Supplementary material

S1 Cohort-level carbon cycling and aggregation

S1.1 Computational framework

The cohort extension retains the main VISIT process structure and resolves age effects on vegetation carbon with limited additional computation. In the full VISIT-4type configuration (RD), primary and secondary forest each contain six cohorts that independently track vegetation carbon, leaf-age distribution and phenological state. Cropland and other natural vegetation retain an area-mean vegetation state. Intermediate configurations used for attribution are defined in main-text Sect. 3.2 and Table 2.

The model separated shared environmental calculations from cohort-specific vegetation calculations (main-text Fig. 3). Cohorts within a forest type received the same grid-cell meteorological forcing and land-cover-level hydrological and soil conditions. Incident PAR was shared, whereas canopy absorption was recalculated from each cohort's own LAI. Each cohort then calculated photosynthesis, autotrophic respiration, carbon allocation, litterfall, phenology, and vegetation-carbon change.

Shared inputs and parameters included incident PAR, air temperature, soil moisture, hydrological fluxes, light-saturated photosynthetic rate, light-use efficiency, and temperature-response parameters. Cohort-specific variables included LAI, absorbed-PAR fraction, canopy extinction coefficient, optimal LAI, maintenance respiration, growth respiration, GPP, NPP, organ allocation, litterfall, leaf-age distribution, and phenological state. Cohort states and fluxes were aggregated to the land-cover level by area weighting after each monthly step; litter inputs were passed to shared soil pools and land-cover outputs were subsequently aggregated to the grid-cell level.

In the following sections, leaf, stem and root carbon pools are denoted by F_{fol}, F_{stm} and F_{rot}, respectively, in Mg C ha^{-1}. The subscripts v, c and m denote land-cover type, cohort and simulation month, respectively.

S1.2 Canopy photosynthesis and respiration

(1) Leaf area index

Each forest cohort calculates LAI from its leaf carbon:

$$LAI_{v,c} = \frac{SLA_v \cdot F_{\mathrm{fol},v,c} \cdot dmTc}{100 \times 2} \quad (S1)$$

Here, SLA_v is specific leaf area (cm^2 g^{-1}), and $dmTc$ is the dry-matter-to-carbon conversion factor. The constants 100 and 2 convert units and total to one-sided leaf area, respectively. The six forest cohorts calculate their own LAI, whereas cropland and other natural vegetation use a single representative vegetation state.

(2) Canopy radiative transfer

Under the shared grid-cell radiation environment, each cohort independently calculates

absorption of direct and diffuse PAR from its own leaf area index ($LAI_{v,c}$). Grid-cell forcing provides monthly incident PAR and its direct-diffuse components. Forest cohorts (V = 0, 1) perform this calculation separately, whereas cropland and other natural vegetation retain one representative state. Canopy radiation is evaluated hourly on the representative day of month m; at solar noon, the sine of solar elevation is:

$$\sin\beta_m = \sin\varphi\sin\delta_m + \cos\varphi\cos\delta_m \tag{S2}$$

Here, φ is grid-cell latitude, and δ_m is solar declination on the representative day; in the hourly calculation, the second term is multiplied by the cosine of the hour angle. When $\sin\beta_m \le 0$ or $LAI_{v,c} = 0$, the cohort is assumed not to absorb PAR in that month. Direct-beam extinction coefficients (k_{b1} and k_{b2}) and canopy reflectance (ρ_b) are determined by solar elevation:

$$k_{b1} = \frac{0.5}{\sin\beta_m}, \quad k_{b2} = \frac{0.46}{\sin\beta_m} \tag{S3a}$$

$$\rho_b = 1 - \frac{\exp(-2\iota_b k_{b1})}{1 + k_{b1}}, \qquad \iota_b = \frac{1-\sqrt{1-\sigma}}{1+\sqrt{1-\sigma}}, \quad \sigma = 0.15 \tag{S3b}$$

For each cohort, direct and diffuse APAR are calculated as:

$$\mathrm{APAR}^b_{v,c} = (1-\rho_b)\mathrm{PAR}^b_m\left[1-\exp\left(-k_{b2}\mathrm{LAI}_{v,c}\right)\right] \tag{S4a}$$

$$APAR^d_{v,c} = (1-0.036)PAR^d_m\left[1-\exp\left(-0.719LAI_{v,c}\right)\right] \tag{S4b}$$

The cohort's direct and diffuse PAR absorption is then used to calculate its $fAPAR_{v,c}$ and effective extinction coefficient $eK_{v,c}$:

$$fAPAR_{v,c} = \frac{APAR^b_{v,c} + APAR^d_{v,c}}{PAR_m} \tag{S5}$$

$$eK_{v,c} = -\frac{\ln(1-fAPAR_{v,c})}{LAI_{v,c}}, \tag{S6}$$

When $\sin\beta_m \le 0$ or $LAI_{v,c} = 0$, we set $fAPAR_{v,c} = 0$, and $eK_{v,c}$ reverts to its grid-cell empirical value. For numerical stability under low LAI, eK values below 0.46 are set to 0.1 and values above 5 are set to 10. Relative to the original VISIT, only land-cover mean LAI is replaced by cohort-specific $LAI_{v,c}$; the radiative-transfer parameterization is otherwise unchanged.

(3) Optimal leaf area index

Optimal LAI regulates subsequent photosynthate allocation. The original VISIT algorithm is retained, except that the canopy extinction coefficient is replaced by the cohort-specific value $eK_{v,c}$:

$$LAI^{\mathrm{opt}}_{v,c} = \frac{1}{eK_{v,c}}\ln\left[\max\left(1, \frac{eK_{v,c}LUE_v PAR_m}{P_{\mathrm{sat},v}\left(\kappa_{v,c}-1\right)}\right)\right] \tag{S7}$$

where

$$\kappa_{v,c} = \frac{P_{\mathrm{sat},v}D_m}{P_{\mathrm{sat},v}D_m - A_{r,v,c}DHN} \tag{S8}$$

Unlike the land-cover mean parameter in the original VISIT, cohort-specific eK and LAI are used here. Optimal LAI therefore reflects the actual canopy state of each age class and avoids systematic bias in young forests.

(4) Maintenance respiration

VISIT reduces stem and root mass-specific maintenance respiration as woody carbon increases using an empirical two-component proxy. For stems, the effective conductive-tissue proxy is:

$$M^{\mathrm{sap}}_{\mathrm{stm}} = F^{p_{\mathrm{stm},v,c}}_{\mathrm{stm},v,c}, \quad p_{\mathrm{stm},v,c} = 1 - 0.33334\frac{F_{\mathrm{stm},v,c}}{50 + F_{\mathrm{stm},v,c}} \tag{S9}$$

Here, Fstm,v,c denotes stem carbon of land-cover type v and cohort c (Mg C ha^{-1}); Mstm,sap is an empirical effective conductive-tissue proxy rather than an explicitly stored sapwood-carbon pool; and pstm,v,c is a dimensionless variable exponent. The numerical term 50 is a fixed, hard-coded carbon-stock scale in the model's Mg C ha^{-1} unit convention and is not biome specific. When Fstm,v,c is small, pstm,v,c approaches 1; as stem carbon increases, pstm,v,c approaches 2/3. Thus, pstm,v,c is an exponent rather than a sapwood fraction. The complementary component is:

$$M_{\mathrm{stm}}^{\mathrm{hrt}} = F_{\mathrm{stm},v,c} - M_{\mathrm{stm}}^{\mathrm{sap}} \tag{$S10$}$$

Mass-specific stem maintenance respiration is the mass-weighted mean of sapwood and heartwood respiration rates:

$$r_{mc,v,c} = \frac{r_{mc}^{s} M_{stm}^{sap} + r_{mc}^{h}(F_{stm,v,c} - M_{stm}^{sap})}{F_{stm,v,c} + 10^{-4}} \tag{S11}$$

Here, rmc,v,c denotes cohort mass-specific stem maintenance respiration; rmc,s is the higher conductive-tissue specific maintenance-respiration parameter; and rmc,h is the lower complementary-component parameter. The 10^{-4} denominator term prevents division by zero when stem carbon is near zero. This calculation updates only the mass-specific maintenance respiration coefficient; it does not create a separate sapwood or heartwood state pool.

Roots use the analogous exponent-and-weighting calculation, replacing stem carbon Fstm,v,c with root carbon Frot,v,c. The root-specific parameters represent the model's fine- and coarse-root components, so this calculation should be interpreted as an empirical respiration proxy rather than as a separately tracked root sapwood/heartwood pool. Biome dependence enters through Olson-class-specific maintenance- and growth-respiration parameters, not through the fixed scale term 50.

(5) Gross primary production

Canopy photosynthesis of each cohort is calculated with the Monsi–Saeki canopy integration model:

$$GPP_{v,c}^{d} = \frac{2P_{\mathrm{sat},v} D_m l T s}{eK_{v,c}} \ln\left[\frac{1+\sqrt{1+b_{v,c}}}{1+\sqrt{1+b_{v,c}\exp\left(-eK_{v,c}LAI_{v,c}\right)}}\right] \tag{$S12$}$$

where

$$b_{v,c} = \frac{eK_{v,c} LUE_v PAR_m}{P_{\mathrm{sat},v}} \tag{S13}$$

Monthly GPP equals daily integrated GPP multiplied by the number of days in the month.

(6) Autotrophic respiration and net primary production

Autotrophic respiration is resolved independently for each land-cover type v and cohort c, and is composed of maintenance respiration and growth respiration. Maintenance respiration of leaves, stems, and roots is calculated from the corresponding carbon pools, mass-specific maintenance-respiration coefficients, and temperature-response functions:

$$R_{fm,v,c} = F_{fol,v,c} \frac{r_{mf}}{1000} f_{Tf} \tag{$S14a$}$$

$$R_{cm,v,c} = F_{stm,v,c} \frac{r_{mc,v,c}}{1000} f_{Tc} \tag{$S14b$}$$

$$R_{rm,v,c} = F_{rot,v,c} \frac{r_{mr,v,c}}{1000} f_{Tr} \tag{S14c}$$

where $F_{fol,v,c}$, $F_{stm,v,c}$, and $F_{rot,v,c}$ are the leaf, stem, and root carbon pools, respectively; r_{mf},

$r_{mc,v,c}$, and $r_{mr,v,c}$ are the corresponding mass-specific maintenance-respiration coefficients; and f_{Tf}, f_{Tc}, and f_{Tr} are temperature-response functions for leaf, stem, and root respiration. The factor 1/1000 ensures consistency between the units of carbon pools and respiration fluxes. Growth respiration is subsequently calculated from the carbon allocated to leaves, stems, and roots:

$$R_{fg,v,c} = r_{gf}T_{pf}, \qquad R_{cg,v,c} = r_{gc}T_{pc}, \qquad R_{rg,v,c} = r_{gr}T_{pr} \tag{S15}$$

where T_{pf}, T_{pc}, and T_{pr} are carbon inputs allocated to leaves, stems, and roots, respectively, and r_{gf}, r_{gc}, and r_{gr} are the corresponding growth-respiration coefficients. These allocation fluxes are determined by the cohort-level carbon-allocation scheme described in Sect. S1.3. Total maintenance respiration and growth respiration are obtained by summing the organ-specific components:

$$R_{m,v,c} = R_{fm,v,c} + R_{cm,v,c} + R_{rm,v,c} \tag{$S16a$}$$

$$R_{g,v,c} = R_{fg,v,c} + R_{cg,v,c} + R_{rg,v,c} \tag{$S16b$}$$

Autotrophic respiration and net primary production are then calculated as:

$$R_{a,v,c} = R_{m,v,c} + R_{g,v,c} \tag{$S17a$}$$

$$NPP_{v,c} = GPP_{v,c} - R_{a,v,c} \tag{S17b}$$

Resolving respiration and NPP separately for each cohort permits age-dependent differences in vegetation structure, metabolism, and carbon allocation while retaining the original environmental forcing framework.

S1.3 Carbon allocation, litterfall and phenology

Before NPP is formed, maintenance respiration is subtracted from GPP to obtain excess primary production (EPP):

$$EPP_{v,c} = GPP_{v,c} - R_{m,v,c} \tag{$S18$}$$

Here, $R_{m,v,c}$ is the sum of leaf, stem, and root maintenance respiration. The resulting $EPP_{v,c}$ is then allocated to leaf, stem, and root at cohort level, with concurrent updates of litter input and leaf-age structure. These processes depend directly on current biomass and canopy state and are therefore calculated independently for each cohort.

(1) Photosynthate allocation

VISIT uses dynamic carbon allocation: the deviation of current from optimal LAI adjusts the fractions of new carbon allocated to leaf, stem, and root. The following calculations apply only when EPPv,c > 0. When the canopy reaches or exceeds optimal leaf area ($LAI_{v,c} > LAI_{v,c}^{\mathrm{opt}}$), leaf allocation decreases and woody and root allocation increase.

$$a_{f,v,c} = a_{\mathrm{ass}}\left[1 - 0.5\left(LAI_{v,c} - LAI_{v,c}^{\mathrm{opt}}\right)\right]^{+} \tag{$S19a$}$$

$$a_{c,v,c} = \left(1 - a_{f,v,c}\right)a_{\mathrm{abg}} \tag{$S19b$}$$

$$a_{r,v,c} = \left(1 - a_{f,v,c}\right)\left(1 - a_{\mathrm{abg}}\right) \tag{$S19c$}$$

The positive-part operator takes the larger value. a_{ass} is the maximum leaf-allocation fraction, and a_{abg} is the aboveground-biomass allocation coefficient. When current cohort LAI does not exceed optimal LAI, leaf allocation is increased to approach the optimal canopy. Let ΔF_{fol} be the additional leaf carbon required to reach optimal LAI; if default leaf allocation is insufficient, it is increased but capped at 0.5. A seasonal factor ds is then applied (1.0 in the growing season and 0.7 otherwise):

$$a_{f,v,c} = \min\left[0.5,\ a_{\mathrm{ass}} \cdot \max\left(1,\ \frac{\Delta F_{\mathrm{fol}}}{a_{\mathrm{ass}}\mathrm{EPP}_{v,c}}\right)\right] d_s \tag{$S19d$}$$

Stem and root allocation continue to follow Eqs. (S19b)–(S19c) using the updated leaf-allocation

term $a_{f,v,c}$. Carbon inputs to each organ are:

$$T_{\mathrm{pf}} = a_{f,v,c} EPP_{v,c} \quad (S20a)$$

$$T_{\mathrm{pc}} = a_{c,v,c} EPP_{v,c} \quad (S20b)$$

$$T_{\mathrm{pr}} = a_{r,v,c} EPP_{v,c} \quad (S20c)$$

Because LAI and optimal LAI were calculated from the leaf carbon of each cohort, young forests generally prioritized canopy expansion whereas mature forests allocated relatively more carbon to woody biomass. Growth respiration was calculated after allocation, and NPP was obtained as EPP minus growth respiration.

(2) Litterfall

After biomass allocation, each cohort independently calculates leaf, stem, and root litterfall. Turnover rates retain the original VISIT parameters and are modified by phenology and environmental conditions:

$$L_{f,v,c} = l_f F_{\mathrm{fol},v,c} \quad (S21a)$$

$$L_{c,v,c} = l_c F_{\mathrm{stm},v,c} \quad (S21b)$$

$$L_{r,v,c} = l_r F_{\mathrm{rot},v,c} \quad (S21c)$$

l_f includes temperature correction. Monthly litterfall equals the daily rate multiplied by the number of days in the month. The sum of the three organ fluxes is the cohort's monthly litter input to the soil carbon pool:

$$L_{v,c} = L_{f,v,c} + L_{c,v,c} + L_{r,v,c} \quad (S22)$$

Biomass and developmental state differ among age classes; their litter inputs therefore differ and influence subsequent soil organic-matter decomposition through area weighting.

(3) Leaf-age distribution and phenology

In addition to carbon pools, each cohort independently maintains leaf-age distribution and phenological state, including accumulated leaf-out and leaf-fall, growing degree days, and growing-season length. Under shared environmental conditions, cohorts update leaf emergence, senescence, and fall from their own thermal accumulation and leaf-age structure. The VISIT 49-layer leaf-age structure is retained:

$$\mathrm{A}_{v,c} = \left(a_{\{0,v,c\}}, a_{\{1,v,c\}}, \ldots, a_{\{48,v,c\}}\right) \quad (S23)$$

Here, $a_{\{k,v,c\}}$ denotes the fraction in leaf-age layer k for land-cover type v and cohort c, where k = 0 denotes newly formed leaves and k = 48 is an open-ended class for leaves aged 48 months or older. The distribution is updated once per monthly model time step. Independent leaf-age distributions allow age classes to develop distinct leaf-age composition and phenological rhythms without mixing their states.

S1.4 Disturbance update

Disturbance was applied in two stages. Area transfers caused by land-use change were applied at the start of the year, before the monthly ecosystem calculations (main-text Sect. 2.3.3). Biomass burning, stand aging, cohort transition, and wood harvest were applied at the end of the year, after the 12 monthly calculations; the land-use transfer recorded at the start of the year was converted to fluxes in the same end-of-year block. Biomass burning modified vegetation carbon without changing cohort area, whereas harvest and land-use change modified both area and vegetation carbon according to main-text Sect. 2.3.

Clearing removed area and carbon from the selected cohorts. Primary-forest logging carry transferred affected area from V0 to Cohort 1 of V1 across the year boundary (main-text Sect. 2.3.3).

Secondary-forest harvest retained area in V1 but reset age and vegetation carbon using the residue-reserved Cohort 1 state (main-text Sect. 2.3.4). Both logging carry and abandonment entered Cohort 1 of V1, but only abandonment was initialized to the sapling reference state. Removed vegetation carbon was allocated as described in main-text Sect. 2.4. Partial disturbance did not alter the carbon density of the undisturbed portion of a cohort.

VISIT first calculates organ-specific biomass-burning losses at the land-cover level. These losses are mapped to forest cohorts using the corresponding land-cover survival fraction:

$$r_{x,v} = \begin{cases} \min\left[1, \max\left(0, \frac{F_{x,v}^{\text{after}}}{F_{x,v}^{\text{before}}}\right)\right], & F_{x,v}^{\text{before}} > \epsilon, \\ 1, & F_{x,v}^{\text{before}} \le \epsilon, \end{cases} \tag{S24}$$

$$F_{x,v,c}^{\text{new}} = r_{x,v} F_{x,v,c}^{\text{old}},\ x \in \{\text{fol}, \text{stm}, \text{rot}\}. \tag{S25}$$

Here, $F_{x,v}^{\text{before}}$ and $F_{x,v}^{\text{after}}$ are the aggregated land-cover carbon densities before and after biomass burning, respectively. The parameter ϵ is a small positive threshold that prevents division by zero. The survival fraction $r_{x,v}$ is restricted to $[0, 1]$. Uniform scaling retains the original VISIT assumption that the fractional fire loss of a given organ does not vary with stand age.

For primary and secondary forests, land-cover NEP is obtained by area weighting:

$$\text{NEP}_v = \sum_{c=1}^{6} \phi_{v,c}\, \text{NEP}_{v,c},\ v \in \{0, 1\} \tag{S26a}$$

where $\phi_{v,c}$ is the area fraction of cohort c within forest type v. Cropland and other natural vegetation have no cohort structure, so their land-cover NEP is calculated directly. After current-year product-pool release, complete NBP is diagnosed at the land-cover level:

$$\text{NBP}_v = \text{NEP}_v - E_{\text{conv},v} - E_{10,v} - E_{100,v} - E_{\text{fire},v} - E_{\text{other},v} \tag{S26b}$$

Here, $E_{\text{conv},v}$ includes instantaneous conversion emissions and harvest-year fuelwood; $E_{10,v}$ and $E_{100,v}$ are releases from the 10- and 100-year product-vintage pathways. These LUC deductions apply to V0, V1 and V3; crop biomass removed when cropland is abandoned is not deducted from NBP (main-text Sect. 3.3.4). $E_{\text{fire},v}$ includes carbon released as CO_2, CO, CH_4 and black carbon during biomass burning. $E_{\text{other},v}$ comprises crop harvest, dissolved organic carbon export, 20% of erosion carbon and biogenic volatile organic compound emissions, minus net methane uptake. Harvest sapling carbon is reserved internally from residues, whereas new forest gains use the reference establishment states in main-text Sect. 2.3.4. Annual stocks used here are the means of 12 monthly output values. Product emissions are not reassigned to current forest cohorts because they originate from biomass removed in earlier years as well as the current year. Cohort diagnostics therefore include NEP and vegetation-carbon change; the reported NBP is available at land-cover and grid-cell levels.

S1.5 Area-weighted cohort aggregation

Cohort vegetation states and fluxes were aggregated to the land-cover level after each monthly step and again after the end-of-year disturbance update. This procedure conserved the area and vegetation carbon represented by cohort states.

For primary and secondary forests, the area fraction of cohort c within forest type v is

$$\phi_{v,c} = \frac{A_{v,c}}{A_v},\ \sum_{c=1}^{6} \phi_{v,c} = 1, \tag{S27}$$

where $A_{v,c}$ and A_v are the cohort area and total area of forest type v, respectively. When $A_v = 0$, all cohort fractions and aggregated outputs for that forest type are set to zero. Land-cover vegetation carbon densities are reconstructed by area weighting:

$$F_{x,v} = \sum_{c=1}^{6} \phi_{v,c} F_{x,v,c},\ x \in \{\text{fol}, \text{stm}, \text{rot}\}. \quad (S28)$$

Cohort carbon fluxes are aggregated in the same way:

$$X_v = \sum_{c=1}^{6} \phi_{v,c} X_{v,c}, \quad (S29)$$

where X denotes GPP, autotrophic respiration, NPP, NEP, or litter input. Diagnostic ratios, such as organ-allocation fractions, are reconstructed from the corresponding aggregated carbon fluxes rather than by directly averaging cohort ratios. Cropland and other natural vegetation have no cohort structure, so their states and fluxes are used directly. Land-cover outputs are then combined using their fractions of modelled land area:

$$\sum_{v=0}^{3} f_v = 1 \quad (S30)$$

$$X_{\text{grid}} = \sum_{v=0}^{3} f_v X_v \quad (S31)$$

Here, f_v is the grid-cell area fraction of land-cover type v. The reconstructed grid-cell outputs include vegetation carbon, GPP, NPP, NEP, NBP, and litter input.

Canopy photosynthesis was calculated before aggregation because it is nonlinear in LAI. Thus, calculating GPP separately for each cohort and then applying Eq. (S31) is not equivalent to calculating GPP from land-cover-mean LAI. The cohort-first approach retains age-related differences in canopy structure, photosynthesis, allocation, and biomass development while preserving the original land-cover-level hydrological and soil framework.

S2 Supplementary figures and evaluation statistics

The full configuration is RD (VISIT-4type), and the reference is R0f (VISIT-2type). The main attribution contrasts are land-cover structure and transitions (RA − R0f), wood harvest including age structure (RC − RA) and secondary-forest traits (RD − RC). These contrasts sum to RD − R0f and are independent of the order in which age structure and harvest are added. Tables S1 and S3 additionally show their separate conditional contributions in both orders. RA has no age cohorts or harvest; RB adds age cohorts; RC adds harvest; RD adds secondary-forest traits; RCp adds harvest to RA without age cohorts.

Annual site statistics use matched years separately for GPP, NEE and ecosystem respiration (RECO). Pooled statistics use 696, 503 and 676 site-years, respectively. Site-level Taylor symbols and the median and Wilcoxon comparisons in main-text Sect. 4.1 use sites with at least five paired years (56, 42 and 53 sites). Only annual Taylor diagrams are included. NEE = −NEP, so positive NEE denotes carbon release to the atmosphere. Site bootstrap intervals resample sites with replacement (2000 samples), retaining all paired years within each selected site.

Grid statistics compare monthly model fluxes with FLUXCOM X-BASE over 2001–2019 on

a common valid-month mask. Positive ΔRMSE = RMSE(earlier configuration) − RMSE(later configuration) denotes lower error in the later configuration. Grid means are weighted by cell area. Spatial uncertainty uses 2000 block-bootstrap samples (5° × 5° blocks for global means, 10° × 10° for subsets). Land-use-history groups use the cumulative harvested area and cleared forest area over 1851–2019 in VISIT-4type, each with a threshold of 1% of cell area.

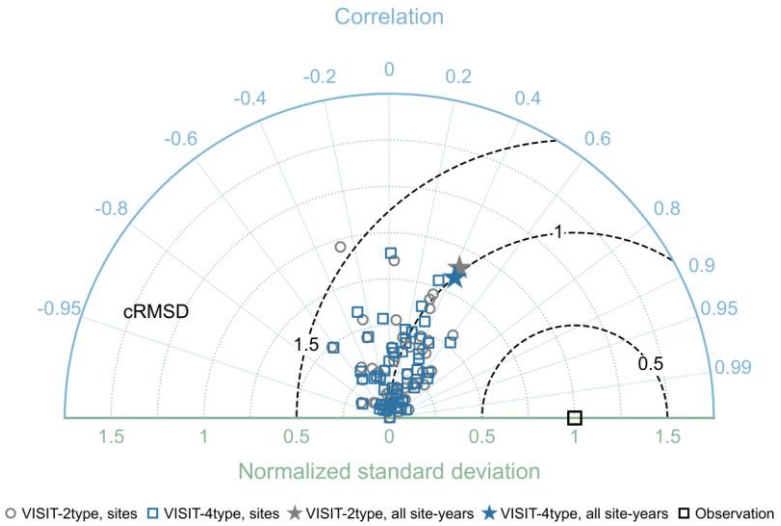


Figure S1. Taylor-diagram evaluation of annual ecosystem respiration (RECO) against eddy-covariance observations. Grey open circles and blue open squares show VISIT-2type and VISIT-4type at the 53 sites with at least five paired years; filled stars show the pooled statistics for 676 paired site-years. The blue outer arc gives correlation, the green radial scale gives standard deviation normalized by observations, and black dashed arcs give normalized cRMSD of 0.5, 1.0 and 1.5 from the observational reference (black open square).

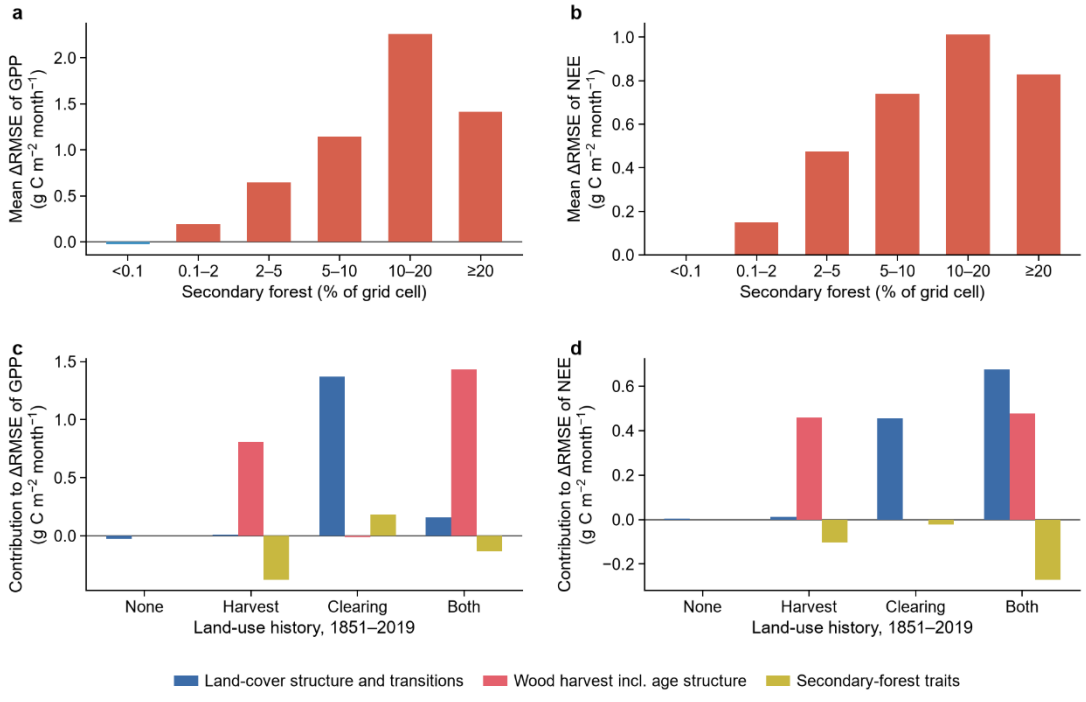


Figure S2. Dependence of the FLUXCOM X-BASE evaluation on land use. (a, b) Area-weighted mean ΔRMSE of monthly GPP and NEE for grid cells grouped by the 2001–2019 mean secondary-forest fraction simulated by VISIT-

4type. (c, d) Contributions to the mean ΔRMSE of the land-use-history groups of Fig. 5c, f from the land-cover structure and transitions (RA − R0f), wood harvest including age structure (RC − RA) and the secondary-forest traits (RD − RC). Positive values indicate lower error in VISIT-4type.

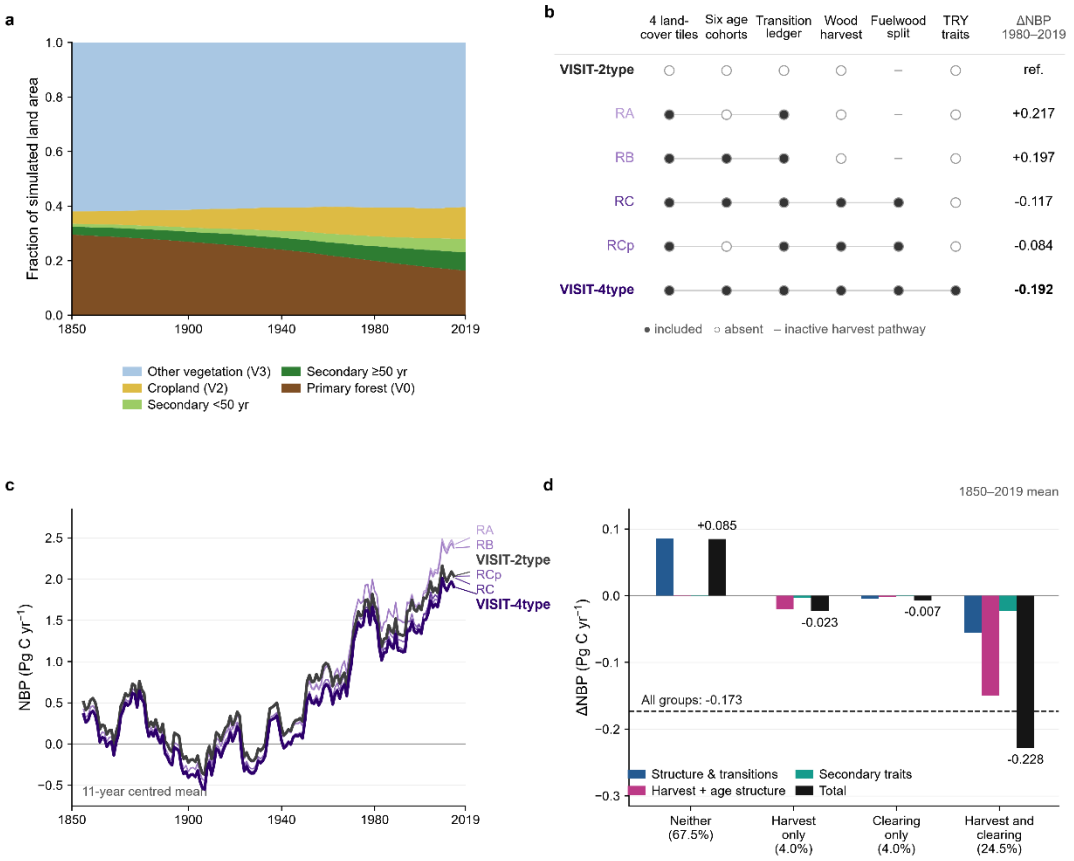


Figure S3. Context for the carbon-budget attribution. (a) Global fractions of modelled land in primary forest, secondary forest younger than 50 years, secondary forest at least 50 years old, cropland and other natural vegetation, including pasture. All five classes sum to one, with only rounding-level normalization of the source fractions. (b) Process matrix for the six configurations; filled circles indicate included processes, open circles indicate absent processes and dashes indicate inactive harvest routing. The final column gives the 1980–2019 mean ΔNBP relative to VISIT-2type, in Pg C yr^{-1}. (c) Absolute NBP of all six experiments as complete 11-year centred means (1855–2014), with VISIT-2type and VISIT-4type emphasized and each curve labelled at the right. (d) Contributions to the 1850–2019 mean ΔNBP integrated over four fixed land-use-history groups. A process is present when cumulative harvest or cleared forest area exceeds 1% of the cell over 1851–2019. Percentages give shares of the modelled land area. The dashed line is the sum over all four groups (−0.173 Pg C yr^{-1}); small differences from the global annual diagnostic reflect aggregation domains and rounding. Differences use RD − R0f and the component contrasts defined above.

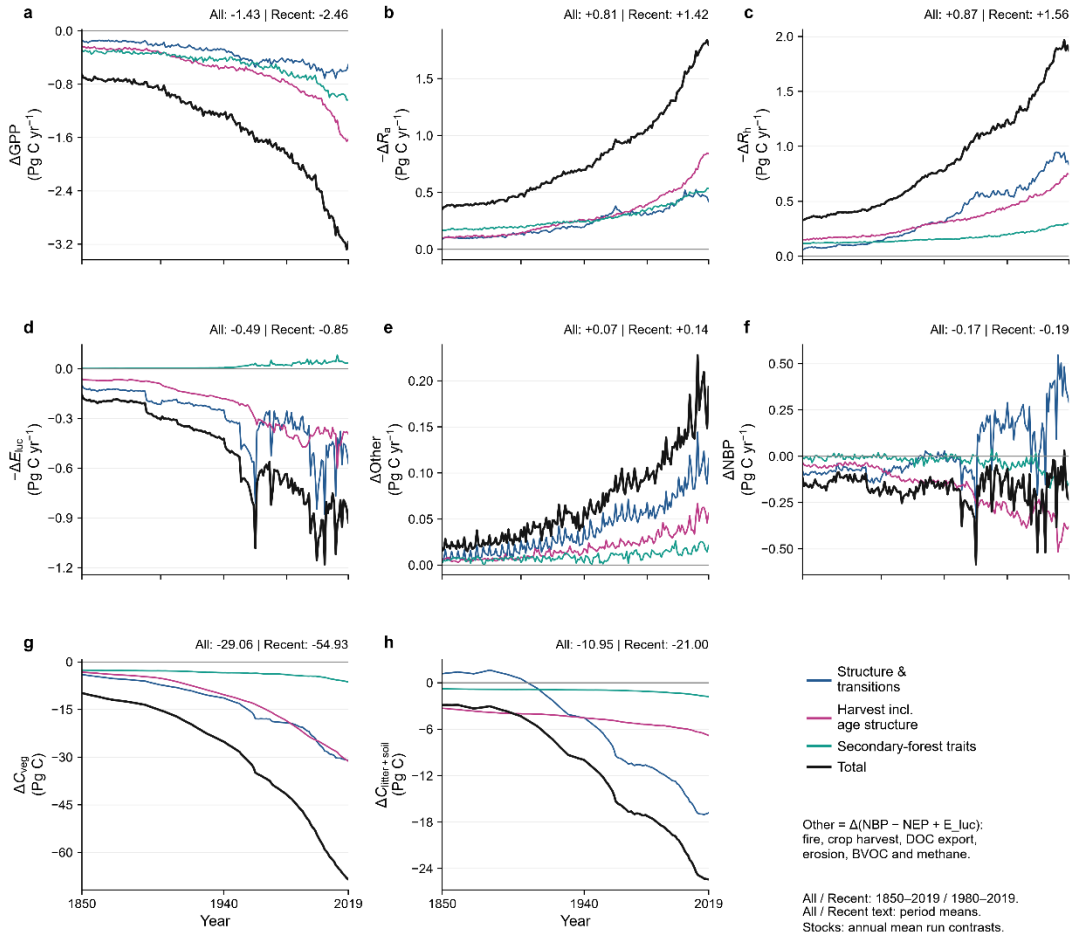


Figure S4. Annual component trajectories underlying Fig. 7. (a–f) ΔGPP, −ΔRa, −ΔRh, −ΔE$_{LUC}$, ΔOther and ΔNBP; flux contributions are positive when they increase the reported land sink and are in Pg C yr^{-1}. (g, h) Direct differences in annual-mean vegetation carbon and litter plus soil carbon, in Pg C, without rebasing the 1850 difference. Blue, magenta and teal represent land-cover structure and transitions (RA − R0f), wood harvest including age structure (RC − RA), and secondary-forest traits (RD − RC); black is their sum (RD − R0f). Annotations give the 1850–2019 and 1980–2019 period means of the displayed variable. Other = NBP − NEP + E$_{LUC}$. The ninth cell gives the shared legend and sign convention.

Table S1 Evaluation statistics by model change

Changes in the evaluation statistics attributed to the model changes. Site ΔRMSE in g C m^{-2} yr^{-1} for all paired site-years (696 for GPP, 503 for NEE, 676 for ecosystem respiration) with 95% intervals from a site bootstrap; grid ΔRMSE in g C m^{-2} month^{-1} as area-weighted means against FLUXCOM X-BASE. Positive ΔRMSE indicates lower error. The four sequential steps, their combined contrast (wood harvest including age structure, RC − RA), which is unchanged by swapping the age and harvest additions, and the alternative order (harvest before age structure, via RCp) are listed; the change in mean simulated site flux is given for each step.

Table S1 (a) Annual site GPP

Component (later − earlier)	ΔRMSE	95% interval	Δmean flux
Structure and transitions (RA − R0f)	0.13	−2.4 to 3.0	−2.91
Age structure (RB − RA)	12.18	3.8 to 22.7	−1.30
Harvest (RC − RB)	4.22	−5.0 to 14.7	−25.99
Harvest including age (RC − RA)	16.40	—	−27.29
Secondary-forest traits (RD − RC)	1.08	−22.9 to 22.6	−13.34
Total (RD − R0f)	17.61	−13.5 to 44.4	−43.54
Age structure added after harvest (RC − RCp)	17.56	5.6 to 31.4	−13.00
Harvest added before age structure (RCp − RA)	−1.16	−5.1 to 2.5	−14.29

In Tables S1a–c, all numerical entries, including confidence limits, are in g C m^{-2} yr^{-1}. Δmean flux is later minus earlier simulated flux; positive ΔRMSE denotes lower error. The pooled ΔRMSE differs from the median per-site RMSE change reported in the main text. Intervals are 95% site-bootstrap intervals from 2000 samples. An em dash denotes an unreported interval for RC − RA. It is not obtained by adding the separate confidence limits.

Table S1 (b) Annual site NEE

Component (later − earlier)	ΔRMSE	95% interval	Δmean flux
Structure and transitions (RA − R0f)	7.94	3.1 to 12.7	−11.86
Age structure (RB − RA)	1.25	−0.2 to 3.6	0.10
Harvest (RC − RB)	2.53	0.6 to 5.1	−2.66
Harvest including age (RC − RA)	3.78	—	−2.56
Secondary-forest traits (RD − RC)	−0.29	−4.4 to 3.1	5.71
Total (RD − R0f)	11.43	5.6 to 16.8	−8.70
Age structure added after harvest (RC − RCp)	2.09	0.0 to 4.4	0.31
Harvest added before age structure (RCp − RA)	1.69	0.6 to 2.9	−2.87

Table S1 (c) Annual site ecosystem respiration

Component (later − earlier)	ΔRMSE	95% interval	Δmean flux
Structure and transitions (RA − R0f)	2.19	−3.0 to 7.9	−13.96
Age structure (RB − RA)	8.86	4.6 to 13.7	−1.12
Harvest (RC − RB)	11.15	0.3 to 23.4	−30.22

Harvest including age (RC − RA)	20.01	—	−31.34
Secondary-forest traits (RD − RC)	2.16	−17.8 to 19.8	−8.99
Total (RD − R0f)	24.36	−8.4 to 53.5	−54.29
Age structure added after harvest (RC − RCp)	16.68	8.2 to 25.7	−13.24
Harvest added before age structure (RCp − RA)	3.33	−1.5 to 8.2	−18.10

Table S1 (d) Monthly grid-scale evaluation

Component (later − earlier)	GPP ΔRMSE	NEE ΔRMSE
Structure and transitions (RA − R0f)	0.08	0.19
Age structure (RB − RA)	0.18	0.04
Harvest (RC − RB)	0.21	0.10
Harvest including age (RC − RA)	0.38	0.14
Secondary-forest traits (RD − RC)	−0.04	−0.07
Total (RD − R0f)	0.42	0.25
Age structure added after harvest (RC − RCp)	0.40	0.08
Harvest added before age structure (RCp − RA)	−0.02	0.05

Area-weighted grid means over 2001–2019, in g C m^{-2} $month^{-1}$. Positive values denote lower error; all configurations use the same evaluation mask.

Table S2. Wood harvest in VISIT-4type and LUH2-GCB2025 by period (means of annual values; carbon per area as the ratio of period sums): harvested area, stem carbon and total biomass removed, LUH2 wood-harvest biomass and their ratios, carbon per harvested area in primary and secondary forest, harvest-weighted vegetation carbon of primary forest, secondary-forest vegetation carbon and LUH2 secmb, and the fate of the removed carbon.

Quantity	Unit	1850–1939	1940–1979	1980–2019
VISIT stem carbon removed	Pg C yr^{-1}	0.179	0.470	0.696
VISIT total biomass removed (stem, leaves and roots)	Pg C yr^{-1}	0.240	0.597	0.913
LUH2 wood-harvest biomass (bioh)	Pg C yr^{-1}	0.404	0.845	1.144
VISIT stem / LUH2 bioh	1	0.444	0.556	0.608
VISIT total biomass / LUH2 bioh	1	0.593	0.706	0.798
Fuelwood emitted in harvest year	Pg C yr^{-1}	0.117	0.294	0.389
Inputs to 10- and 100-year product pools	Pg C yr^{-1}	0.028	0.077	0.134
Residues entering litter and soil	Pg C yr^{-1}	0.086	0.214	0.367

Carbon retained as initial regrowth biomass	Pg C yr^{-1}	0.010	0.011	0.022
Primary forest: VISIT stem carbon per harvested area	Mg C ha^{-1}	37.584	55.470	69.391
Primary forest: VISIT total biomass removed per harvested area	Mg C ha^{-1}	47.795	67.895	84.143
Primary forest: harvest-area-weighted tile vegetation carbon	Mg C ha^{-1}	47.394	65.498	80.741
Primary forest: LUH2 bioh per harvested area	Mg C ha^{-1}	73.197	86.965	92.939
Secondary forest: VISIT stem carbon per harvested area	Mg C ha^{-1}	0.920	5.110	4.711
Secondary forest: VISIT total biomass removed per harvested area	Mg C ha^{-1}	1.830	7.896	7.660
Secondary forest: LUH2 bioh per harvested area	Mg C ha^{-1}	4.574	15.464	11.770
VISIT realized harvest area	Mha yr^{-1}	22.028	20.350	42.926
LUH2 requested harvest area	Mha yr^{-1}	22.543	20.668	43.812
VISIT secondary-forest vegetation carbon density	Mg C ha^{-1}	45.797	42.475	43.178
LUH2 secondary mean biomass density (secmb)	Mg C ha^{-1}	57.667	50.334	48.931

Fluxes and areas are means of annual values. Carbon per harvested area is the ratio of carbon summed over the period to the corresponding summed harvested area. Mha = 10^6 ha. A unit of 1 denotes a dimensionless ratio. Stem carbon is the principal VISIT quantity compared with LUH2 bioh; total removed biomass is included for context. The four fates (fuelwood, products, residues and initial regrowth biomass) sum to total biomass removed before rounding. Product values are annual pool inputs, not annual pool releases. Primary harvest-area-weighted tile vegetation carbon uses the primary-tile vegetation carbon density multiplied by realized harvest area, rather than the carbon density of only selected harvested cohorts. Secondary-forest vegetation carbon density is compared only where LUH2 forest accounts for at least 80% of secondary land and VISIT secondary forest occupies at least 1% of the cell; LUH2 secondary-land area provides the spatial weights. For 2010–2019, the annual harvest series gives mean realized harvest area of 70.5 Mha yr^{-1} and total removed biomass of 1.01 Pg C yr^{-1} (Fig. 6a).

Table S3 Carbon stocks and the spatial attribution of NBP

(a) Annual-mean global vegetation, litter plus soil, and ecosystem carbon stocks in 2019 for six simulations, together with their separate 1850–2019 mean NBP. (b) The corresponding conditional configuration contrasts. (c) Mean ΔNBP by land-use-history group. (d) Mean ΔNBP by latitude band. (e) Stock–flux residuals of the six simulations.

Table S3 (a) Annual-mean carbon stocks in 2019 and full-period mean NBP

Simulation	Vegetation C	Litter + soil C	Ecosystem C	Mean NBP
R0f	531.8	1312.4	1844.2	0.704
RA	501.0	1295.6	1796.5	0.729
RB	500.6	1295.8	1796.4	0.721
RC	469.7	1288.7	1758.4	0.558
RD	463.3	1287.0	1750.3	0.531
RCp	470.1	1291.5	1761.6	0.584

The three stock columns are annual means of the 12 monthly stock outputs, in Pg C; ecosystem carbon is vegetation plus litter plus soil. Mean NBP is the arithmetic mean of the 170 annual flux outputs over 1850–2019, in Pg C yr^{-1}. The stock columns describe the ecosystem pools reported in the archived output and exclude a separate wood-product inventory. Positive NBP denotes a net land sink in the reported diagnostic. R0f = VISIT-2type; RD = VISIT-4type. Other simulation definitions are given above and in main-text Table 2. Values are rounded independently.

Table S3 (b) Annual-mean stock and mean-NBP differences by model component

Component (later − earlier)	Δvegetation C	Δlitter + soil C	Δecosystem C	Mean ΔNBP
Structure and transitions (RA − R0f)	−30.9	−16.8	−47.7	+0.026
Age structure (RB − RA)	−0.4	0.3	−0.1	−0.009
Harvest (RC − RB)	−30.9	−7.1	−38.0	−0.163
Harvest including age (RC − RA)	−31.3	−6.8	−38.1	−0.171
Secondary-forest traits (RD − RC)	−6.4	−1.8	−8.1	−0.027
Total (RD − R0f)	−68.5	−25.4	−93.9	−0.173
Age structure after harvest (RC − RCp)	−0.4	−2.8	−3.2	−0.026
Harvest before age structure (RCp − RA)	−30.9	−4.0	−34.9	−0.146

Stock entries are differences in 2019 annual-mean stocks (Pg C), not changes between year-end snapshots. The NBP column gives 1850–2019 mean differences (Pg C yr^{-1}). Positive values denote larger stocks or a larger reported sink in the later configuration. The three main contrasts sum to RD − R0f before rounding. The last two rows use the alternative order of adding harvest and age structure and sum to RC − RA. Each individual contrast is conditional on the preceding configuration; the combined harvest-and-age contrast is unchanged by this reordering.

Table S3 (c) Mean ΔNBP over 1850–2019 by land-use history

Group	Area (10^6 km^2)	Structure and transitions	Harvest including age	Traits	Total

No harvest or clearing	89.135	0.086	0.000	0.000	0.085
Harvest only	5.281	0.000	−0.020	−0.003	−0.023
Clearing only	5.269	−0.004	−0.001	−0.001	−0.007
Harvest and clearing	32.434	−0.055	−0.150	−0.023	−0.228
All land	132.119	0.026	−0.172	−0.027	−0.173

Flux entries are Pg C yr^{-1} and are contributions integrated over the land-use-history group, rather than per-unit-area means. Group totals approximate the global annual aggregation; small differences arise from aggregation domains and rounding. Classification uses VISIT-4type cumulative harvested and cleared forest area over 1851–2019, with a threshold of 1% of each grid cell for each process. Positive ΔNBP denotes a larger land sink.

Table S3 (d) Mean ΔNBP over 1850–2019 by latitude band

Component	North of 30° N	30° S–30° N	South of 30° S	Global
Structure and transitions (RA − R0f)	−0.017	0.036	0.007	0.026
Harvest including age (RC − RA)	−0.060	−0.106	−0.006	−0.172
Secondary-forest traits (RD − RC)	0.006	−0.035	0.002	−0.027
Total (RD − R0f)	−0.070	−0.105	0.003	−0.173

Entries are Pg C yr^{-1}, integrated over each latitude band. Positive ΔNBP denotes a larger land sink. Bands sum to the global value before rounding.

Table S3 (e) Stock–flux residuals over 1851–2019

Simulation	ΔEcosystem C	Cumulative NBP	ΔProduct pools	Residual
R0f	175.0	118.4	–	56.6
RA	130.1	122.9	3.0	10.2
RB	129.8	121.4	3.1	11.5
RC	98.6	93.8	7.1	11.9
RD	93.8	89.2	7.0	11.7
RCp	102.6	98.2	6.4	10.9

ΔEcosystem C is the change in annual-mean vegetation, litter and soil carbon from 1850 to 2019, and cumulative NBP is summed over 1851–2019 (Pg C). ΔProduct pools is the input to the 10- and 100-year product pools minus their releases over 1851–2019; in VISIT-2type, product pools are part of the litter pool and are included in ΔEcosystem C. Residual = ΔEcosystem C + ΔProduct pools − cumulative NBP; positive values denote carbon added to stocks without a corresponding flux.