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FORCCHN V2.0: an individual-based model for predicting multiscale forest carbon dynamics

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Methods S1. Daily processes of FORCCHN2

Photosynthesis Gross primary productivity of an individual tree is given by:

$$GPP_i = \min(f_c \cdot f_{dry} \cdot f_T \cdot GPPM_i, an \cdot aNS) \qquad \text{(S1)}$$

where GPP_i is the daily gross primary productivity of the *i*th individual tree (kgC/d), $GPPM_i$ is the maximal daily gross primary productivity of the *i*th tree (kgC/d) (Oikawa 1985); f_c, f_{dry}, f_T and $an \times aNS$ represent the effects of carbon dioxide (Kaduk and Heimann 1996), water, temperature and soil available nitrogen on GPP, respectively. *aNS* is the soil available nitrogen (kgN/m^2); and *an* is the C/N ratio parameter of the assimilation with *an*=150;

$$GPPM_i = \frac{2 \cdot Am_j \cdot DL}{Kl_j} ln \frac{1 + \sqrt{1 + Kl_j \cdot Sl_j \cdot \frac{PAR_i}{Am_j}}}{1 + \sqrt{Kl_j \cdot Sl_j \cdot PAR_i \cdot \frac{\exp(-Kl_j \cdot LAI_i)}{Am_j}}} \qquad \text{(S2)}$$

where *DL* (daylength) is the possible sunshine duration (h); PAR_i is the amount of photosynthetic active radiation at the top of the canopy at noon (W/m^2); and LAI_i is the leaf area index of the *i*th tree. For the *i*th individual in the *j*th plant functional type: Am_j, Kl_j and Sl_j represent the maximal photosynthesis [kgC/(m^2·h)], the extinction coefficient and the initial slope of light intension and photosynthesis [(kgC/(m^2·h))/(W/m^2)], respectively.

$$f_c(C_s) = 1 + \frac{C_s - C_0}{C_s + 2C_0} \qquad \text{(S3)}$$

where C_s is the CO$_2$ concentration of the simulation year; C_0 is CO$_2$ reference concentration, and C_0=340 ppm.

$$f_{dry}(sw,rh)=\left\{\frac{min\left[1,\frac{sw}{FC}+\max(rh-0.5,0.1)\right]}{dry}\right\}^{0.5} \tag{S4}$$

where *sw* is soil water content (cm); *FC* is field capacity (cm); *rh* is air relative humidity; and *dry* is the individual’s capability of enduring drought that ranges from 0 to 1.

$$f_T(T)=\left(\frac{T_{max}-T}{T_{max}-T_{opt}}\right)^{\frac{T_{max}-T_{opt}}{T_{max}-T_{min}}}\cdot\left(\frac{T-T_{min}}{T_{opt}-T_{min}}\right)^{\frac{T-T_{min}}{T_{opt}-T_{min}}} \tag{S5}$$

where *Tmin*, *Topt* and *Tmax* denote the lowest, the optimum and the highest temperature of photosynthesis (ºC), respectively; *T* is daily mean temperature (ºC).

Autotrophic respiration The autotrophic respiration of each plant includes maintenance respiration and growth respiration. The formula for maintenance respiration is expressed as:

$$RM_{ik}=t_{resp}\times r_k C_{ik} \tag{S6}$$

where RM_{ik} is daily maintenance respiration of *i*th individual tree (kgC/d); *k* represents tree organ, including leaves, branches, stems, main roots, and fine roots; r_k is the relative respiration rate of tree organ at 15ºC (1/d); C_{ik} is the carbon amount (kgC), and when *k* denotes leaves or fine root, C_i is leaf content or fine root content; When *k* denotes stem or main root, C_{ik} is sapwood content (kgC);

$$RG_i=t_{resp}\times r_g\times(GPP_i-RM_i) \tag{S7}$$

where RG_i the daily growth respiration of *i*th individual tree (kgC/d) (Ruimy et al., 1996); r_g the growth respiration coefficient, and r_g=0.25.

In Equation S6 and S7, *t_resp* represents the effect of air temperature on plant respiration, this value is computed as:

$$t_{resp} = t_{resp1} + t_{resp2} \tag{S8}$$

$$t_{resp1} = \frac{DL}{24} \times e^{\frac{\ln(tg_1)}{10\times(T_d-15)}} \tag{S9}$$

$$tg_1 = 2 \times e^{-0.009\times(T_d-15)} \tag{S10}$$

$$t_{resp2} = \frac{24-DL}{24} \times e^{\frac{\ln(tg_2)}{10\times(T_n-15)}} \tag{S11}$$

$$tg_2 = 2.2 \times e^{-0.009\times(T_n-15)} \tag{S12}$$

where t_{resp1} and t_{resp2} represent the effect of daytime air temperature and nighttime air temperature on plant respiration, respectively; T_d is daytime air temperature (°C); T_n is nighttime air temperature (°C); *DL* is the possible sunshine duration for each day (h).

Litter production The litter fluxes of leaves and fine roots are computed as follows:

$$L_{ik} = l_k \times C_{ik} \tag{S13}$$

where *k* is leaf or fine roots; L_{ik} is the flux of leaf litter or fine roots of the *i*th individual tree (kgC/d); C_{ik} the corresponding carbon amount (kgC/d); l_k the relative litter fall rate (1/d).

Soil organic matter respiration and transfer progress: the model runs on a daily timescale for soil processes, and therefore adopts a modified soil carbon budget model based on CENTURY to characterize forest soils. The CENTURY model was originally developed for simulating and forecasting carbon cycle and productivity of grasslands, but now it is widely used for forest ecosystems.

Leaf litter and fine root litter can simultaneously fall into the soil structural litter pool and the soil metabolic litter pool, and the proportions are calculated by:

$$f_m = 0.85 - 0.018 \times \frac{N_r}{L_r} \tag{S14}$$

$$f_s = 1 - f_m \tag{S15}$$

where f_m is the proportion into metabolic pool; f_s is the proportion into structural pool; N_r and L_r are the respective nitrogen and lignin content in fresh litter.

There are ten soil carbon pools in FORCCHN, the decomposition rate and respiration release in each carbon pool are calculated as:

$$D_u = s_u \times g_T \times g_W \times e^{-b \times Ls} \times C_u \tag{S16}$$

$$R_u = p_u \times D_u \tag{S17}$$

$$SD_{uv} = p_v \times (D_u - R_u) \tag{S18}$$

$$\sum p_v = 1 \tag{S19}$$

$$g_T = e^{\frac{3.36 \times (T_S - 40)}{T_S + 31.79}} \tag{S20}$$

$$g_W = 1 - (\frac{sw}{ff \times FC} - 1)^2 \tag{S21}$$

where D_u is daily carbon decomposition of the uth soil carbon pool [kgC/(m^2·d)]; s_u the relative decomposition rate of the uth pool (1/d); g_t and g_w represent the effect of temperature and water on the decomposition rate, respectively; b is an exponential term that describes the extent to which decomposition is reduced by lignin with b=5.0. L_s is the lignin content in the soil structural litter pool; C_u is the difference between carbon content and lignin content of the uth pool (kgC/m^2); R_u is daily carbon respiration release of the uth pool [kgC/(m^2·d)]; p_u is the respiration proportion of the uth pool; SD_{uv} is daily carbon content transported from uth pool to vth pool [kgC/(m^2·d)]; p_v is the proportion transported to the vth pool; sw is the soil water content (cm); ff is a constant with ff=0.6; FC is the field capacity (cm); T_s is the soil temperature (°C).

Soil water dynamics For the dynamics of soil water content, we refer to the calculation method of the Bridging Event and Continuous Hydrological (BEACH) model (Sheikh et al., 2009). The soil water (W_s) at the daily step is determined by the total precipitation (*Pre*), interception (*Incep*), infiltration (*Inf*), and actual transpiration (E_a):

$$\frac{dW_s}{dt} = Pre(t) - Incep(t) - Inf(t) - E_a(t) \tag{S22}$$

The interception by vegetations is estimated by:

$$Incep = 0.25 \times LAI \times \left(1 - \frac{1}{1 + \frac{f \times Pre}{0.25 \times LAI}}\right) \tag{S23}$$

$$f = 1 - e^{-\mu \times LAI} \tag{S24}$$

where *LAI* is the leaf area index; *f* is the proportion of soil covered by vegetation; μ is the light use efficiency parameter (i.e. set as 0.6 for trees).

The model assumes that infiltration proceeds until the uptake capacity of the surface layer (0–0.20 m) has been reached as a result of precipitation.

$$Inf = min[Pre - Incep, (W_F - W_s) \times depth_1] \tag{S25}$$

where W_F is the saturated soil moisture content (m^3 m^{-3}); $depth_1$ is the surface layer thickness (m).

The actual transpiration (E_a) is determined by potential evapotranspiration (E_0):

$$E_a = K_r \times K_e \times E_0 \tag{S26}$$

$$K_r = \frac{W_s - \frac{1}{3} \times W_p}{25 - \frac{1}{3} \times W_p} \tag{S27}$$

$$K_e = -0.5 + \max\{0.55, 1.2 + [0.04 \times (u_2 - 2) - 0.004 \times (RH_{min} - 45)] \times (\frac{h}{3})^{0.3}\} \tag{S28}$$

where K_r is a dimensionless evaporation reduction coefficient dependent on the soil water content; W_p is the wilting point; K_e is the soil evaporation coefficient; u_2 is the wind speed; RH_{min} is the air relative humidity; h is the tree height.

Light distribution For the light competition of different trees, we used a standard gap-model formulation to describe the vertical radiation environment. The gap model's light distribution process was described by Xiaodong & Shugart (2005):

$$AL_m = AL_{top} \times e^{(-l_{nee} \cdot LAI_{nee} - l_{bro} \cdot LAI_{bro})} \tag{S29}$$

where *AL* was the available light; *m* was the *m*th height (unit: m); *top* was the top height of the forest canopy; l_{nee} and l_{bro} were the coniferous and broadleaf extinction coefficient; LAI_{nee} *and* LAI_{bro} were the sums of the leaf areas in the plot of all higher broadleaf trees and needle trees.

Leaf and fine roots growth We adopted a method based on thermal time to simulate the growth of leaf biomass (G_P) and fine roots biomass (G_F) (Schiestl-Aalto *et al.*, 2015). We assumed that leaf biomass increment is related to the maximum daily growth rate and the NSC storage pool:

$$\frac{dG_P}{dt} = k_N(t) \times g(t) \times f(s(t)) \times MG \tag{S30}$$

$$\frac{dG_F(t)}{dt} = \frac{1}{2} \times k_N(t) \times \frac{dG_P}{dt} \tag{S31}$$

where k_N is the impact of NSC storage pool on growth; *g* is the response of growth to environmental factors; *f* is the response of growth to the leaf development stage *s*; *MG* is the maximum daily growth rate. The *k* is a limiting factor for growth if the NSC storage below a critical level:

$$k_N(t) = \min\{1, \frac{1 - e^{\delta \times NP(t)}}{1 - e^{\delta \times NP_0}}\} \tag{S32}$$

where δ is a parameter; *NP* is the NSC storage; NP_0 is the critical level, which is set as the initial storage size in the corresponding year. Note that the NP_0 is assumed to be 3% of the aboveground wood biomass in the first year (Fang *et al.*, 2020).

The parameters *g* and *f* describe phenology variations. The short-term growth response (*g*) is:

$$g(t) = \begin{cases} 0, & T(t) < 0 \\ (1 + e^{-\alpha \times (T(t) - \beta)})^{-1}, & T(t) \geq 0 \end{cases} \tag{S33}$$

where α and β are parameters, and $T(t)$ is the daily average temperature (°C). For temperate trees, the leaves have vital activities above 0 °C. The leaves of tropical trees can keep active growth throughout the whole year.

The development stage function ($f(s(t))$) of leaf growth is based on the assumption that the leaf development is the highest in the middle of growing period and equally low in the early and late season. And the process is written as:

$$f(t) = \begin{cases} 0, & s(t) < 0 \text{ or } s(t) > s^c \\ \frac{1}{2}(\sin\left(\frac{2\pi}{s^c} \times \left(s(t) - \frac{s^c}{4}\right)\right) + 1), & 0 \leq s(t) \leq s^c \end{cases} \tag{S34}$$

where *s* is the development stage of the leaf, s_c is the threshold for cessation of growth. Growth begins at t_b time when the thermal time requirement for growth onset, ($s(t_b)>0$), is exceeded; and the growth ceases at t_c time when the requirement for growth cessation, ($s(t_c)>s_c$), is exceeded. The development stage (*s*) is calculated by:

$$\frac{ds(t)}{dt} = g(t), t_0 < t \tag{S35}$$

$$\mathrm{s}(t_0) = s^0 \tag{S36}$$

$$\mathrm{s}(t_c) = s^c \tag{S37}$$

where s^0 is the initialized value of s; t_0 is the tree dormant time, the beginning on the first day of the year. We estimated s^0 and s^c fell in a reasonable range taken from Fang *et al.* (2020) and Schiestl-Aalto *et al.* (2015).

The maximum daily growth rate of leaves (MG) has been shown to relate to the maximum leaf biomass (B_{max}) in previous years (Schiestl-Aalto *et al.*, 2013).

$$MG_i = B_{max,i-1} \times R_p \tag{S38}$$

where i is the ith year; R_p is the growth coefficient.

Spring phenology The spring phenology sub-model was based on the effective temperature and thermal time. Following this approach, the daily temperature response was simulated by using a sigmoid function of the average temperature (Cannell & Smith 1983; Schiestl-Aalto *et al.* 2015). Leaf growth began at the time (Y_{SOS}) when heat requirement exceeded the threshold (S_A):

$$Y_{SOS} = t,\ if\ s_{heat}(t) \geq S_A \tag{S39}$$

$$s_{heat}(t) = \sum_{j=1}^{t} \frac{1}{1 + e^{-0.185(T(j)-18.4)}},\ if\ T(j) > T_A \tag{S40}$$

where s_{heat} was the daily sum of heat rates; T_A was the threshold parameter to determine the effective high temperature; T was the air average temperature; t was the time to begin growth; j was the day of the year.

Autumn phenology Compared to the modeling of spring phenology, modeling of autumn phenology was more challenging (Piao *et al.* 2019). Here, we used the accumulated cold degree-days and considered the effects by photoperiod (Delpierre *et* *al.* 2009). Similar to the spring phenology, leaves began to color at the time (Y_{EOS}) when the chilling accumulation exceeded the threshold (S_B):

$$Y_{EOS} = t,\ if\ s_{cold}(t) \geq S_B \tag{S41}$$

$$s_{cold}(t) = \sum_{j=1}^{t} (T_B - T(j)) \frac{P(j)}{P_{start}},\ \ if\ P(j) < P_{start}\ and\ T(j) < T_B \tag{S42}$$

where s_{cold} was the daily sum of chilling rates; T_B was the threshold to determine the effective low temperature; P_{start} was the threshold to determine the effective photoperiod.

Phenology parameterization Using the LAI data of the first observed year, parameters S_{A0} indicating the initial heat parameter that estimated by the spring phenological dates:

$$S_{A0} = -\sum_{t=1}^{t_{y_0,onset}} g_{heat}(t) \tag{S43}$$

where $y_{0,onset}$ is the spring phenological dates in the first year.

We only estimated the T_B in one site ($T_{B,1}$, which was set to 30.0 °C at the Acadia National Park site), other sites were estimated by the average temperature between the first day and the observed dates of autumn phenology in one year (T_{cease}) (Acadia National Park site had the T_{cease} of 8.6 °C)

$$T_{B,i} = \frac{T_{B,1}}{T_{cease,1}} \times T_{cease,i} \tag{S44}$$

where *i* represents the *i*th site (i.e. *i*th cell of 0.5 degree in this study).

S_B was the chilling threshold of leaf cessation that estimated by the autumn phenological dates:

$$S_B = \sum_{t=1}^{t_{y_0,cease}} g_{cold}(t) \tag{S45}$$

where $t_{y0,cease}$ is the autumn phenological dates in the first year.

Light competition For the light competition of different tree, we used a standard gap-model formulation to describe the vertical radiation environment. The gap model's light distribution process was described by Xiaodong & Shugart (2005):

$$AL_m = AL_{top} \times e^{(-l_{nee} \cdot LAI_{nee} - l_{bro} \cdot LAI_{bro})} \tag{S46}$$

where *AL* was the available light; *m* was the *m*th height (unit: m); *top* was the top height of the forest canopy; k_{nee} and k_{bro} were the coniferous and broadleaf extinction coefficient; LAI_{nee} *and* LAI_{bro} were the sum of the leaf areas in the plot of all higher broadleaf trees and needle trees.

Methods S2. Annual processes of FORCCHN2

The primary annual processes consist of increments of tree height, basal diameter, and production of CWD (coarse wood debris). The model assumes that annual litter production falls into one of two cases based on two assumed thresholds. On one hand, if the year-end NSC slow pool is greater than the first threshold, only the flower litter production reaches the maximum possible amount. On the other hand, if the year-end NSC slow pool is greater than the second threshold, both flower and fruit litter production are maximal. The formulas are given as:

$$L_{i,year}\begin{cases} BF_{i,year} & BF_{i,year} \le lm_1 \\ lm_1 + (BF_{i,year} - lm_1) \times 0.3 & lm_1 < BF_{i,year} \le lm_2 \\ lm_2 & BF_{i,year} > lm_2 \end{cases} \tag{S47}$$

$$DC_i = BF_{i,year} - L_{i,year} \tag{S48}$$

where $L_{i,year}$ is annual litter production of the ith individual tree (kgC); $BF_{i,year}$ is the annual NSC slow pool (kgC); l_{m1} and l_{m2} are the first and the second thresholds of litter production, respectively (kgC), and l_{m1}=0.0001; DC_i is NSC storage (kgC), and 95% DC_i is transferred to support the growth of organs:

$$DC_i = \frac{[f_{wood}(d + \Delta d, h + \Delta h, b, hr, astem) - f'_{wood}(d, h, b, hr, astem)]}{0.95} \tag{S49}$$

$$\Delta h = cp \times \Delta d \tag{S50}$$

where *fwood* is the wood biomass added in the current year (kgC); *f'wood* is the wood biomass added in the previous year (kgC); *d* is the basal diameter (m); $\triangle d$ the increment of basal diameter (m); *h* is the tree height (m); $\triangle h$ is the increment of tree height (m); *b* is the twig height (m); *hr* is the root depth (m); *astem* is the bulk density of wood (kgC/m^3); *cp* is a constant decided by illumination gradients of tree canopy.

Tree death Individual trees are assumed to die when daily net photosynthate and NSC pools are not enough to support the growth of leaves (in some cases where previous years photosynthate has been allocated to the growth of canopy height and basal diameter (**Eqn S50**), the plant autotrophic respiration might be greater than the photosynthesis in some abnormal weather conditions). When tree death occurs in a given year, the C, N from dead trees is assumed to completely transfer to the soil pools at the end of the year (on the 31st December), and continue to participate in new C, N cycle in the coming year. In the current study, since the simulated time period is less than 50 years, we assume the new individual trees do not contribute materially to forest processes.

Methods S3. Model initialization processes

DBH estimation Although different tree species and individual trees have variable growth rates, the model uses a uniform method to express the initial vegetation conditions. Previous studies showed a linear relationship between the individual tree DBH and leaf area index (Petersen et al. 2007), the model LAI is calculated as follows:

$$DBH = \frac{LAI}{45} + 0.02 \qquad \text{(S51)}$$

where DBH (m) is the diameter at breast height, LAI is the leaf area index.

Tree height estimation The model uses tree diameter-height curves (Ogawa 1969) to simulate each tree's height:

$$\frac{1}{TH} = \frac{1}{a \times DBH^b} + \frac{1}{H^*} \qquad \text{(S52)}$$

where TH (m) is the tree height; a, b, and H^* are the regression coefficients, a=0.82, b=1.25, H^*=37.26 (Wang *et al.* 2006).

The height of lowest living branch (BH) is calculated by:

$$BH = \frac{1}{3} TH \qquad \text{(S53)}$$

Initialized Biomass estimation The initialized leaf biomass (G_{L0}) is calculated by tree species:

$$G_{L0}(i) = \begin{cases} 0, & i = \text{deciduous tree} \\ 1.99DBH^{2.13}BH^{-0.39}, & i = \text{evergreen tree} \end{cases} \tag{S54}$$

The initialized fine root biomass (G_{F0}) is proportional to leaf biomass:

$$G_{F0} = \frac{1}{2}G_{L0} \tag{S55}$$

The initialized wood biomass comprises stem biomass (G_{AS0}), twig biomass (G_{AT0}), and root biomass (G_{B0}):

$$G_{W0} = G_{AS0} + G_{AT0} + G_{B0} \tag{S56}$$

$$G_{AS0} = 2.02 \times Astem \times DBH^2 \times TH \tag{S57}$$

$$G_{AT0} = 1.12 \times Astem \times DBH^2 \times TH \times (1 + \frac{2}{TH}^{3})^2 \times \left(1 - \frac{2}{TH}\right) \tag{S58}$$

$$G_{B0} = 2.02 \times Astem \times DBH^2 \times TH \times [(1 + \frac{2}{TH}^{3})^2 \times \left(1 + \frac{2}{TH}\right) - 1] \tag{S59}$$

where *Astem* is a parameter taken from Table S1.

Methods S4. Statistical analyses

We used Pearson correlation coefficient (*r*), model efficiency (*E*), root mean square error (*RMSE*), mean absolute error (*MAE*), and bias (*bias*):

$$E = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \tag{S60}$$

$$bias = \frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i) \tag{S61}$$

where the X_i and Y_i are the predicted and measured data, respectively; $\bar{X}$ and $\bar{Y}$ represent their mean values. The range of *E* was $-\infty$ to 1, and *E* close to 1 means a perfect match between the predictions and measurement.

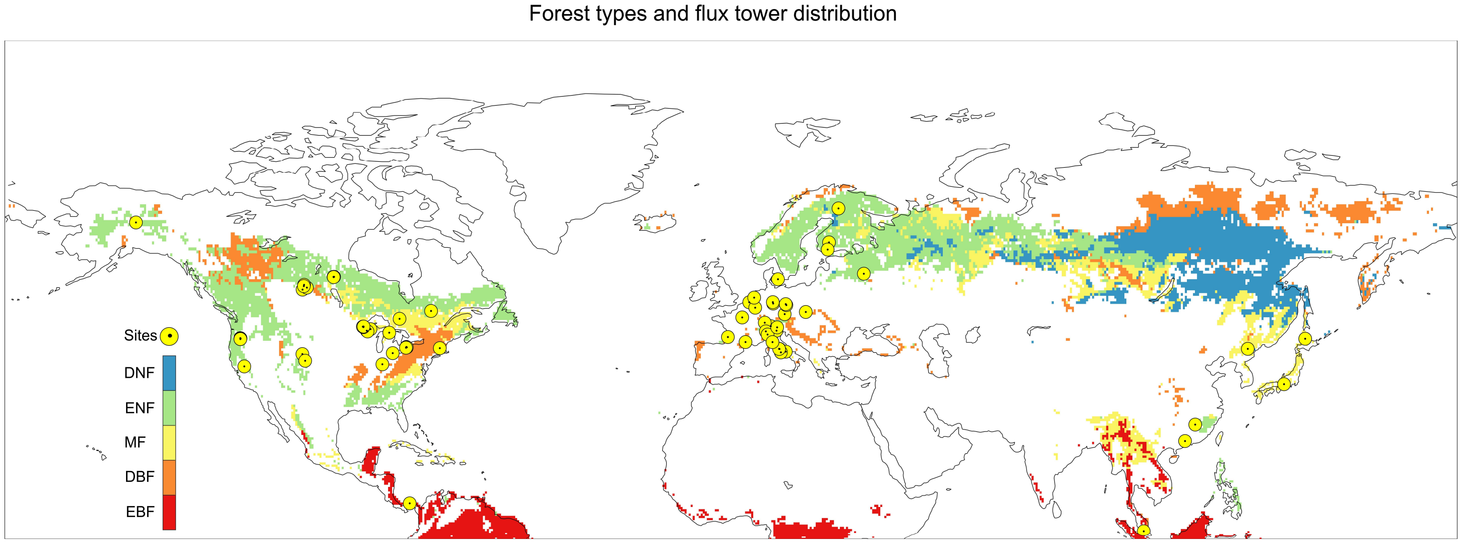
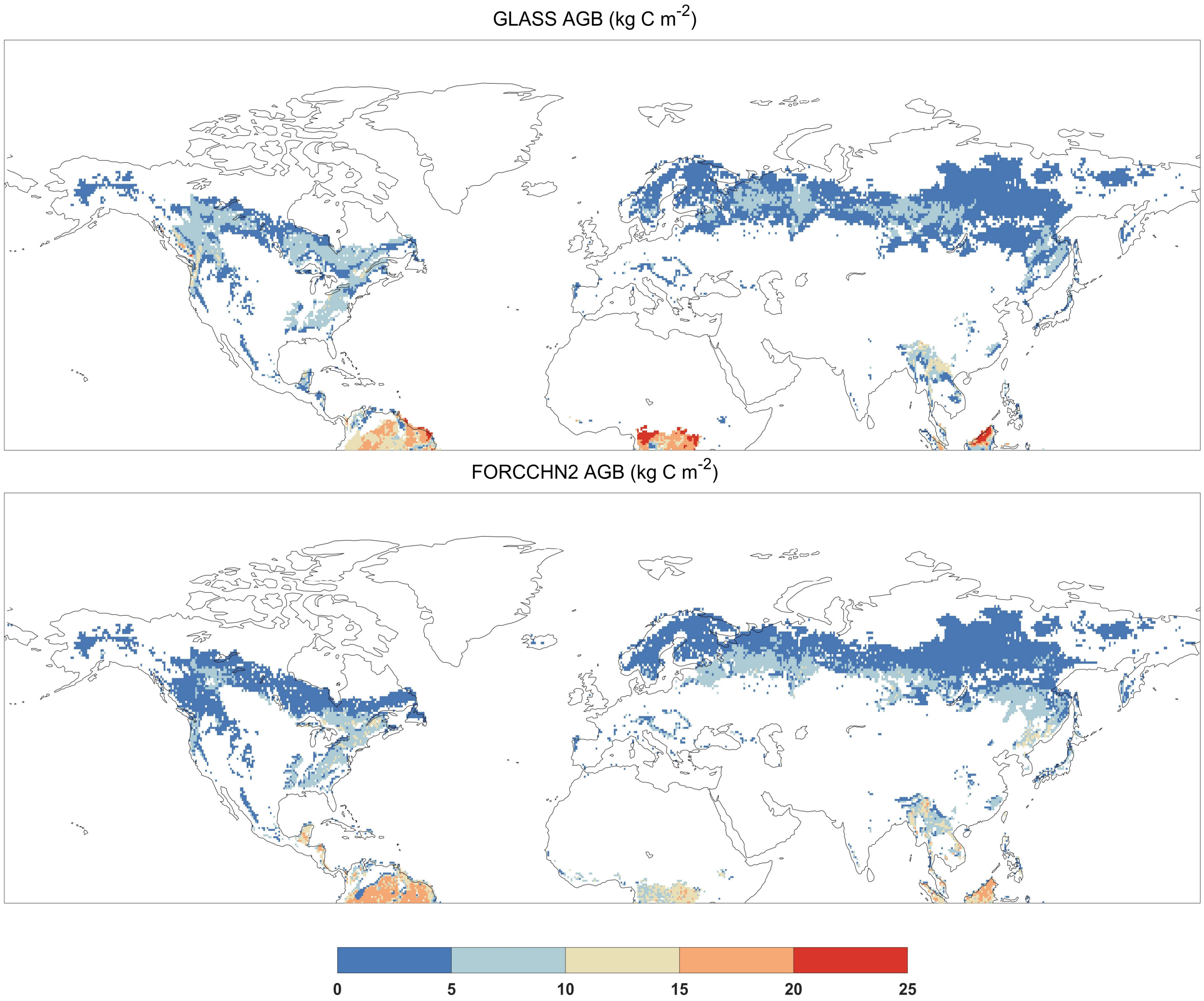


Fig. S1. Spatial distribution of studied EC sites and forest types based on Simple Biosphere (SiB) model of International Satellite Land Surface Climatology Project (ISLSCP II). EBF: the evergreen broadleaf forest; ENF: evergreen needleleaf forest; DBF: deciduous broadleaf forest; DNF: deciduous needleleaf forest; MF: mixed forest.



GLASS AGB (kg C m^{-2})

FORCCHN2 AGB (kg C m^{-2})

Fig. S2. The FORCCHN2-simulated and satellite-derived aboveground biomass (AGB) across the Northern Hemisphere. The satellite AGB are extracted from the GLASS product.

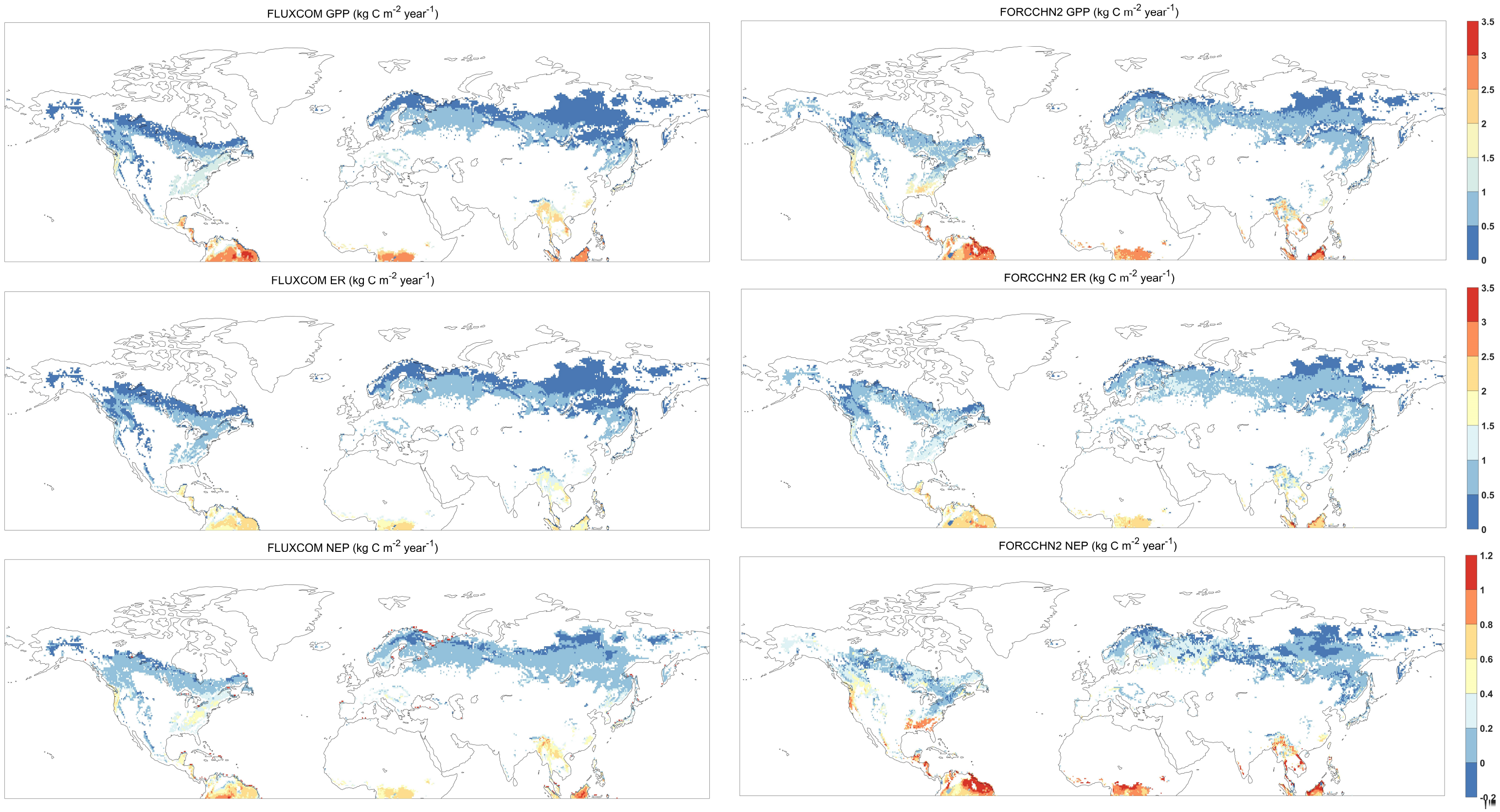


Fig. S3. The mean spatial distribution of FORCCHN2 and FLUXCOM gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem productivity (NEP) across the Northern Hemisphere during 1980–2013. The fluxes of FLUXCOM are extracted from the ‘RS+METEO’ dataset. The FLUXCOM NEP is equaled to the negative of net ecosystem CO2 exchange (NEE). The spatial resolution is 0.5º×0.5º.

Table S1. The studied EC Site information of the observed flux. ENF: evergreen needleleaf forest; EBF: evergreen broadleaf forest; DBF: deciduous broadleaf forest; MF: mixed forest.

Sites	Elevation (m)	Latitude (°)	Longitude (°)	Forest types
BE-Bra	16	51.3076	4.5198	MF
BE-Vie	493	50.3049	5.9981	MF
CA-Gro	340	48.2167	-82.1556	MF
CA-Man	259	55.8796	-98.4808	ENF
CA-NS1	260	55.8792	-98.4839	ENF
CA-NS2	260	55.9058	-98.5247	ENF
CA-NS3	260	55.9117	-98.3822	ENF
CA-NS4	260	55.9144	-98.3806	ENF
CA-NS5	260	55.8631	-98.485	ENF
CA-Oas	530	53.6289	-106.198	DBF
CA-Obs	628.94	53.9872	-105.118	ENF
CA-Qfo	382	49.6925	-74.3421	ENF
CA-SF1	536	54.485	-105.818	ENF
CA-SF2	520	54.2539	-105.878	ENF
CA-TP1	265	42.6609	-80.5595	ENF
CA-TP2	212	42.7744	-80.4588	ENF
CA-TP3	184	42.7068	-80.3483	ENF
CA-TP4	184	42.7102	-80.3574	ENF
CA-TPD	260	42.6353	-80.5577	DBF
CH-Dav	1639	46.8153	9.8559	ENF
CH-Lae	689	47.4783	8.3644	MF
CN-Cha	1242	42.4025	128.0958	MF
CN-Din	240	23.1733	112.5361	EBF
CN-Qia	111	26.7414	115.0581	ENF
CZ-BK1	875	49.5021	18.5369	ENF
DE-Hai	430	51.0792	10.4522	DBF
DE-Lkb	1308	49.0996	13.3047	ENF
DE-Lnf	451	51.3282	10.3678	DBF
DE-Obe	734	50.7867	13.7213	ENF
DE-Tha	385	50.9626	13.5651	ENF
DK-Sor	40	55.4859	11.6446	DBF
FI-Hyy	181	61.8474	24.2948	ENF
FI-Let	111	60.6418	23.9595	ENF
FI-Sod	180	67.3624	26.6386	ENF
FR-Fon	103	48.4764	2.7801	DBF
FR-LBr	61	44.7171	-0.7693	ENF
FR-Pue	270	43.7413	3.5957	EBF
IT-CA1	200	42.3804	12.0266	DBF

IT-Col	1560	41.8494	13.5881	DBF
IT-Cp2	19	41.7043	12.3573	EBF
IT-Cpz	68	41.7052	12.3761	EBF
IT-Isp	210	45.8126	8.6336	DBF
IT-La2	1350	45.9542	11.2853	ENF
IT-Lav	1353	45.9562	11.2813	ENF
IT-PT1	60	45.2009	9.061	DBF
IT-Ren	1730	46.5869	11.4337	ENF
IT-Ro1	235	42.4081	11.93	DBF
IT-Ro2	160	42.3903	11.9209	DBF
IT-SR2	4	43.732	10.2909	ENF
IT-SRo	6	43.7279	10.2844	ENF
JP-MBF	676	44.3869	142.3186	DBF
JP-SMF	397	35.2617	137.0788	MF
MY-PSO	102	2.973	102.3062	EBF
NL-Loo	25	52.1666	5.7436	ENF
PA-SPn	78	9.3181	-79.6346	DBF
RU-Fyo	265	56.4615	32.9221	ENF
US-Blo	1315	38.8953	-120.633	ENF
US-GLE	3197	41.3665	-106.24	ENF
US-Ha1	340	42.5378	-72.1715	DBF
US-MMS	275	39.3232	-86.4131	DBF
US-Me2	1253	44.4523	-121.557	ENF
US-Me3	1005	44.3154	-121.608	ENF
US-Me4	922	44.4992	-121.622	ENF
US-Me5	1188	44.4372	-121.567	ENF
US-Me6	998	44.3233	-121.608	ENF
US-NR1	3050	40.0329	-105.546	ENF
US-Oho	230	41.5545	-83.8438	DBF
US-PFa	470	45.9459	-90.2723	MF
US-Prr	210	65.1237	-147.488	ENF
US-Syv	540	46.242	-89.3477	MF
US-UMB	234	45.5598	-84.7138	DBF
US-UMd	239	45.5625	-84.6975	DBF
US-WCr	520	45.8059	-90.0799	DBF
US-Wi3	411	46.6347	-91.0987	DBF
US-Wi4	352	46.7393	-91.1663	ENF
US-Wi5	353	46.6531	-91.0858	ENF
US-Wi8	348	46.7223	-91.2524	DBF
US-Wi9	350	46.7385	-91.0746	ENF

Table S2. Physiological and ecological parameters in the original FORCCHN2 model. ST: shade-tolerant; SIT: shade-intolerant

Parameters	**Rain forest tree**		**Evergreen broadleaf tree**		**Deciduous broadleaf tree**		**Evergreen conifer tree**		**Deciduous conifer tree**
	ST	**SIT**	**ST**	**SIT**	**ST**	**SIT**	**ST**	**SIT**	
L_o	5.5	11.0	5.5	11.0	5.5	11.0	5.5	11.0	11.0
Am	5.5×10^{-4}	5.5×10^{-4}	5.5×10^{-4}	5.5×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}
Sl	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}
Kl	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	3.5×10^{-1}
r_L	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	6.0×10^{-3}	3.0×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	1.2×10^{-2}
r_W	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
r_R	1.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
lm_2	0.50	0.50	0.40	0.40	0.40	0.40	0.50	0.50	0.50
CN_L	40.0	40.0	45.0	45.0	40.0	40.0	60.0	60.0	50.0
CN_W	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
CN_R	40.0	40.0	45.0	45.0	40.0	40.0	60.0	60.0	50.0
Hmax	40.0	60.0	50.0	40.0	40.0	40.0	60.0	60.0	50.0
Dmax	2.0	3.0	2.0	1.5	2.0	1.5	2.0	2.0	2.0
Amax	200.0	100.0	400.0	200.0	400.0	200.0	1000.0	300.0	500.0
e_L	600.0	600.0	600.0	600.0	200.0	700.0	700.0	700.0	300.0
e_R	20.0	20.0	20.0	20.0	30.0	30.0	15.0	15.0	28.0
$cLAI_L$	15.0	15.0	15.0	15.0	45.0	20.0	18.0	18.0	40.0
Astem	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0
Tmin	5.0	5.0	3.0	1.0	-1.0	-5.5	-5.5	-2.5	-5.5
Topt	27.0	29.0	27.0	25.0	23.0	20.0	18.0	23.0	16.0
Tmax	50.0	50.0	50.0	50.0	45.0	45.0	40.0	40.0	35.0
DRY	1.0	0.8	0.9	0.8	0.8	0.6	0.9	0.7	0.5
l_L	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	1.1×10^{-4}	1.1×10^{-4}	2.0×10^{-3}	2.0×10^{-3}	1.1×10^{-4}
Lr/Nr	40.0	40.0	40.0	40.0	30.0	50.0	80.0	80.0	50.0

l_R	5.0×10^{-5}	5.0×10^{-5}	5.0×10^{-5}	5.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}	8.0×10^{-5}	8.0×10^{-5}	8.0×10^{-5}
cp	10	100	10	100	10	100	10	100	100

L_o-the photosynthesis compensate point; *Am*-the Maximal photosynthesis; *Sl*-the initial slope of light intension and photosynthesis[kg C/(m^2·h)/(W/m^2)]; *Kl*-the extinction coefficient; r_L-the relative breath rate of foliage (1/d); r_W-the relative breath rate of wood (1/d); r_R-the relative breath rate of root(1/d); lm_2- the threshold value of fruit; CN_L-the C:N ratio of foliage; CN_w-the C:N ratio of wood; CN_R-the C:N ratio of root; *Hmax*-the maximal tree height (m); *Dmax*-the maximal tree diameter (m); *Amax*-the maximal tree age (a); e_L-the coefficient of leaf content (kgC/m^2);e_R-the coefficient of root content (kgC/m^2); $cLAI_L$-the coefficient of leaf area (m^2/kgC); *Astem*-the bulk density of wood (kgC/m^3); *Tmin*-the lowest temperature of photosynthesis (°C); *Topt*-the optimum temperature of photosynthesis (°C); *Tmax*-the highest temperature of photosynthesis (°C); *DRY*-the capability of enduring drought; l_L-the relative litter rate of leaves(1/d); *Lr/Nr*-the ration of lignin and nitrogen content; l_R-the relative litter rate of root(1/d); *cp*-the constant depends on the light gradient.

Table S3. Phenological parameters in the FORCCHN2 model

Parameter	Meaning	Value	Unit
S_{A0}	The initial heat parameter on the first day of the year (calculated by first year)	(Eqn S43)	-
S_B	a predetermined level to determine Y_{cease} (calculated by first year)	(Eqn S45)	-
c	A parameter of temperature response factor	0.185	-
d	A parameter of temperature response factor	18.4	℃
T_B	The threshold parameter to determine the effective temperature (calculated by first year)	(Eqn S44)	℃

Table S4. Parameters of soil decomposition rate in the FORCCHN2 model.

Symbol	Unit	Litter and matter pool	Value
S1	d^{-1}	Above-ground metabolic litter pool	0.08
S2	d^{-1}	Above-ground structural litter pool	0.021
S3	d^{-1}	Below-ground metabolic litter pool	0.1
S4	d^{-1}	Below-ground structural litter pool	0.027
S5	d^{-1}	Fine woody litter pool	0.01
S6	d^{-1}	Coarse woody litter pool	0.002
S7	d^{-1}	Below-ground coarse litter pool	0.002
S8	d^{-1}	Above-ground active pool	0.04
S9	d^{-1}	Active soil organic matter pool	0.04
S10	d^{-1}	Slow soil organic matter pool	0.001
S11	d^{-1}	Resistant soil organic matter pool	3.5×10^{-5}

Table S5. Initialized allocation parameter of each soil pool in the FORCCHN2 model. These parameters are used as s_u in Eqn 16.

Litter and matter pool	Value (1/d)
Above-ground metabolic litter pool	0.01
Above-ground structural litter pool	0.01
Below-ground metabolic litter pool	0.01
Below-ground structural litter pool	0.01
Fine woody litter pool	0.01
Coarse woody litter pool	0.01
Below-ground coarse litter pool	0.01
Above-ground active pool	0.01
Active soil organic matter pool	0.02
Slow soil organic matter pool	0.02
Resistant soil organic matter pool	0.88