\theta_{\mathcal{V}} \equiv \theta(T_{\mathcal{V}})$ yields:

$$p_c = \left[p_a^{\frac{\mathcal{R}}{\mathcal{M}_d\, q_{pd}}} + \frac{G\,(z_a - \bar{z}_c)}{q_{pd}\,\overline{\theta_{\mathcal{V}}}}\, p_0^{\frac{\mathcal{R}}{\mathcal{M}_d\, q_{pd}}}\right]^{\frac{\mathcal{M}_d\, q_{pd}}{\mathcal{R}}}, \tag{S66}$$

where $\overline{\theta_{\mathcal{V}}}$ is the virtual potential temperature averaged between z_a and $\bar{z}_c$. Once pressure is updated at the biophysics time step, temperature and enthalpy are also updated using Eq. (S64) and Eq. (S44), respectively. Because canopy air pressure is known at all times, canopy air density ρ_c can be determined diagnostically using Eq. (S62).

S7 Soil thermal and hydraulic properties

Most of the soil hydraulic properties in ED-2.2 are derived from LEAF-3 (Walko et al., 2000) and use the soil classification based on the United States Department of Agriculture (e.g. Cosby et al., 1984). Soils in tropical forests often fall under the *Clay* class of the USDA classification, even though their sand, silt, and clay fractions often vary significantly from the average values of this class. To avoid large deviations from observations, we further split the original *Clay* class into four categories, named as *Clayey sand*, *Clayey silt*, *Clay*, and *Heavy Clay*, as shown in Fig. S6; the default fractions of each component for the default soil texture types in ED-2.2 are listed in Table S7. In addition to the standard classes, the model can derive site-specific properties based on the actual clay, silt, and sand fractions, which can be provided directly by the user.

The main hydraulic properties follow the parameterization by Cosby et al. (1984), shown here for reference:

$$\vartheta_{\mathrm{Po}} = 0.0505 - 0.0142\, f_{\mathcal{V}_{\mathrm{Sand}}} - 0.0037\, f_{\mathcal{V}_{\mathrm{Clay}}}, \tag{S67}$$

$$\Psi_{\mathrm{Po}} = -0.01 \cdot 10^{2.17 - 1.58\, f_{\mathcal{V}_{\mathrm{Sand}}} - 0.63\, f_{\mathcal{V}_{\mathrm{Clay}}}}, \tag{S68}$$

$$b = 3.10 - 0.3 \cdot f_{\mathcal{V}_{\mathrm{Sand}}} + 15.7 \cdot f_{\mathcal{V}_{\mathrm{Clay}}}, \tag{S69}$$

$$\Upsilon_{\Psi_{\mathrm{Po}}} = 6.817 \times 10^{-6} \cdot 10^{-0.60 + 1.26\, f_{\mathcal{V}_{\mathrm{Sand}}} - 0.64\, f_{\mathcal{V}_{\mathrm{Clay}}}}, \tag{S70}$$

where $f_{\mathcal{V}_{\mathrm{Sand}}}$ and $f_{\mathcal{V}_{\mathrm{Clay}}}$ are the volumetric fraction of sand and clay, respectively; ϑ_{Po} ($\mathrm{m_W^3\,m^{-3}}$) is the volumetric soil porosity (maximum soil moisture possible), Ψ_{Po} (m) is the soil matric potential at porosity, b is the slope of the logarithmic water retention curve, and $\Upsilon_{\Psi}^{(\mathrm{Po})}$ ($\mathrm{kg_W\,m^{-2}\,s^{-1}}$) is the soil hydraulic conductivity at bubbling pressure, assumed to occur when soil moisture $\vartheta = \vartheta_{\mathrm{Po}}$.

Soil hydraulic conductivity is defined after Brooks and Corey (1964), with an additional correction term applied to hydraulic conductivity to reduce conductivity in case the soil is partially or completely frozen:

$$\Psi = \Psi_{\mathrm{Po}} \left(\frac{\vartheta_{\mathrm{Po}}}{\vartheta} \right)^{b}, \tag{S71}$$

$$\Upsilon_{\Psi} = \left[10^{-7(1-\ell)} \right] \Upsilon_{\Psi_{\mathrm{Po}}} \left(\frac{\vartheta_{\mathrm{Po}}}{\vartheta} \right)^{2b+3}, \tag{S72}$$

where Ψ_{Po} and $\Upsilon_{\Psi_{\mathrm{Po}}}$ are the soil-texture dependent, matric potential and hydraulic conductivity at bubbling pressure, assumed to be the same as porosity (ϑ_{Po}); and ℓ is the fraction of liquid water of soil moisture.

Additional reference points are determined using the above equations combined with Eq. (S71) and (S72). The permanent wilting point ϑ_{Wp} and residual soil moisture ϑ_{Re} are defined as the soil moisture when soil matric potential is equivalent to -1.5 and -3.1 MPa, respectively:

$$\vartheta_{\mathrm{Wp}} = \vartheta_{\mathrm{Po}} \cdot \left(- \frac{g \, \rho_\ell \, \Psi_{\mathrm{Po}}}{1.5 \cdot 10^6} \right)^{\frac{1}{b}}, \tag{S73}$$

$$\vartheta_{\mathrm{Re}} = \vartheta_{\mathrm{Po}} \cdot \left(- \frac{g \, \rho_\ell \, \Psi_{\mathrm{Po}}}{3.1 \cdot 10^6} \right)^{\frac{1}{b}}, \tag{S74}$$

where g is the gravity acceleration and ρ_ℓ is the density of liquid water (Table S3). The field capacity ϑ_{Fc} is defined as the soil moisture at which the soil hydraulic conductivity is $0.1\ \mathrm{kg_W\,m^{-2}\,day^{-1}}$:

$$\vartheta_{\mathrm{Fc}} = \vartheta_{\mathrm{Po}} \cdot \left(\frac{1.16 \cdot 10^{-9}}{\Upsilon_{\Psi_{\mathrm{Po}}}} \right)^{\frac{1}{2\,b+3}}. \tag{S75}$$

Soil thermal conductivity at soil layer j ($\Upsilon_{\mathrm{Q}_{g_j}}$) is a function of the soil texture and soil moisture, and is determined using the *de Vries* weighted average of conductivities of each constituent of the soil (e.g. Parlange et al., 1998):

$$\Upsilon_{\mathrm{Q}_{g_j}} = \frac{\displaystyle\sum_{\kappa=0}^{3} \left[\left(\frac{3\,\Upsilon_{\mathrm{Q}_\ell}}{2\,\Upsilon_{\mathrm{Q}_\ell} + \Upsilon_{\mathrm{Q}_\kappa}} \right) \mathcal{V}_\kappa \left(z_{g_j} \right) \Upsilon_{\mathrm{Q}_\kappa} \right] + \vartheta_{g_j} \Upsilon_{\mathrm{Q}_\ell}}{\displaystyle\sum_{\kappa=0}^{3} \left[\left(\frac{3\,\Upsilon_{\mathrm{Q}_\ell}}{2\,\Upsilon_{\mathrm{Q}_\ell} + \Upsilon_{\mathrm{Q}_\kappa}} \right) \mathcal{V}_\kappa \left(z_{g_j} \right) \right] + \vartheta_{g_j}}, \tag{S76}$$

$$\mathcal{V}_\kappa \left(z_{g_j} \right) = \begin{cases} \vartheta_{\mathrm{Po}} - \vartheta_{g_j} & \kappa = 0 \\ \mathcal{V}_\kappa^{\mathrm{Dry}} \left(1 - \vartheta_{\mathrm{Po}} \right) & \kappa \neq 0 \end{cases}, \tag{S77}$$

where $\mathcal{V}_\kappa \left(z_{g_j} \right)$ is the volumetric fraction for soil components air, sand, silt, and clay ($\kappa = 0, 1, 2, 3$, respectively) at soil layer j; $\Upsilon_{\mathrm{Q}_\kappa}$ is the thermal conductivity for air, sand, silt, and clay (Table S6), respectively; $\Upsilon_{\mathrm{Q}_\ell}$ is the thermal conductivity of water (Table S3); $\mathcal{V}_\kappa^{\mathrm{Dry}}$ is the dry matter volumetric fraction; and ϑ_{Po} is the soil porosity. In Eq. (S76), the weights are the product between the volumetric fraction and a function that represents both the ratio of the thermal gradient of the soil constituents and the thermal gradient of water and the shape of each soil constituent (Camillo and Schmugge, 1981); in ED-2.2 we assume all particles to be spherical.

S8 Thermal and hydraulic properties of temporary surface water

The fraction of ground covered by the temporary surface water (f_{TSW}) is determined following Niu and Yang (2007), with the same coefficients used in the Community Land Model (NCAR-CLM Oleson et al., 2013):

$$f_{\mathrm{TSW}} = \begin{cases} 0 & \text{if } N_S = 0 \\ \tanh\left[\frac{\sum_{j=1}^{N_S} z_{s_j}}{2.5 z_{0\varnothing}} \left(\frac{\overline{\rho}_s}{\rho_{\circledast}}\right)^{-1.0}\right] & \text{if } N_S > 0 \end{cases}, \tag{S78}$$

$$\overline{\rho}_s = \frac{\sum_{j=1}^{N_S} W_{s_j}}{\sum_{j=1}^{N_S} z_{s_j}}, \tag{S79}$$

where N_S is the number of temporary surface water layers, z_{s_j} (m) is the vertical position of the temporary surface water layer j; W_{s_j} ($\mathrm{kg\,m^{-2}}$) is the water mass of temporary surface water layer j, $z_{0\varnothing}$ is the bare soil roughness (Table S4); $\rho_{\circledast}$ is the fresh snow density (Table S3).

The thermal conductivity of each temporary surface water layer ($\Upsilon_{\mathrm{Q}_{s_j}}$) is a function of the layer temperature T_{s_j} and bulk layer density, and is found using the same parameterization as LEAF-2 (Walko et al., 2000):

$$\Upsilon_{\mathrm{Q}_{s_j}} = y_0 \cdot \left[y_1 + y_2 \frac{W_{s_j}}{\Delta z_{s_j}} + y_3 \left(\frac{W_{s_j}}{\Delta z_{s_j}}\right)^2 + y_4 \left(\frac{W_{s_j}}{\Delta z_{s_j}}\right)^3 \right] \cdot \exp\left(y_5 T_{s_j}\right), \tag{S80}$$

where $(y_0; y_1; y_2; y_3; y_4; y_5) = \left(1.093 \times 10^{-3}; 0.03; 3.03 \times 10^{-4}; -1.77 \times 10^{-7}; 2.25 \times 10^{-9}; 0.028\right)$ are empirical constants.

S9 Optical properties of vegetation, soil, and temporary surface water.

The inverse of the optical depth per unit of plant area index (μ) for a radiation beam coming from any given angle of incidence Z is determined from the same parameterization described by Sellers (1985) and Oleson et al. (2013):

$$\mu\left(Z, \chi_k\right) = \frac{\cos Z}{E\left(Z, \chi_k\right)}, \tag{S81}$$

where $E(Z,\chi_k)$ is the average projection of all leaves and branches onto the horizontal, defined after Goudriaan (1977):

$$E(Z,\chi_k) = Y_{1_k} + Y_{2_k} \cos Z, \tag{S82}$$
$$Y_{1_k} = 0.5 - 0.633\,\chi_k - 0.33\,\chi_k^2, \tag{S83}$$
$$Y_{2_k} = 0.877\left(1 - 2\,Y_{1_k}\right), \tag{S84}$$

where Z is 0 when the beam is coming from the zenith and π when coming from the nadir (Fig. 4 in the main text); and χ_k is the mean orientation of leaves and branches, a PFT-dependent parameter that ranges from -1 (vertical leaves) to +1 (horizontal leaves), with 0 corresponding to spherically distributed leaves (Table S5). Equation (S82) is valid only when $-0.4 \le \chi_k \le 0.6$, which is the case for most plants in the wild (Goudriaan, 1977), and also all plant functional types in ED-2.2.

In the case of direct radiation, $\mu_k^{\odot} = \mu(Z^{\odot}, \chi_k)$, where $Z^{\odot}$ is the solar zenith angle, whereas all angles between 0 and $\pi/2$ contribute equally to downward diffuse radiation. In the case of upward radiation, the actual angles are between $\pi/2$ and π; in practice, the contribution of each angle is similar to the downward hemisphere except for the sign, hence the negative sign on the left-hand side of Eq. (47) in the main text. The contribution of all different zenith angles is represented by $\overline{\mu}_k$, which is the average across all possible angles (Sellers, 1985):

$$\overline{\mu}_k = \int_0^{\frac{\pi}{2}} \frac{\cos Z}{E(Z,\chi_k)} \sin Z \,\mathrm{d}Z = \frac{1}{Y_{2_k}}\left[1 + \frac{Y_{1_k}}{Y_{2_k}} \ln\left(\frac{Y_{1_k}}{Y_{1_k} + Y_{2_k}}\right)\right]. \tag{S85}$$

The scattering parameters ς_{mk}, β_{mk} and $\beta_{mk}^{\odot}$ for each band m and cohort k are found using the same formulation as the Community Land Model (CLM, Oleson et al., 2013), which is mostly derived from Goudriaan (1977) and Sellers (1985). The scattering coefficient is defined as:

$$\varsigma_{mk} = \varsigma_{R_{mk}} + \varsigma_{T_{mk}}, \tag{S86}$$

where $\varsigma_{R_{mk}}$ and $\varsigma_{T_{mk}}$ are the PFT- and spectral-band-dependent reflectance and transmittance, respectively (Table S5). The cohort parameters are found by taking the weighted average of the PFT-dependent, leaf ($\varsigma_{R_{mk}}^{\mathrm{Leaf}}; \varsigma_{T_{mk}}^{\mathrm{Leaf}}$) and branchwood ($\varsigma_{R_{mk}}^{\mathrm{Wood}}; \varsigma_{T_{mk}}^{\mathrm{Wood}}$) properties, using $f_{\mathrm{Clump}_k} \Lambda_k$ and Ω_k as weights, respectively.

Both the bulk diffuse backscattering β_{mk} and forwarding scattering $1-\beta_{mk}$ contain contribution from reflectance and transmittance because leaves and branches are not perfectly horizontal; therefore the fraction depends on the mean leaf and branch inclination relative to the horizontal plane ($\mathcal{A}_k$), which is related to the leaf orientation by the same approximation used by Oleson et al. (2013):

$$\beta_{mk} = \frac{1}{2\,\varsigma_{mk}} \left[\varsigma_{R_{mk}} + \varsigma_{T_{mk}} + \left(\varsigma_{R_{mk}} - \varsigma_{T_{mk}}\right) \cos^2 \mathcal{A}_k\right], \tag{S87}$$

$$\cos \mathcal{A}_k \approx \frac{1+\chi_k}{2}. \tag{S88}$$

For direct radiation, backscattering $\beta^{\odot}_{mk}$ and single-scattering albedo $\varsigma^{\odot}_{mk}$ are the same as Sellers (1985) and Oleson et al. (2013), and are determined by taking the limit $\varsigma_{mk} \to 0$ of Eq. (46) and (47) in the main text, assuming isotropic scattering of leaves and branches, and the projected area from Eq. (S82):

$$\beta^{\odot}_{mk} = \frac{\overline{\mu}_k + \mu^{\odot}_k}{\overline{\mu}_k} \, \frac{\varsigma^{\odot}_{mk}}{\varsigma_{mk}}, \tag{S89}$$

$$\begin{aligned}
\frac{\varsigma^{\odot}_{mk}}{\varsigma_{mk}} &= \frac{1}{2} \int_0^{\frac{\pi}{2}} \frac{E\left(Z^{\odot},\chi_k\right) \cos Z}{E\left(Z^{\odot},\chi_k\right) \cos Z + E\left(Z,\chi_k\right) \cos Z^{\odot}} \sin Z \, \mathrm{d}Z \\
&= \frac{1}{2\left(1+Y_{2_k}\,\mu^{\odot}_k\right)} \left\{1 - \frac{Y_{1_k}\,\mu^{\odot}_k}{1+Y_{2_k}\,\mu^{\odot}_k} \ln\left[\frac{1+\left(Y_{1_k}+Y_{2_k}\right)\mu^{\odot}_k}{Y_{1_k}\,\mu^{\odot}_k}\right]\right\}.
\end{aligned} \tag{S90}$$

The effective ground scattering coefficient ς_{m0} is the weighted average of the exposed soil scattering and the combined backscattering of temporary surface water and soil scattering of irradiance transmitted through the temporary surface water:

$$\varsigma_{m0} = \left(1 - f_{\mathrm{TSW}}\right) \varsigma_{R_{mg}} + f_{\mathrm{TSW}}\, \varsigma_{R_{ms}} \left(1 + \varsigma_{T_{ms}}\, \varsigma_{R_{mg}}\right), \tag{S91}$$

where f_{TSW} is the fraction of ground covered by temporary surface water, $\varsigma_{R_{mg}}$ is the reflectance of the top soil layer; and $\varsigma_{R_{ms}}$ and $\varsigma_{T_{ms}}$ are the reflectance and transmittance of the temporary surface water, respectively. Soil reflectance is a function of the soil color and volumetric soil moisture at the topmost layer, determined from the same parameterization and soil color classes as in Oleson et al. (2013):

$$\varsigma_{R_{mg}} = \min\left[\varsigma^{\mathrm{Po}}_{R_m} + 0.11 - 0.40\,\vartheta_{g_{N_G}}, \varsigma^{\mathrm{Re}}_{R_m}\right], \tag{S92}$$

where $\varsigma^{\mathrm{Re}}_{R_m}$ and $\varsigma^{\mathrm{Po}}_{R_m}$ are the soil color-dependent reflectance for dry and saturated soils, respectively.

The temporary surface water reflectance $\varsigma_{R_{ms}}$ depends on the liquid fraction, snow grain size and age, impurities, and the direction of incoming radiation, but here we simply assume a linear interpolation of soil reflectance at saturation and pure snow reflectance ($\varsigma^{\circledast}_{R_{ms}}$; Table S4), assumed constant for each band:

$$\varsigma_{R_{ms}} = \varsigma^{\circledast}_{R_{ms}} + \ell_{s_{N_S}} \left(\varsigma^{\mathrm{Po}}_{R_m} - \varsigma^{\circledast}_{R_{ms}} \right). \tag{S93}$$

Following Verseghy (1991) and Walko et al. (2000), the transmissivity of intercepted irradiance for PAR and NIR is solved following Beer's law, with a direction-independent extinction coefficient:

$$\varsigma_{T_{ms}} = \begin{cases} \exp\left(-\frac{\sum_{j=1}^{N_S} \Delta \bar{z}_{s_j}}{f_{\mathrm{TSW}} \overline{\mu}_s} \right) & \text{, if } m \in (1,2) \\ 0 & \text{, if } m = 3 \end{cases}, \tag{S94}$$

where $\overline{\mu}_s = 0.05\,\mathrm{m}$ is the inverse of the optical depth per unit of temporary surface water depth, defined here to be the same coefficient used by Verseghy (1991) and Walko et al. (2000), and the additional f_{TSW}^{-1} term accounts for the clumping of the temporary surface water, when the water does not cover all ground. Temporary surface water is assumed to be opaque for the TIR band ($m = 3$), following Walko et al. (2000).

S10 Solving the two-stream linear system of canopy radiation in ED-2.2.

Because we assume that the optical properties are constant within each layer, it is possible to find an analytical solution for the full profile of direct and diffuse radiation. First, let $\dot{Q}^{\odot}_{mk}$, $\dot{Q}^{\Downarrow}_{mk}$, and $\dot{Q}^{\Uparrow}_{mk}$ be the solution for band m and interface k immediately beneath the cohort (i.e. at $\tilde{\Pi} = \tilde{\Pi}_k$), and $\dot{Q}^{\odot}_{0_{mk}}$, $\dot{Q}^{\Downarrow}_{0_{mk}}$, and $\dot{Q}^{\Uparrow}_{0_{mk}}$ be the solution for band m and interface k immediately above the cohort (i.e. at $\tilde{\Pi} = 0$), as shown in Fig. 4. The direct radiation profile within each layer is simply given by:

$$\dot{Q}^{\odot}_{mk} = \dot{Q}^{\odot}_{0_{mk}} \exp\left(-\frac{\tilde{\Pi}_k}{\mu^{\odot}_k} \right), \tag{S95}$$

$$\dot{Q}^{\odot}_{0_{mk}} = \dot{Q}^{\odot}_{m(k+1)}, \tag{S96}$$

$$\dot{Q}^{\odot}_{m(N_T+1)} = \dot{Q}^{\odot}_{m(\infty,a)}, \tag{S97}$$

where $\dot{Q}^{\odot}_{m(\infty,a)}$ is the above-canopy, incoming direct radiation for band m and serves as the top boundary condition. Because the value at interface $N_T + 1$ is known, it is possible to determine all levels by integrating the layers from top to bottom.

For the diffuse components, an analytic solution can be found by defining two auxiliary variables

$\dot{Q}^{+}_{mk} \equiv \dot{Q}^{\Downarrow}_{mk} + \dot{Q}^{\Uparrow}_{mk}$ and $\dot{Q}^{-}_{mk} = \dot{Q}^{\Downarrow}_{mk} - \dot{Q}^{\Uparrow}_{mk}$. By subtracting (adding) Eq. (46) from (to) Eq. (47), and using Eq. (S95)-(S97) we obtain

$$\frac{\mathrm{d}\dot{Q}^{+}_{mk}}{\mathrm{d}\tilde{\Pi}} = -\frac{1-(1-2\beta_{mk})\,\varsigma_{mk}}{\overline{\mu}_k}\,\dot{Q}^{-}_{mk} + \frac{\left(1-2\beta^{\odot}_{mk}\right)\,\varsigma_{mk}}{\mu^{\odot}_{mk}}\,\dot{Q}^{\odot}_{m(k+1)}, \tag{S98}$$

$$\frac{\mathrm{d}\dot{Q}^{-}_{mk}}{\mathrm{d}\tilde{\Pi}} = -\frac{1-\varsigma_{mk}}{\overline{\mu}_k}\dot{Q}^{+}_{mk} + \frac{\varsigma_{mk}}{\mu^{\odot}_{k}}\,\dot{Q}^{\odot}_{m(k+1)} + \frac{2\,(1-\varsigma_{mk})}{\overline{\mu}_k}\,\dot{Q}^{\blacklozenge}_{mk}. \tag{S99}$$

By differentiating Eq. (S98) and Eq. (S99) and substituting the first derivatives by Eq. (S99) and Eq. (S98), we obtain two independent, second-order ordinary differential equations:

$$\frac{\mathrm{d}^2\dot{Q}^{+}_{mk}}{\mathrm{d}\tilde{\Pi}^2} = \varkappa^2_{mk}\,\dot{Q}^{+}_{mk} + \kappa^{+}_{mk}\,\exp\left(-\frac{\tilde{\Pi}}{\mu^{\odot}_{k}}\right) - 2\varkappa^2_{mk}\,\dot{Q}^{\blacklozenge}_{ik}, \tag{S100}$$

$$\frac{\mathrm{d}^2\dot{Q}^{-}_{mk}}{\mathrm{d}\tilde{\Pi}^2} = -\varkappa^2_{mk}\,\dot{Q}^{-}_{mk} + \kappa^{-}_{mk}\,\exp\left(-\frac{\tilde{\Pi}}{\mu^{\odot}_{k}}\right), \tag{S101}$$

where

$$\varkappa^2_{mk} = \frac{\left[1-(1-2\beta_{mk})\,\varsigma_{mk}\right]\,(1-\varsigma_{mk})}{\overline{\mu}^2_k}, \tag{S102}$$

$$\kappa^{+}_{mk} = -\left[\frac{1-(1-2\beta_{mk})\,\varsigma_{mk}}{\overline{\mu}_k} + \frac{1-2\beta^{\odot}_{mk}}{\mu^{\odot}_{k}}\right]\,\frac{\varsigma_{mk}\,\dot{Q}^{\odot}_{m(k+1)}}{\mu^{\odot}_{k}}, \tag{S103}$$

$$\kappa^{-}_{mk} = -\left[\frac{(1-\varsigma_{mk})\,\left(1-2\beta^{\odot}_{mk}\right)}{\overline{\mu}_k} + \frac{1}{\mu^{\odot}_{k}}\right]\,\frac{\varsigma_{mk}\,\dot{Q}^{\odot}_{m(k+1)}}{\mu^{\odot}_{k}}. \tag{S104}$$

The solution of Eq. (S100)-(S101) is the combination of the homogeneous and the particular solution, and can be determined analytically:

$$\dot{Q}^{+}_{mk}\left(\tilde{\Pi}\right) = x^{+-}_{mk}\,\exp\left(-\varkappa_{mk}\,\tilde{\Pi}\right) + x^{++}_{mk}\,\exp\left(+\varkappa_{mk}\,\tilde{\Pi}\right) + \frac{\kappa^{+}\,\mu^{\odot 2}_{k}}{1-\varkappa^2_{mk}\,\mu^{\odot 2}_{k}}\,\exp\left(-\frac{\tilde{\Pi}}{\mu^{\odot}_{k}}\right) + 2\,\dot{Q}^{\blacklozenge}_{mk} \tag{S105}$$

$$\dot{Q}^{-}_{mk}\left(\tilde{\Pi}\right) = x^{--}_{mk}\,\exp\left(-\varkappa_{mk}\,\tilde{\Pi}\right) + x^{-+}_{mk}\,\exp\left(+\varkappa_{mk}\,\tilde{\Pi}\right) + \frac{\kappa^{-}\,\mu^{\odot 2}_{k}}{1-\varkappa^2_{mk}\,\mu^{\odot 2}_{k}}\,\exp\left(-\frac{\tilde{\Pi}}{\mu^{\odot}_{k}}\right) \tag{S106}$$

where x^{+-}_{mk}, x^{++}_{mk}, x^{--}_{mk}, and x^{-+}_{mk} are coefficients to be determined. We can reduce the number of coefficients to two by differentiating Eq. (S105)-(S106) and comparing them to Eq. (S98)-(S99), and using the fact that they must be equal for any $\tilde{\Pi}$, $\mu_k^{\odot}$, $\varkappa_{mk}$, and $\dot{Q}^{\blacklozenge}_{mk}$. We call these parameters $x_{m(2k-1)}$ and $x_{m(2k)}$, $k \in \{1,2,\ldots,N_T\}$. By further recalling the definition of $\dot{Q}^{+}_{mk}$ and $\dot{Q}^{-}_{mk}$, we obtain the profile of downward and upward diffuse irradiances:

$$\dot{Q}^{\Downarrow}_{mk}\left(\tilde{\Pi}\right) = x_{m(2k-1)}\,Đ^{+}_{mk}\exp\left(-\varkappa_{mk}\tilde{\Pi}\right) + x_{m(2k)}\,Đ^{-}_{mk}\exp\left(+\varkappa_{mk}\tilde{\Pi}\right) + Þ^{+}_{mk}\exp\left(-\frac{\tilde{\Pi}}{\mu_k^{\odot}}\right) + \dot{Q}^{\blacklozenge}_{mk}, \tag{S107}$$

$$\dot{Q}^{\Uparrow}_{mk}\left(\tilde{\Pi}\right) = x_{m(2k-1)}\,Đ^{-}_{mk}\exp\left(-\varkappa_{mk}\tilde{\Pi}\right) + x_{m(2k)}\,Đ^{+}_{mk}\exp\left(+\varkappa_{mk}\tilde{\Pi}\right) + Þ^{-}_{mk}\exp\left(-\frac{\tilde{\Pi}}{\mu_k^{\odot}}\right) + \dot{Q}^{\blacklozenge}_{mk}, \tag{S108}$$

where

$$Đ^{\pm}_{mk} = \frac{1}{2}\left[1 \pm \sqrt{\frac{1-\varsigma_{mk}}{1-\left(1-2\beta_{mk}\right)\varsigma_{mk}}}\right], \tag{S109}$$

$$Þ^{\pm}_{mk} = \frac{\left(\kappa^{+}_{mk} \pm \kappa^{-}_{mk}\right)\mu_k^{\odot 2}}{2\left(1-\varkappa^2_{mk}\,\mu_k^{\odot 2}\right)}. \tag{S110}$$

To determine all vector elements $\left(x_{m(2k-1)}, x_{m(2k)}\right); k \in \{1,2,\ldots,N_T,N_T+1\}$ we need three independent systems of $2N_T+2$ equations (one system of equations for each spectral band). For $k \in \{1,2,\ldots,N_T\}$, the solution must meet the boundary conditions for all middle interfaces (Fig. 4), with one additional boundary condition for upward radiation coming out of the ground (Line 1), and another for incoming downward radiation from above the canopy (Line $2N_T+2$):

$$\begin{array}{lll}
\text{Line 1:} & \dot{Q}^{\Uparrow}_{m1} - \varsigma_{m0}\left(\dot{Q}^{\Downarrow}_{mk} + \dot{Q}^{\odot}_{mk}\right) - \left(1-\varsigma_{m0}\right)\dot{Q}^{\blacklozenge}_{m0} = 0 & \\
\text{Line } 2k\text{:} & \dot{Q}^{\Downarrow}_{0_{mk}} - \dot{Q}^{\Downarrow}_{m(k+1)} = 0 & ,\ k \in \{1,2,\ldots,K=N_T\} \\
\text{Line } 2k+1\text{:} & \dot{Q}^{\Uparrow}_{0_{mk}} - \dot{Q}^{\Uparrow}_{m(k+1)} = 0 & ,\ k \in \{1,2,\ldots,K=N_T\} \\
\text{Line } 2N_T+2\text{:} & \dot{Q}^{\Downarrow}_{0_{m(N_T+1)}} - \dot{Q}^{\Downarrow}_{m(\infty,a)} = 0 &
\end{array} \tag{S111}$$

where ς_{i0} is the ground (soil and temporary surface water) scattering coefficient (Section S9), $\dot{Q}^{\blacklozenge}_{m0}$ is the ground black body emission, and $\dot{Q}^{\Downarrow}_{m(\infty,a)}$ is the above-canopy, downward diffuse radiation for the band. For the top boundary condition, it is also assumed that $\tilde{\Pi}_{N_T+1} = 0$; $\overline{\mu}_{N_T+1} = 1$; $\dot{Q}^{\blacklozenge}_{m(N_T+1)} = 0$; $\varsigma_{m(N_T+1)} = 1$ (no absorption or emission); and $\beta_{m(N_T+1)} = \beta^{\odot}_{m(N_T+1)} = 0$ (all irradiance is transmitted). Because $\varsigma_{m(N_T+1)} = 1$ creates singularities for $Đ^{\pm}_{m(N_T+1)}$, we use the limit $\varsigma_{m(N_T+1)} \to 0$, so that $Đ^{+}_{m(N_T+1)} = 1$ and $Đ^{-}_{m(N_T+1)} = 0$. Substituting Eq. (S95)-(S97) and Eq.(S107)-(S108) into Eq. (S111) yields

$$\mathbf{S}_m \cdot \mathbf{x}_m = \mathbf{y}_m, \tag{S112}$$

where $\mathbf{x}_m = \left(x_{m1}, x_{m2}, \ldots, x_{m(2N_T+1)}, x_{m(2N_T+2)}\right)$ are the constants from Eq. (S107) and Eq. (S108); $\mathbf{S}_m$ is a $(2N_T+2) \times (2N_T+2)$ sparse matrix with following non-zero elements:

$$\begin{array}{ll}
S_{m(1,1)} = \left(Đ^{-}_{m1} - \varsigma_{m0} Đ^{+}_{m1}\right) \exp\left(-\varkappa_{m1}\,\tilde{\Pi}_1\right) & \\
S_{m(1,2)} = \left(Đ^{+}_{m1} - \varsigma_{m0} Đ^{-}_{m1}\right) \exp\left(+\varkappa_{m1}\,\tilde{\Pi}_1\right) & \\
S_{m(2k,2k-1)} = Đ^{+}_{mk} & ,k \in (1,2,\ldots,N_T+1) \\
S_{m(2k,2k)} = Đ^{-}_{mk} & ,k \in (1,2,\ldots,N_T+1) \\
S_{m(2k,2k+1)} = -Đ^{+}_{m(k+1)} \exp\left(-\varkappa_{m(k+1)}\,\tilde{\Pi}_{m(k+1)}\right) & ,k \in (1,2,\ldots,N_T) \\
S_{m(2k,2k+2)} = -Đ^{-}_{m(k+1)} \exp\left(+\varkappa_{m(k+1)}\,\tilde{\Pi}_{m(k+1)}\right) & ,k \in (1,2,\ldots,N_T) \\
S_{m(2k+1,2k-1)} = Đ^{-}_{mk} & ,k \in (1,2,\ldots,N_T+1) \\
S_{m(2k+1,2k)} = Đ^{+}_{mk} & ,k \in (1,2,\ldots,N_T+1) \\
S_{m(2k+1,2k+1)} = -Đ^{-}_{m(k+1)} \exp\left(-\varkappa_{m(k+1)}\,\tilde{\Pi}_{m(k+1)}\right) & ,k \in (1,2,\ldots,N_T) \\
S_{m(2k+2,2k+2)} = -Đ^{+}_{m(k+1)} \exp\left(+\varkappa_{m(k+1)}\,\tilde{\Pi}_{m(k+1)}\right) & ,k \in (1,2,\ldots,N_T)
\end{array}, \tag{S113}$$

and $\mathbf{y}_m = \left(y_{m1}, y_{m2}, \ldots, y_{m(2N_T+1)}, y_{m(2N_T+2)}\right)$, where

$$\begin{array}{ll}
y_{m1} = \varsigma_{m0}\,\dot{Q}^{\odot}_{m1} + (1-\varsigma_{m0})\left(\dot{Q}^{\blacklozenge}_{m0} - \dot{Q}^{\blacklozenge}_{m1}\right) - \left(Þ^{-}_{m1} - \varsigma_{m0}\,Þ^{+}_{m1}\right) \exp\left(-\frac{\tilde{\Pi}}{\mu^{\odot}_{1}}\right) & \\
y_{m(2k)} = Þ^{+}_{m(k+1)} \exp\left(-\frac{\tilde{\Pi}_{k+1}}{\mu^{\odot}_{k+1}}\right) - Þ^{+}_{mk} + \dot{Q}^{\blacklozenge}_{m(k+1)} - \dot{Q}^{\blacklozenge}_{mk} & ,k \in (1,2,\ldots,N_T) \\
y_{m(2k+1)} = Þ^{-}_{m(k+1)} \exp\left(-\frac{\tilde{\Pi}_{k+1}}{\mu^{\odot}_{k+1}}\right) - Þ^{-}_{mk} + \dot{Q}^{\blacklozenge}_{m(k+1)} - \dot{Q}^{\blacklozenge}_{mk} & ,k \in (1,2,\ldots,N_T) \\
y_{m(2N_T+2)} = \dot{Q}^{\Downarrow}_{m(\infty,a)} - Þ^{+}_{m(N_T+1)} - \dot{Q}^{\blacklozenge}_{m(N_T+1)} &
\end{array}. \tag{S114}$$

S11 Overview of the momentum transfer model

The momentum transfer model must first quantify two characteristic scales associated with the vertical structure of the vegetation, namely the displacement height (z_d) and the roughness length (z_0). The displacement height is defined according to Shaw and Pereira (1982) and represents the effective height of the mean drag from all cohorts and soil surface. The roughness length is defined after Raupach (1994, 1995) and represents the limit above the displacement height below which the typical logarithmic-based, surface layer wind profile is no longer valid. When the patch contains cohorts, we determine z_d and z_0 by adapting the model proposed by Massman (1997). This model is convenient because it does not assume fixed vegetation structures, therefore it can be determined and updated based on the demography of each patch. In ED-2.2, we use the discrete form of the original formulation, assuming that cohorts are dispersed uniformly in their patch space, such that the leaf and branch area indices are homogeneous in the horizontal plane for any given patch. The canopy environment is split in a fixed vertical grid with N_C layers spanning from the ground to the maximum vegetation height.

In the original formulation by Massman (1997), the displacement height is normalized by the canopy height; in ED-2.2 we apply a correction to scale the height with the effective canopy depth ($\overline{z}_c$) while accounting for the contribution from all cohorts including the tallest cohort (z_{t_1}):

$$z_d = \overline{z}_c \left\{ 1 - \frac{1}{z_{t_1}} \sum_{j=1}^{N_C} \left[\exp\left(-2 \, \frac{\Xi_{N_C} - \Xi_j}{\xi_{\mathrm{sfc}}} \right) \Delta z_{c_j} \right] \right\}, \tag{S115}$$

$$z_0 = \left(\overline{z}_c - z_d \right) \exp\left(-\kappa \sqrt{\frac{2}{\xi_{\mathrm{sfc}}}} + \tilde{\psi}_0 \right), \tag{S116}$$

where κ is the von Kármán constant (Table S3); $\Delta z_{c_j} = z_{c_j} - z_{c_{j-1}}$ is the layer thickness ($z_{c_0} = 0$); ξ_{sfc} is the vegetated surface drag coefficient, which is related to the ratio of the wind speed at the top cohort and the surface (Albini, 1981); Ξ_j is the cumulative cohort drag area per unit of ground area at layer j; and $\tilde{\psi}_0$ is the flux profile function of momentum at the roughness height (see Supplement S12.1), here approximated to 0.190 as in Raupach (1995).

Following Massman (1997), ξ_{sfc}, ξ_{c_j} and Ξ_{c_j} are defined as:

$$\xi_{\mathrm{sfc}} = 2 \left[y_1 + y_2 \exp\left(y_3 \Xi_{c_{N_C}} \right) \right]^2, \tag{S117}$$

$$\Xi_{c_j} = \sum_{j'=1}^{j} \frac{\xi_{c_{j'}} \, \varpi_{c_{j'}}}{\mathcal{P}_{c_{j'}}} \Delta z_{c_{j'}}, \tag{S118}$$

$$\varpi_{c_j} = \sum_{k=1}^{N_T} \left(\begin{cases} 0 & \text{, if } z_{t_k} < z_{c_{j-1}} \text{ or } z_{t_k}^{-} > z_{c_j} \\ \dfrac{\Pi_{t_k}}{\min\left(z_{c_j}, z_{t_k}\right) - \max\left(z_{t_k}^{-}, z_{c_{j-1}}\right)} & \text{, otherwise} \end{cases} \right), \tag{S119}$$

where ξ_{c_j} is the leaf-level drag coefficient due to cohorts at layer j; and $(y_1; y_2; y_3) = (0.320; 0.264; 15.1)$ are empirical constants (Massman, 1997). The sheltering factor for momentum ($\mathcal{P}_j$) accounts for the effects of adjacent leaves interfering in the viscous flow of air. The plant (leaves and wood) area density function at layer j (ϖ_j) is calculated assuming that the leaf and branch-wood area indices of individual cohorts are evenly distributed between the height of the crown bottom $z_{t_k}^{-}$ and the cohort height z_{t_k}, as determined by the allometric equations (see Supplement S16).

Wohlfahrt and Cernusca (2002) pointed out that the drag coefficient ξ and the shelter factor $\mathcal{P}$ are not completely separable, and provided a functional form of the combined ratio instead of describing ξ and $\mathcal{P}$ independently. The function used in ED-2.2 is an adaptation of the original fit as a function of plant area density function (Wohlfahrt and Cernusca, 2002), using a logistic function to reduce the number of parameters (Fig. S7):

$$\frac{\xi_{c_j}}{\mathcal{P}_{c_j}} = y_4 + \frac{y_5}{1+\exp\left(y_6\,\varpi_{c_j}\right)}, \tag{S120}$$

where $(y_4; y_5; y_6) = (0.086; 1.192; 0.480)$.

In case no above-ground vegetation exists (i.e. a patch with no cohorts), we assume that the roughness height $z_{0\varnothing}$ is the bare soil roughness z_{0g} plus any snow or water standing on top of the ground z_{0s}:

$$z_{0\varnothing} = z_{0g}\left(1 - f_{\mathrm{TSW}}\right) + z_{0s} f_{\mathrm{TSW}}; \tag{S121}$$

the default values of z_{0g} and z_{0s} are available in Table S4.

S12 Derivation of conductances

S12.1 Canopy air space conductance

To obtain the conductance at the top of the canopy air space, we solve the surface layer model that is based on the Monin-Obukhov similarity theory (Monin and Obukhov, 1954; Foken, 2006). First, we define the momentum ($\dot{U}_{a,c}$) and buoyancy ($\dot{\Theta}_{a,c}$) fluxes between the free atmosphere and the canopy air space at the top of the canopy air space. Following (Monteith and Unsworth, 2008), these fluxes can be represented either by the gradient or the eddy flux form:

$$\dot{U}_{a,c} = \rho_c K_U \frac{\partial u}{\partial z} = \rho_c \overline{u_z' u_{\mathbf{x}}'}, \tag{S122}$$

$$\dot{\Theta}_{a,c} = -\rho_c K_\Theta q_{p_c} \frac{\partial \theta_{\mathcal{V}}}{\partial z} = -\rho_c\, q_{p_c}\, \overline{u_z' \theta_{\mathcal{V}}'}, \tag{S123}$$

where K_U and K_Θ are the eddy diffusivities of momentum and buoyancy, respectively; $u_{\mathbf{x}}$ is the horizontal wind speed, u_z is the vertical velocity; $\theta_{\mathcal{V}}$ is the virtual potential temperature; and q_{p_c}

is the specific heat of the canopy air space (Supplement S5.3). The eddy diffusivities of enthalpy, moisture and CO_2 are assumed to be the same as the buoyancy, a common assumption based on observations (Stull, 1988).

The Monin-Obukhov similarity theory is based on the Buckingham's Π-theory (Stull, 1988), which requires as many fundamental scales as fundamental dimensions. The fundamental dimensions are the canopy air density (ρ_c) and three characteristic scales, namely the friction velocity ($u^\star$), characteristic virtual temperature gradient ($\theta^\star_{\mathcal{V}}$), and the diffusivity-corrected Obukhov length $\mathcal{L}$ (Panofsky, 1963):

$$u^\star = \sqrt{\frac{\dot{U}_{a,c}}{\rho}} = \sqrt{\left|\overline{u'_{\mathbf{x}} u'_z}\right|}, \tag{S124}$$

$$\theta^\star_{\mathcal{V}} = -\frac{1}{\kappa\, u^\star}\,\frac{\dot{\Theta}_{a,c}}{\rho\, q_{p_c}} = -\frac{\overline{u'_z \theta'_{\mathcal{V}}}}{u^\star}, \tag{S125}$$

$$\mathcal{L} = \frac{1}{\mathrm{Pr}}\,\frac{\dot{U}_{a,c}}{\dot{\Theta}_{a,c}}\,\frac{\theta_{\mathcal{V}_0}}{g}\,\frac{u^\star}{\kappa} \approx \frac{\left(\theta_{\mathcal{V}_a} + \theta_{\mathcal{V}_c}\right) u^{\star 2}}{2\,\kappa\, g\, \theta^\star_{\mathcal{V}}}, \tag{S126}$$

where κ is the von Kármán constant, g is the gravity acceleration, and $\mathrm{Pr} \equiv K_U/K_\Theta$ is the turbulent Prandtl number (Table S3-S4). Another important dimensionless quantity is the bulk Richardson number Ri_B, defined as:

$$\mathrm{Ri}_B = \frac{2\, g\, \left(z^\star - z_0\right)\left(\theta_{\mathcal{V}_a} - \theta_{\mathcal{V}_c}\right)}{\left(\theta_{\mathcal{V}_a} + \theta_{\mathcal{V}_c}\right) u_a^2}, \tag{S127}$$

where $z^\star \equiv z_a - z_d$, z_a is the reference height, z_d is the displacement height, and z_0 is the roughness scale; both z_d and z_0 are determined by the momentum transfer model based on Massman (1997) (Supplement S11). The bulk Richardson number is informative on whether the layer between the canopy air space and the reference height z_a is unstable, neutral, or stable.

To determine the three remaining unknowns ($u^\star; \theta^\star_{\mathcal{V}}; \mathcal{L}$), we start from the general definition of dimensionless length scale ζ and two particular cases:

$$\zeta\left(z\right) = \frac{z - z_d}{\mathcal{L}}, \tag{S128}$$

$$\zeta^\star = \frac{z^\star}{\mathcal{L}} = \zeta_0 + \kappa\,\mathrm{Ri}_B \left(\frac{u_a}{u^\star}\right)^2 \frac{\theta^\star_{\mathcal{V}}}{\theta_{\mathcal{V}_a} - \theta_{\mathcal{V}_c}}, \tag{S129}$$

$$\zeta_0 = \frac{z_0}{\mathcal{L}} = \frac{z_0}{z^\star}\zeta^\star, \tag{S130}$$

where $z^\star = z_a - z_d$, where z_a (m) is the reference height above canopy, typically the height where the meteorological forcing measurements would be located in an eddy covariance tower; z_d is the displacement height (Eq. S115); z_0 (m) is the roughness length (Eq. S116); κ is the von Kármán constant (Table S3), Ri_B is the bulk Richardson number (Eq. S127); u_a is the wind speed at the reference height z_a; and $\theta_{\mathcal{V}_a}$ and $\theta_{\mathcal{V}_c}$ are the virtual temperature at the reference height and the canopy air space, respectively.

By choosing an appropriate combination of factors, Monin and Obukhov (1954) have shown that the dimensionless gradients of wind and temperature (here based on virtual potential temperature and the accounting for the Prandtl number) can be written as a function of the characteristic scales and dimensionless stability functions for momentum (φ_U) and heat (φ_Θ), which can be thought as correction factors for the logarithmic wind profile under non-neutral conditions (Monteith and Unsworth, 2008):

$$\frac{\partial}{\partial \zeta}\left(\frac{u_{\mathbf{x}}}{u^\star}\right) = \frac{1}{\kappa\,\zeta}\varphi_U\left(\zeta\right), \tag{S131}$$

$$\frac{\partial}{\partial \zeta}\left(\frac{\theta_{\mathcal{V}}}{\theta_{\mathcal{V}}^\star}\right) = \frac{\mathrm{Pr}}{\kappa\,\zeta}\varphi_\Theta\left(\zeta\right). \tag{S132}$$

Following Panofsky (1963), if we define the flux profile functions for momentum (ψ_U) and heat (ψ_Θ):

$$\psi_U\left(\zeta\right) = \int_0^\zeta \frac{1-\varphi_U\left(\zeta'\right)}{\zeta'}\,\mathrm{d}\zeta', \tag{S133}$$

$$\psi_\Theta\left(\zeta\right) = \int_0^\zeta \frac{1-\varphi_\Theta\left(\zeta'\right)}{\zeta'}\,\mathrm{d}\zeta', \tag{S134}$$

and integrate Eq. (S131)-(S132) between ζ_0, where wind is assumed to be zero, and any reference level ζ using the Leibniz integration rule, we obtain the horizontal wind and virtual potential temperature profile functions:

$$u_{\mathbf{x}}\left(\zeta\right) = \frac{u^\star}{\kappa}\left[\ln\left(\frac{\zeta}{\zeta_0}\right) - \psi_U\left(\zeta\right) + \psi_U\left(\zeta_0\right)\right], \tag{S135}$$

$$\theta_{\mathcal{V}}\left(\zeta\right) = \theta_{\mathcal{V}_c} + \frac{\mathrm{Pr}\,\theta_{\mathcal{V}}^\star}{\kappa}\left[\ln\left(\frac{\zeta}{\zeta_0}\right) - \psi_\Theta\left(\zeta\right) + \psi_\Theta\left(\zeta_0\right)\right]. \tag{S136}$$

If we substitute Eq. (S135)-(S136) for the specific case when $\zeta = \zeta^\star$ into Eq. (S129), we obtain an equation where the only unknown is $\zeta^\star$:

$$\zeta^{\star} = \frac{\mathrm{Ri}_B}{\mathrm{Pr}} \left(\frac{z^{\star}}{z^{\star} - z_0}\right) \frac{\left[\ln\left(\frac{\zeta^{\star}}{\zeta_0}\right) - \psi_U\left(\zeta^{\star}\right) + \psi_U\left(\zeta_0\right)\right]^2}{\ln\left(\frac{\zeta^{\star}}{\zeta_0}\right) - \psi_{\Theta}\left(\zeta^{\star}\right) + + \psi_{\Theta}\left(\zeta_0\right)}. \tag{S137}$$

The flux profile functions used here are the same as described by Beljaars and Holtslag (1991). These functions are the Businger-Dyer flux profile equations for the unstable case (Businger et al., 1971), but they are modified for the stable case to avoid the underestimated flux between the canopy air space and the air above canopy under stable conditions:

$$\psi_U\left(\zeta\right) = \begin{cases} 2\,\ln\left[\frac{1+Y(\zeta)}{2}\right] + \ln\left[\frac{1+Y^2(\zeta)}{2}\right] - 2\arctan\left[Y\left(\zeta\right)\right] + \frac{\pi}{2} & \text{, if } \mathrm{Ri}_B < 0 \\ y_1\zeta + y_2\left(\zeta - \frac{y_3}{y_4}\right)\exp\left(-y_4\zeta\right) + \frac{y_2\,y_3}{y_4} & \text{, if } \mathrm{Ri}_B \geq 0 \end{cases}, \tag{S138}$$

$$\psi_{\Theta}\left(\zeta\right) = \begin{cases} 2\,\ln\left[\frac{1+Y^2(\zeta)}{2}\right] & \text{, if } \mathrm{Ri}_B < 0 \\ 1 - \left(1 - \frac{y_1}{y_5}\zeta\right)^{y_5} + x_2\left(\zeta - \frac{y_3}{y_4}\right)\exp\left(-y_4\zeta\right) + \frac{y_2\,y_3}{y_4} & \text{, if } \mathrm{Ri}_B \geq 0 \end{cases}, \tag{S139}$$

$$Y(\zeta) = \sqrt[4]{1 - y_6\zeta}, \tag{S140}$$

where $\mathbf{y} = \left(-1; -\frac{2}{3}; 5; 0.35; \frac{3}{2}; 13\right)$ are empirical and adjustable parameters. Equation (S137) cannot be solved analytically, therefore $\zeta^{\star}$ is calculated using a root-finding technique. Once $\zeta^{\star}$ is determined, we can find $u^{\star}$ using Eq. (S135), and define the canopy conductance G_c ($\mathrm{m\,s^{-1}}$) using Eq. (S136) as the starting point, similarly to Oleson et al. (2013):

$$G_c = \frac{u^{\star}\,\theta^{\star}_{\mathcal{V}}}{\theta_{\mathcal{V}_a} - \theta_{\mathcal{V}_c}} = \frac{\kappa\,u^{\star}}{\mathrm{Pr}\left[\ln\left(\frac{\zeta^{\star}}{\zeta_0}\right) - \psi_{\Theta}\left(\zeta^{\star}\right) + \psi_{\Theta}\left(\zeta_0\right)\right]}. \tag{S141}$$

S12.2 Derivation leaf and wood boundary layer conductances

Following Monteith and Unsworth (2008), convection can be of two types: forced convection, which depends on mechanic mixing associated with the fluid velocity; and free convection, which is due to buoyancy of the boundary layer fluid. Although convection is often dominated by either forced or free convection, in ED-2.2 we always assume that the total conductance is a simple combination of forced and free convection conductances as if they were parallel:

$$G_{Qx_k} = G^{\mathrm{Free}}_{Qx_k} + G^{\mathrm{Forced}}_{Qx_k}, \tag{S142}$$

where x_k can be either the leaf (λ_k) or the branch wood (β_k) boundary layer. For each convective regime, we define the conductance in terms of the Nusselt number Nu, a dimensionless number that corresponds to the ratio between heat exchange through convection and conduction:

$$G_{Qx_k} = \frac{\eta_c \, \mathrm{Nu}}{x^\star}. \tag{S143}$$

where η_c is the thermal diffusivity of canopy air space and $x^\star$ is the characteristic size of the obstacle. For leaves, the characteristic size $x^\star_{\lambda_k}$ is a PFT-dependent constant corresponding to the typical leaf width , whereas for branch wood the typical size $x^\star_{\beta_k}$ is assumed to be the typical diameter of twigs (Table S5).

Free convection is a result of the thermal gradient between the obstacle surface and the fluid, and this is normally expressed in terms of the Grashof number Gr, a dimensionless index that relates buoyancy and viscous forces. In ED-2.2 we use the same empirical functions as Monteith and Unsworth (2008), using flat plate geometry for leaves and horizontal cylinder geometry for branch wood:

$$\mathrm{Nu}^{(\mathrm{Free})}_{\lambda_k} = \max\left[\underbrace{0.50\,\mathrm{Gr}^{\frac{1}{2}}_{\lambda_k}}_{\text{Laminar}}, \underbrace{0.13\,\mathrm{Gr}^{\frac{1}{3}}_{\lambda_k}}_{\text{Turbulent}}\right], \tag{S144}$$

$$\mathrm{Nu}^{(\mathrm{Free})}_{\beta_k} = \max\left[\underbrace{0.48\,\mathrm{Gr}^{\frac{1}{2}}_{\beta_k}}_{\text{Laminar}}, \underbrace{0.09\,\mathrm{Gr}^{\frac{1}{3}}_{\beta_k}}_{\text{Turbulent}}\right], \tag{S145}$$

$$\mathrm{Gr}_{x_k} = \frac{\varepsilon_c \, g \, \left(x^\star_{x_k}\right)^3}{\nu_c^2} \left|T_{x_k} - T_c\right|, \tag{S146}$$

where ε_c is the thermal dilatation coefficient for the canopy air space and ν_c is the kinematic viscosity of the canopy air space; x_k represents either the leaf (λ_k) or wood (β_k) surface; and g is the gravity acceleration. Like in Monteith and Unsworth (2008), thermal diffusivity and dynamic viscosity (both in $\mathrm{m^2\,s^{-1}}$) are assumed to be linear functions of the canopy air space temperature:

$$\eta_c = 1.89 \cdot 10^{-5} \left[1 + 0.007\,(T_c - T_0)\right], \tag{S147}$$

$$\nu_c = 1.33 \cdot 10^{-5} \left[1 + 0.007\,(T_c - T_0)\right], \tag{S148}$$

where the first term on the right hand side are the reference values at temperature $T_0 = 273.15\,\mathrm{K}$. Under the assumption that canopy air space is a perfect gas, thermal dilatation is $\varepsilon_c = T_c^{-1}$ (Dufour and van Mieghem, 1975).

For forced convection the flow of air through the object at different temperature causes the heat exchange, therefore Nusselt number is written as a function of the Reynolds number Re, a dimensionless index that relates inertial and viscous forces. Like in the free convection case, we use the same empirical functions as Monteith and Unsworth (2008) and the same shapes as the free convection case:

$$\mathrm{Nu}_{\lambda_k}^{(\mathrm{Forced})} = \max\left[\underbrace{0.60\,\mathrm{Re}_{\lambda_k}^{0.5}}_{\text{Laminar}}, \underbrace{0.032\,\mathrm{Re}_{\lambda_k}^{0.8}}_{\text{Turbulent}}\right], \tag{S149}$$

$$\mathrm{Nu}_{\beta_k}^{(\mathrm{Forced})} = \max\left[\underbrace{0.32 + 0.51\,\mathrm{Re}_{\beta_k}^{0.52}}_{\text{Laminar}}, \underbrace{0.24\,\mathrm{Re}_{\beta_k}^{0.60}}_{\text{Turbulent}}\right], \tag{S150}$$

$$\mathrm{Re}_{x_k} = \frac{u_{t_k}\, x_{x_k}^{\star}}{\eta_c}, \tag{S151}$$

where u_{t_k} is the wind speed experienced by the cohort k, and x_k represents either the leaf (λ_k) or wood (β_k) surface.

The wind profile within the canopy air space is determined in two steps. Above the tallest cohort, we assume that the wind can be determined from the similarity theory; from Eq. (S128) we define $\zeta_{c_j} = \zeta\left(z_{c_j}\right)$, and use wind profile function from the similarity theory (Eq. S135) to determine the wind speed at the top of the vegetated layer $u_{c_{N_C}} = u\left(\zeta_{c_{N_C}}\right)$. Within the canopy, we estimate the wind speed reduction using the wind profile as a function of cumulative drag (Ξ_j; Albini, 1981; Massman, 1997); the wind speed experienced by the cohort is the average wind between the layers where the bottom ($\hat{z}_{t_k}$) and top (z_{t_k}) of the crown are located:

$$u_{c_j} = u_{c_{N_C}} \exp\left(-\frac{\Xi_{c_{N_C}} - \Xi_{c_j}}{\xi_{\mathrm{sfc}}}\right) \tag{S152}$$

$$u_{t_k} = \max\left[0.25\,\mathrm{m\,s^{-1}}, \frac{u_{c_{N_C}}}{z_{c_{j(k)}} - z_{c_{\hat{j}(k)}}} \sum_{j'=\hat{j}(k)}^{j(k)} \left(u_{c_{j'}} \Delta z_{c_{j'}}\right)\right], \tag{S153}$$

where $c_{\hat{j}(k)}$ and $c_j(k)$ are the canopy air space layers corresponding to the bottom and top of the cohort's crown. The minimum wind speed of $0.25\,\mathrm{m\,s^{-1}}$ is imposed to avoid conductance to become unrealistically low and to account for some mixing due to gusts when the mean wind is very weak. Once the heat conductance is determined, we use the same vapor to heat ratio as Leuning et al. (1995) to calculate the water vapor conductance:

$$G_{W x_k} = 1.075\, G_{Q x_k}, \tag{S154}$$

where x_k represents either the leaf (λ_k) or wood (β_k) surface. Similarly, we define the CO_2 boundary layer conductance for leaves using the ratio of diffusivities and convection between water and CO_2 ($f_{G\lambda}$, Table S4), following Cowan and Troughton (1971):

$$\hat{G}_{W \lambda_k} = f_{G\lambda}\, \hat{G}_{C \lambda_k}. \tag{S155}$$

S12.3 Derivation of surface conductance

The total resistance between the surface and the canopy air space is a combination of the air resistance if the surface were bare, and the resistance due to the presence of the vegetated canopy, assuming that these resistances are serial and thus additive (as mentioned by Walko et al., 2000); using that conductance is the inverse of resistance:

$$\frac{1}{G_{\mathrm{Sfc}}} = \frac{1}{G_{\mathrm{Bare}}} + \frac{1}{G_{\mathrm{Veg}}}, \tag{S156}$$

where G_{Sfc} is the total surface conductance, G_{Bare} is the bare-ground equivalent conductance, and G_{Veg} is the conductance associated with vegetation presence. The bare ground conductance G_{Bare} can be approximated to be G_c (Eq. S141; see also Sellers et al., 1996). Two methods have been implemented conductance due to vegetation presence, one based on the Simple Biosphere Model (SiB-2, Sellers et al., 1996) ($G_{\mathrm{Veg}}^{\mathrm{SiB}}$), and one based on Massman and Weil (1999) ($G_{\mathrm{Veg}}^{\mathrm{MW99}}$), which incorporates the second-order closure method that accounts for the amount of shear in the sub-layer above the canopy and the geometric attributes that define the drag of air. Results in the main text used the SiB-2 based vegetation conductance.

S12.3.1 SiB-2 based vegetation conductance

In the SiB-2 based approach, we assume that the total resistance due to vegetation presence (inverse of conductance G_{Veg}) is equivalent to the total contribution of diffusivity from ground to the top of vegetated layer:

$$\frac{1}{G_{\mathrm{Veg}}^{\mathrm{SiB}}} = \int_{z_{0\varnothing}}^{z_{t_k}} \frac{1}{K_{\Theta}(z)} \mathrm{d}z \approx \sum_{j=1}^{N_C} \frac{\mathrm{Pr}}{K_{U_{c_j}}} \Delta z_{c_j}, \tag{S157}$$

$$z_{0\varnothing} = z_{0s} f_{\mathrm{TSW}} + z_{0g} (1 - f_{\mathrm{TSW}}), \tag{S158}$$

where $j = 1, 2, \ldots, N_C$ are the discrete vertical layers used to describe the canopy air space, Δz_{c_j} is the thickness of canopy air space layer j, the index $z_{0\varnothing}$ is combined contribution to roughness from the temporary surface water (z_{0s}) and bare-ground (z_{0g}), f_{TSW} is the fraction of ground covered by temporary surface water, K_{Θ} is the eddy diffusivity for heat, $K_{U_{c_j}}$ is the eddy diffusivity for momentum of canopy air space layer j, $\mathrm{Pr} = K_U K_{\Theta}^{-1}$ is the Prandtl number (Table S4; Businger et al., 1971). We further assume that $K_{U_{c_j}}$ is proportional to u_{c_j}, the horizontal wind speed at canopy air space layer j, and that Y_U is the scaling factor, i.e. $K_{U_{c_j}} \equiv Y_U u_{\mathbf{x}}$ (Sellers et al., 1986), and that within the vegetated layer the winds are determined through Eq. (S152). Therefore, Eq. (S157) becomes

$$\frac{1}{G_{\mathrm{Veg}}^{\mathrm{SiB}}} = \sum_{j=1}^{N_C} \left[\frac{\mathrm{Pr}}{Y_U u_{c_j}} \exp\left(\frac{\Xi_{c_{N_C}} - \Xi_{c_j}}{\xi_{\mathrm{Sfc}}} \right) \right], \tag{S159}$$

where ξ_{Sfc} is the drag coefficient of vegetated surfaces (Eq. S117) and Ξ_{c_j} is the cumulative cohort drag area per unit of ground area at layer j (Eq. S118). If we assume that Y_U is constant and the wind profile is continuous, and combine Eq. (S122), Eq. (S124), Eq. (S131), and Eq. (S133) at the dimensionless length scale $\zeta(z_{c_{N_C}}) = \zeta_{c_{N_C}}$ (Eq. S128), Y_U can be estimated as:

$$Y_U = \frac{\kappa u^{\star} (z_{t_1} - z_d)}{u_{c_{N_C}}} \frac{1}{1 - \zeta_{c_{N_C}} \frac{\partial \psi_U}{\partial \zeta} (\zeta_{c_{N_C}})}. \tag{S160}$$

S12.3.2 Second Order Closure of Turbulent Transport from the Surface to Canopy

The method of Massman and Weil (1999) is a second-order closure method that derives $G_{\mathrm{Veg}}^{\mathrm{MW99}}$ from the shear in the sub-layer above the canopy and the geometric attributes of the canopy that define the drag of fluid. Massman and Weil (1999) base their method on some key simplifications to the the turbulent kinetic energy (TKE) budget equation: (1) no horizontal variability exists within any given patch (horizontal homogeneity); (2) the turbulent flow has proportional isotropy, i.e., the variance in each of the three wind directions is proportional to TKE.

$$\text{TKE} = \frac{1}{2} \left[\underbrace{\sigma_{u_x}^2 + \sigma_{u_y}^2}_{\sigma_{u_\mathbf{x}}^2} + \sigma_{u_z}^2 \right], \tag{S161}$$

$$\sigma_{u_\mathbf{x}}^2 = \overline{u'_\mathbf{x} u'_\mathbf{x}}, \tag{S162}$$

$$\sigma_{u_z}^2 = \overline{u'_z u'_z}, \tag{S163}$$

where $u_\mathbf{x} = \sqrt{u_x^2 + u_y^2}$ is the horizontal wind along the direction of the mean wind, and $u'_?$ is the departure from the mean wind in any of the wind directions. With the horizontal homogeneity and proportional isotropy assumptions, it is possible to derive an analytical solution to the TKE budget, and ultimately obtain an analytical solution for the vertical profile of standard deviation of wind speed (Eq. 10 of Massman and Weil, 1999):

$$\sigma_{u_k}(z_{c_j}) = \mathcal{S}_{u_k}\, y\, u^\star \left\{ Y_1 \exp\left[-\frac{3\left(\Xi_{c_{N_C}} - \Xi_{c_j}\right)}{\xi_{\text{Sfc}}} \right] + Y_2 \exp\left[-\frac{\sqrt{3}\, y \left(\Xi_{c_{N_C}} - \Xi_{c_j}\right)}{\beta} \right] \right\}^{\frac{1}{3}}, \tag{S164}$$

$$y = \left(\mathcal{S}_x^2 + \mathcal{S}_y^2 + \mathcal{S}_z^2 \right)^{-\frac{1}{2}}, \tag{S165}$$

$$Y_1 = -\frac{3\beta \left(2\,\xi_{\text{Sfc}}\right)^{\frac{1}{2}}}{3\beta^2\, y - y^3\, \xi_{\text{Sfc}}^2}, \tag{S166}$$

$$Y_2 = \frac{1}{y^3} - Y_1, \tag{S167}$$

where Ξ_c is the cumulative drag profile (Eq. S118); ξ_{Sfc} is the vegetated surface drag coefficient (Eq. S117); and $\left(\mathcal{S}_{u_x}; \mathcal{S}_{u_y}; \mathcal{S}_{u_z}\right) = (2.40; 1.90; 1.25)$ are adjustable parameters that represent the ratio between above-canopy velocity variance and the momentum flux, taken from Raupach et al. (1991) as in Massman and Weil (1999); and the u_k subscript represents one of the wind directions (u_x, u_y, or u_z). In addition, the empirical β represents a joint eddy mixing length scale for both shear- and wake-driven turbulence. A sensitivity study of β using the ED-2.2 model implementation found that this parameter should be between 0.01 and 0.03 (Knox, 2012) to ensure that the turbulence intensity ($\iota_U = \sigma_{u_z}/u_\mathbf{x}$) is stable over the canopy depth as it approaches the soil surface. These values of β are also similar to the value of 0.05 found by Massman and Weil (1999). Depending on the the magnitude of ξ_{Sfc} and the choice of β, it is possible that Eq. (S164) yields negative (non-physical) values of σ_{u_k}; to avoid unrealistic solutions, β is dynamically set in ED-2.2. The model assigns an initial guess of $\beta = 0.03$ and, in case the solution is non-physical, it iteratively reduces the parameter until $\sigma_{u_?}$ becomes positive.

Similar to the heat conductance between leaves, branches and the canopy air space (Section S12.2), the conductance between ground and canopy air space is related to the Nusselt number (Nu), following Eq. (S143). To account for the effects of both free (buoyant) convection and forced (mechanic) convection, the Nusselt number is parameterized as a function of the Reynolds (Re) and the Prandtl (Pr) numbers, with an additional modification to account for turbulence intensity (ι_U) (Sauer and Norman, 1995; Massman and Weil, 1999). To ensure that the conductance encompasses the entire canopy air space, we use the average turbulence intensity ($\overline{\iota_U}$) between the soil surface and the canopy air space depth (z_c):

$$\overline{\iota_U} = \frac{1}{z_c} \sum_{j=1}^{N_C} \frac{\sigma_{u_z}\left(z_{c_j}\right)}{u_{\mathbf{x}}\left(z_{c_j}\right)} \Delta z_{c_j}, \tag{S168}$$

$$G_{\text{Veg}}^{\text{MW99}} = z_0^{1/2} \left(1 + 2\,\overline{\iota_U}\right) \frac{\eta_c}{x_{\text{Veg}}^{\star}} \,\text{Re}^{b_1}\,\text{Pr}^{b_2}\, u_{\mathbf{x}}(z_{t_1}) \sqrt{\frac{u_{\mathbf{x}}\left(z_0\right)}{u_{\mathbf{x}}\left(z_{t_1}\right)}}. \tag{S169}$$

where $(b_1;b_2) = (-1/2;-2/3)$ (Sauer and Norman, 1995); and $x_{\text{Veg}}^{\star}$ is the mixing length scale for vegetated surface, and z_0 is the roughness length scale (Eq. S116).

S13 Phase equilibrium (saturation) of water vapor

The partial pressure of water vapor at phase equilibrium ($p^{\equiv}$) is solely a function of temperature, following the Clapeyron equation (Dufour and van Mieghem, 1975; Murphy and Koop, 2005). Whether the phase equilibrium of water vapor refers to ice-vapor ($p_{vi}^{\equiv}$) or liquid-vapor ($p_{v\ell}^{\equiv}$) transitions also depends on the temperature, and in ED-2.2, we use the law of minimum:

$$p^{\equiv}\left(T\right) = \min\left[p_{vi}^{\equiv}\left(T\right), p_{v\ell}^{\equiv}\left(T\right)\right]. \tag{S170}$$

Both $p_{vi}^{\equiv}$ and $p_{v\ell}^{\equiv}$ are defined after the parameterization by (Murphy and Koop, 2005), which have high degree of accuracy ($< 0.05\%$) between 123 K and 332 K, and thus includes all the range of near-surface temperatures solved by ED-2.2:

$$p_{vi}^{\equiv}\left(T\right) = \exp\left[9.550426 - \frac{5723.265}{T} + 3.53068\,\ln\left(T\right) - 0.00728332\,T\right], \tag{S171}$$

$$p_{v\ell}^{\equiv}\left(T\right) = \exp\left\{Y_1\left(T\right) + Y_2\left(T\right)\tanh\left[0.0415\,\left(T - 218.8\right)\right]\right\}, \tag{S172}$$

$$Y_1\left(T\right) = 54.842763 - \frac{6763.22}{T} - 4.210\,\ln\left(T\right) + 0.000367\,T, \tag{S173}$$

$$Y_2(T) = 53.878 - \frac{1331.22}{T} - 9.44523 \ln(T) + 0.014025\, T. \tag{S174}$$

Importantly, Eq. (S171) and Eq. (S172) yield the same value (within $4.1 \cdot 10^{-6}\%$ accuracy) at the water's triple point, which guarantees continuity of Eq. (S170).

The saturation specific humidity $w^{\equiv}$ is obtained using Eq. (S170) and the definition of specific humidity:

$$w^{\equiv}(T,p) = \frac{\mathcal{M}_w\, p^{\equiv}(T)}{\mathcal{M}_d\,[p - p^{\equiv}(T)] + \mathcal{M}_w\, p^{\equiv}(T)}, \tag{S175}$$

where $\mathcal{M}_d$ and $\mathcal{M}_w$ are the molar masses of dry air and water, respectively (Tab S3).

S14 Solver for the CO_2 assimilation rates and transpiration

Variables w_{l_k}, $\dot{V}_{C_k}^{\max}$, $\dot{R}_k$, ϕ_k, $\mathcal{K}_{O_k}$, $\mathcal{K}_{C_k}$, Γ_k, and $\mathcal{K}_{\mathrm{ME}_k}$ are functions of leaf temperature and canopy air space pressure, and thus can be determined directly. In constrast, nine variables are unknown for each limitation case as well as for the case when the stomata are closed: $\dot{E}_k$, $\dot{A}_k$, $\dot{V}_{C_k}$, $\dot{V}_{O_k}$, c_{l_k}, c_{λ_k}, w_{λ_k}, $\hat{G}_{Wl_k}$, and $\hat{G}_{Cl_k}$. To solve the remaining unknowns, we first substitute Eq. (80) and either Eq. (83), Eq. (85) or Eq. (87) into Eq. (79) and write a general functional form for $\dot{A}_k$, similarly to Medvigy (2006), that is a function of only one unknown, c_{l_k}:

$$\dot{A}_k\left(c_{l_k}\right) = \frac{F_k^{\mathrm{A}}\, c_{l_k} + F_k^{\mathrm{B}}}{F_k^{\mathrm{C}}\, c_{l_k} + F_k^{\mathrm{D}}} - \dot{R}_k, \tag{S176}$$

where parameters F depend on the limitation and the photosynthetic pathway, as shown in Table S8.

We then combine Eq. (74) and Eq. (S155) to eliminate $\hat{G}_{Cl_k}$ and c_{λ_k}, and write an alternative equation for $\hat{G}_{Wl_k}$:

$$\hat{G}_{Wl_k} = \frac{f_{Gl}\, \hat{G}_{W\lambda_k}\, \dot{A}_k}{\hat{G}_{W\lambda_k}\left(c_c - c_{l_k}\right) - f_{G\lambda}\, \dot{A}_k}. \tag{S177}$$

To eliminate c_{λ_k} and w_{λ_k} from Eq. (89), we use Eq. (74) and Eq. (75). Then, we eliminate $\hat{G}_{Wl_k}$ by replacing the left hand side of Eq. (89) by the alternative Eq. (S177), yielding to the following function $\mathcal{F}(c_{l_k})$ for which we seek the solution $\mathcal{F}(c_{l_k}) = 0$:

$$\mathcal{F}(c_{l_k}) = \mathcal{F}_1(c_{l_k})\,\mathcal{F}_2(c_{l_k})\,\mathcal{F}_3(c_{l_k}) - 1, \tag{S178}$$

$$\mathcal{F}_1(c_{l_k}) = \frac{\left(f_{Gl} - f_{G\lambda}\,\frac{\hat{G}^{\varnothing}_{Wl_k}}{\hat{G}_{W\lambda_k}}\right)\dot{A}_k - \hat{G}^{\varnothing}_{Wl_k}\left(c_c - c_{l_k}\right)}{m_k\,\dot{A}_k}, \tag{S179}$$

$$\mathcal{F}_2(c_{l_k}) = \frac{\hat{G}_{W\lambda_k}\left(c_c - \Gamma_k\right) - f_{G\lambda}\,\dot{A}_k}{\hat{G}_{W\lambda_k}\left(c_c - c_{l_k}\right) + \left(f_{Gl} - f_{G\lambda}\right)\dot{A}_k}, \tag{S180}$$

$$\mathcal{F}_3(c_{l_k}) = 1 + \frac{w_c - w_{l_k}}{\Delta w_k}\,\frac{\hat{G}_{W\lambda_k}\left(c_c - c_{l_k}\right) - f_{G\lambda}\,\dot{A}_k}{\hat{G}_{W\lambda_k}\left(c_c - c_{l_k}\right) + \left(f_{Gl} - f_{G\lambda}\right)\dot{A}_k}. \tag{S181}$$

For the limitation cases in which Eq. (S176) does not depend on c_{l_k}, Eq. (S178) is reduced to a quadratic equation. For the other cases, Eq. (S178) becomes a fifth-order polynomial, which cannot be solved algebraically. Nevertheless, Eq. (S178) is still convenient because it highlights the range of plausible solutions, corresponding to the singularities associated with $\mathcal{F}_1$ and $\mathcal{F}_2$ — the singularities associated with $\mathcal{F}_3$ requires c_{l_k} to exceed c_c, which could be only achieved with negative $\hat{G}_{l_k w}$ or $\dot{A}_k < -\dot{M}_k$, and none of them are meaningful. Function $\mathcal{F}_1$ is singular when $\dot{A}_k = 0$; from Eq. (S177), this would $\hat{G}_{Wl_k}$ to be 0, unless $c_{l_k} = c_c$. Function $\mathcal{F}_2$ is singular when $\dot{A}_k = \hat{G}_{C\lambda_k}\left(c_c - c_{l_k}\right)$; from Eq. (S177), this happens only when $c_{l_k} = c_c$ or at $\lim_{\hat{G}_{Wl_k}\to\infty}$. The singularities for when $c_c \neq c_{l_k}$ are obtained by substituting Eq. (S176) into Eq. (74), and by taking the $\lim_{\hat{G}_{Wl_k}\to 0}\left(\dot{A}_k\right)$ and $\lim_{\hat{G}_{Wl_k}\to\infty}\left(\dot{A}_k\right)$:

$$c_{l_k}^{\min} + \frac{\digamma_k^{\mathrm{D}}\,\dot{M}_k - \digamma_k^{\mathrm{B}}}{\digamma_k^{\mathrm{C}}\,\dot{M}_k - \digamma_k^{\mathrm{A}}} = 0, \tag{S182}$$

$$\left(c_{l_k}^{\max}\right)^2 + \frac{\hat{G}_{C\lambda_k}\,\digamma_k^{\mathrm{D}} + \digamma_k^{\mathrm{B}} - \digamma_k^{\mathrm{C}}\left(\hat{G}_{C\lambda_k}\,c_c + \dot{M}_k\right)}{\hat{G}_{C\lambda_k}\,\digamma_k^{\mathrm{C}}}\,c_{l_k}^{\max} + \frac{\digamma_k^{\mathrm{B}} - \digamma_k^{\mathrm{D}}\left(\hat{G}_{C\lambda_k}\,c_c + \dot{M}_k\right)}{\hat{G}_{C\lambda_k}\,\digamma_k^{\mathrm{C}}} = 0. \tag{S183}$$

From Eq. (S183) up to two roots are possible, but normally only one is plausible. In case both values are greater than c_c, we use c_c as the upper boundary, because c_c is also a singularity; otherwise the root between $c_{l_k}^{\min}$ and c_c is selected. If none of them are in this range, then there is no viable solution for this limitation, and we assume that the stomata must be closed. Once the boundaries are defined, we seek the solution in the $\left]c_{l_k}^{\min}; c_{l_k}^{\max}\right[$ interval, where there is only one possible solution, as illustrated in Fig. S8.

Once all cases are determined, the solution is determined by a law of minimum (Collatz et al., 1991, 1992; Moorcroft et al., 2001):

$$\dot{A}_k = \min\left(\dot{A}_k^{\text{RuBP}}, \dot{A}_k^{\text{InSL}}, \dot{A}_k^{\text{PAR}}\right), \tag{S184}$$

$$\dot{E}_k = \dot{E}_k^{L\star}, \tag{S185}$$

where $L\star$ is the limiting case chosen in Eq. (S184). When available light or c_{l_k} is near or below their compensation point, it is possible that none of the limiting cases yields a viable solution. In this case, we assume that photosynthesis cannot occur and that stomata are closed.

S15 Soil moisture limitation on photosynthesis

The stomatal conductance equation by Leuning (1995) was developed using well-watered seedlings, therefore it does not consider soil moisture limitation, which can be important in seasonally dry ecosystems. To account for soil water stress, we define a phenomenological scaling function $f_{W l_k}$:

$$f_{W l_k} = \frac{1}{1 + \dfrac{\text{Demand}}{\text{Supply}}} = \frac{1}{1 + \dfrac{\mathcal{M}_w \, \Lambda_k \, \dot{E}_k}{\hat{G}_{r_k} \, C_{r_k} \, W^\star_{g_{j0}}}}, \tag{S186}$$

$$W^\star_{g_j} = \sum_{j'=j}^{N_G} \left[\rho_\ell \left(\vartheta_{\text{Fc}} - \vartheta_{\text{Wp}}\right) \Psi^\star_{g_{j'}} \Delta z_{g_{j'}}\right], \tag{S187}$$

$$\Psi^\star_{g_j} = \ell_{g_j} \frac{\max\left[\min\left(\Psi_{g_j} + \frac{z_{g_j} + z_{g_{j+1}}}{2}, \Psi_{\text{Fc}}\right), \Psi_{\text{Wp}}\right] - \Psi_{\text{Wp}}}{\Psi_{\text{Fc}} - \Psi_{\text{Wp}}}, \tag{S188}$$

where $\hat{G}_{r_k}$ $(\mathrm{m^2\,kg_C^{-1}\,s^{-1}})$ is a PFT-dependent scaling parameter related to fine root conductance (Table S5); n_k $(\mathrm{plant\,m^{-2}})$ is the demographic density of cohort k; C_{r_k} $(\mathrm{kg_C\,m^{-2}})$ is the fine root biomass per individual; Λ_k $(\mathrm{m^2\,m^{-2}})$ is the leaf area index of cohort k; $W^\star_{g_j}$ $(\mathrm{kg_W\,m^{-2}})$ is the available water for photosynthesis integrated from soil layer j to surface; $j0$ is the deepest soil layer that the cohort k can access water; z_{g_j} and Δz_{g_j} are the depth and thickness of soil layer j; ρ_ℓ $(\mathrm{kg_w m^{-3}})$ is the density of liquid water; ϑ_{Fc} and ϑ_{Wp} $(\mathrm{m^3\,m^{-3}})$ are the volumetric soil moistures at field capacity and at permanent wilting point, Ψ_{g_j} (m) is the matric potential of layer j, Ψ_{Fc} and Ψ_{Wp} (m) are the matric potentials at field capacity and wilting point, $\Psi^\star_{g_j}$ (unitless) is a factor that represents the reduction of available water due to force needed to extract the water.

S16 Allometric equations

In ED-2.2, size is defined by a suite of dimensions, including tree height z_{t_k} and rooting depth z_{r_k} which directly affect the cohort access to light and water, and the carbon stocks in different tissues. Most allometric equations use the diameter at the breast height (DBH, cm) as the size-dependent explanatory variable. The only time DBH becomes the dependent variable is when the code calculates the growth of structural tissues (Δt_{CD}): structural carbon stocks are updated based on the cohort's net carbon balance, and DBH is calculated to be consistent with the updated structural carbon stocks. In this supplement, we present the allometric equations of ED-2.2 for tropical PFTs; the temperate counterparts have been previously described in Albani et al. (2006) and Medvigy et al. (2009).

The height of any cohort k (z_{t_k}) and the height at the bottom of the crown ($z_{t_k}^{-}$) are based on Poorter et al. (2006) allometric equation for moist forests in Bolivia. We included two modifications to the original equation: (1) a maximum height of $z_{t_k} = 35$ m (Moorcroft et al., 2001) is imposed to avoid excessive extrapolation of the allometric equations for carbon stocks; (2) we impose that the equivalent $z_{t_k}^{-}$ for grasses is fixed at 1% of the total height, to avoid numeric singularities while assuming that most of the grass vertical profile has leaves.

$$z_{t_k} = \min\left\{35.0, 61.7\left[1 - \exp\left(-0.0352 \cdot \mathrm{DBH}_k^{0.694}\right)\right]\right\}. \tag{S189}$$

$$z_{t_k}^{-} = \begin{cases} \max\left(0.05, 0.01\, z_{t_k}\right) & \text{, if cohort } k \text{ is grass} \\ \max\left(0.05, z_{t_k} - 0.31\, z_{t_k}^{1.098}\right) & \text{, if cohort } k \text{ is tree} \end{cases}. \tag{S190}$$

Maximum leaf biomass ($C_{l_k}^{\bullet}$, $\mathrm{kg\,m^{-2}}$), corresponding to the state when leaves are fully flushed, is derived from the allometric equations presented by Cole and Ewel (2006) and Calvo-Alvarado et al. (2008) for several commercial species in Costa Rica:

$$C_{l_k}^{\bullet} = n_{t_k} \mathcal{C}_{0l_k} \mathrm{DBH}_k^{\mathcal{C}_{1l_k}}, \tag{S191}$$

where n_{t_k} ($\mathrm{plant\,m^{-2}}$) is the plant demographic density, and $\mathcal{C}_{0l}$ and $\mathcal{C}_{1l}$ are the PFT-dependent coefficients (Tab S5).

Maximum root biomass ($C_{r_k}^{\bullet}$, $\mathrm{kg\,m^{-2}}$) and maximum sapwood biomass ($C_{\sigma_k}^{\bullet}$, $\mathrm{kg\,m^{-2}}$) are determined from $C_{l_k}^{\bullet}$ using the same functional form as Moorcroft et al. (2001), whose formulation of sapwood biomass was was based on the pipe model by Shinozaki et al. (1964a,b):

$$C_{r_k}^{\bullet} = f_{r_k} C_{l_k}^{\bullet}, \tag{S192}$$

$$C_{\sigma_k}^{\bullet} = \frac{\mathrm{SLA}_k}{f_{\sigma_k}} \, z_{t_k} \, C_{l_k}^{\bullet}, \tag{S193}$$

where f_{r_k} and f_{σ_k} are PFT-dependent parameters, currently assumed to be the same as in the original ED-1 (Moorcroft et al., 2001, Table S5); SLA (Table S5) is the specific leaf area, determined from Kim et al. (2012) fit of specific leaf area as a function of leaf turnover rate, using the GLOPNET leaf economics dataset (Wright et al., 2004).

Total structural (heartwood) biomass (C_{h_k}, $\mathrm{kg_C\,m^{-2}}$) is based on Baker et al. (2004) equation of above-ground biomass, which is in turn based on the allometric equation by Chave et al. (2001) for French Guiana. This allometric equation was used instead of the allometric equation based on Chambers et al. (2001) because in ED-2.2 the function relating C_{h_k} and DBH_k must be bijective (i.e. given n_{t_k}, each DBH_k is associated with a single value of C_{h_k} and vice versa), which cannot be attained with the polynomial fits of higher order. Structural biomass was assumed to be the difference between above-ground biomass and the biomass of leaves and 70% of the total sapwood, corresponding to the above-ground fraction. The estimate was fitted against DBH, yielding to:

$$C_{h_k} = \begin{cases} n_{t_k} \, \mathcal{C}_{0h_k} \, \mathrm{DBH}^{\mathcal{C}_{1h_k}} & \text{, if } \mathrm{DBH}_k \leq \mathrm{DBH}_{\mathrm{Crit}} \\ n_{t_k} \, \mathcal{C}_{2h_k} \, \mathrm{DBH}^{\mathcal{C}_{3h_k}} & \text{, if } \mathrm{DBH}_k > \mathrm{DBH}_{\mathrm{Crit}} \end{cases}, \tag{S194}$$

where $\mathrm{DBH}_{\mathrm{Crit}}$ is the minimum DBH that results in $z_{t_k} = 35.0$ m, and the coefficients $\mathcal{C}_{0h}$, $\mathcal{C}_{1h}$, $\mathcal{C}_{2h}$, $\mathcal{C}_{3h}$ are defined for each PFT (Table S5).

The size-dependent rooting depth (z_{r_k}) is defined from an exponential function that allows tree depths to reach 5 m once trees reach canopy size ($z_{t_k} = 35$ m):

$$z_{r_k} = -1.114 \, \mathrm{DBH}_k^{0.422}. \tag{S195}$$

The maximum rooting depth is shallow compared to Nepstad et al. (1994) results, however it produces a rooting profile similar to other dynamic global vegetation models, and reflects that little variation in soil moisture exists at very deep layers (Christoffersen, 2013).

Leaf area index (Λ_k, $\mathrm{m_{Leaf}^2\,m^{-2}}$) is determined from leaf biomass and specific leaf area:

$$\Lambda_k = \mathrm{SLA}_k \, C_{l_k}, \tag{S196}$$

where n_k ($\mathrm{plant\,m^{-2}}$) is the demographic density of cohort k.

No allometric equation was found for wood area index (Ω_k, $\mathrm{m_{Wood}^2\,m^{-2}}$) for evergreen forests. We assumed the same allometric equation for temperate zone by Hörmann et al. (2003) for trees, and imposed maximum area at $\mathrm{DBH}_{\mathrm{Crit}}$, similarly to C_{l_k}:

$$\Omega_k = \begin{cases} 0 & \text{if cohort } k \text{ is grass} \\ n_k \, 0.0096 \, \min\left(\mathrm{DBH}, \mathrm{DBH_{Crit}}\right)^{2.0947} & \text{if cohort } k \text{ is tree} \end{cases} . \tag{S197}$$

Crown area index (X_k, $\mathrm{m^2_{Crown}\,m^{-2}}$) is also based on Poorter et al. (2006), but re-written so it is a function of DBH_k. Like in the previous cases, crown area was capped at $\mathrm{DBH_{Crit}}$, and local crown area was not allowed to exceed 1.0 or to be less than the leaf area index:

$$X_k = \min\left\{1.0, \max\left[\Lambda_k, n_k \, 1.126 \, \mathrm{DBH}^{1.052}\right]\right\}. \tag{S198}$$

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