Supplementary materials

Text 1. Descriptions of photosynthesis module in the CABLE model

Leaf photosynthesis, stomatal conductance, and heat and water transfer in CABLE are calculated using the two-leaf approach (Wang and Leuning, 1998) for both sunlit leaves and shaded leaves. The two-leaf model uses the same set of equations for calculating photosynthesis, transpiration and sensible heat fluxes for an individual leaf, but with the bulk formulation for the parameters for all sunlit and shaded leaves separately. For a given leaf parameter P, the corresponding parameter values for the two big leaves are calculated as:

$$P_1 = \int_0^{\Lambda} p(\lambda) f_{sun}(\lambda) d\lambda \text{ (big sunlit leaves)} \quad \text{(S1)}$$

$$P_2 = \int_0^{\Lambda} p(\lambda)\,(1 - f_{sun}(\lambda)) d\lambda \text{ (big shaded leaves)} \quad \text{(S2)}$$

f_{sun} is the fraction of sunlit leaves within a canopy, calculated by f_{sun}= exp(-k_bλ), where k_b is the extinction coefficient of direct beam radiation for a canopy with black leaves. λ is cumulative LAI.

CABLE calculates plant photosynthesis rate according to Leuning (1990). Leuning (1990) described a method to calculate stomatal conductance, CO_2 assimilation, and intercellular CO_2 by solving equations describing the supply of CO_2 through stomata and demand for CO_2 in photosynthesis (Farquhar et al., 1980) simultaneously. Since C_3 plants have similar mechanisms for photosynthesis and respond to eCO_2 much stronger than C_4 plants, C_3 plants are only considered in this study. Canopy net photosynthesis rate is calculated as:

$$A = \min\{A_c, A_q, A_p\} - R_d = G_{st}(C_S - C_i) \quad \text{(S3)}$$

$$A_c = V_{cmaxbig} * \frac{C_i - \Gamma_*}{C_i + K_C(1 + O_i/K_O)} \quad \text{(S4)}$$

$$A_q = J_{cmaxbig} * \frac{C_i - \Gamma_*}{C_i + 2\Gamma_*} \quad \text{(S5)}$$

$$A_p = 0.5 * V_{cmaxbig} \quad \text{(S6)}$$

Where A_c, A_q and A_p are canopy assimilation rates limited by Rubisco activity, RuBP regeneration and sink respectively. R_d is day respiration, which is proportional to $V_{cmaxbig}$. $V_{cmaxbig}$ is the maximum catalytic activity of Rubisco of big leaves. C_i is intercellular CO_2 concentration. Γ_* is the CO_2 compensation point in the absence of day respiration. K_c and K_O are Michaelis-Menten constants for CO_2 and O_2 respectively. O_i is intercellular oxygen concentration. Γ_*, K_c and K_O are only functions of leaf temperature. $J_{cmaxbig}$ is the maximum rate of photosynthesis at saturating C_i for a given absorbed photo irradiance of big leaves. For sunlit and shaded leaves, $V_{cmaxbig}$ and $J_{cmaxbig}$ are defined as follows:

$$V_{cmaxbig,sun} = v_{cmax,25} * f_{vcmax}\left(T_{f,sun}\right) * \int_0^{\Lambda} \exp(-k_b\lambda)\exp(-k_n\lambda)\, d\lambda = v_{cmax,25} * f_{vcmax}\left(T_{f,sun}\right) * \frac{1-\exp[-\mathrm{LAI}(k_n+k_b)]}{k_n+k_b} \quad \text{(S7)}$$

$$V_{cmaxbig,sha} = v_{cmax,25} * f_{vcmax}\left(T_{f,sha}\right) * \int_0^{\Lambda} [1-\exp(-k_b\lambda)]\exp(-k_n\lambda)\, d\lambda = v_{cmax,25} * f_{vcmax}\left(T_{f,sha}\right) * \left\{\frac{1-\exp(-k_n\mathrm{LAI})}{k_n} - \frac{1-\exp[-\mathrm{LAI}(k_n+k_b)]}{k_n+k_b}\right\} \quad \text{(S8)}$$

$$J_{cmaxbig,sun} = j_{cmax,25} * f_{jcmax}\left(T_{f,sun}\right) * \int_0^{\Lambda} \exp(-k_b\lambda)\exp(-k_n\lambda)\, d\lambda = j_{cmax,25} * f_{jcmax}\left(T_{f,sun}\right) * \frac{1-\exp[-\mathrm{LAI}(k_n+k_b)]}{k_n+k_b} \quad \text{(S9)}$$

$$J_{cmaxbig,sha} = j_{cmax,25} * f_{jcmax}\left(T_{f,sha}\right) * \int_0^{\Lambda} [1-\exp(-k_b\lambda)]\exp(-k_n\lambda)\, d\lambda = j_{cmax,25} * f_{jcmax}\left(T_{f,sha}\right) * \left\{\frac{1-\exp(-k_n\mathrm{LAI})}{k_n} - \frac{1-\exp[-\mathrm{LAI}(k_n+k_b)]}{k_n+k_b}\right\} \quad \text{(S10)}$$

Where $v_{cmax,25}$ is maximum carboxylation rate when photosynthesis is limited by Rubisco activity of a leaf. $j_{cmax,25}$ is maximum potential electron transport rate of a leaf. Subscripts "*sun*" and "*sha*" denote the sunlit and shaded components. It's assumed $j_{cmax,25}$=2$v_{cmax,25}$ in the model. $f_{vcmax}\left(T_{f,sun}\right)$ and $f_{jcmax}\left(T_{f,sun}\right)$ describe the temperature dependence of $v_{cmax,25}$ and $j_{cmax,25}$ for sunlit leaves respectively. $f_{vcmax}\left(T_{f,sha}\right)$ and $f_{jcmax}\left(T_{f,sha}\right)$ describe the temperature dependence of $v_{cmax,25}$ and $j_{cmax,25}$ for shaded leaves respectively. k_b is extinction coefficient of a canopy of black leaves for direct beam radiation. k_n is an empirical parameter used to describe the vertical distribution of leaf nitrogen in the canopy. In our simulation, k_n is uniformly assigned as 0.001 for different plant functional types.

G_{st} is stomatal conductance, and is calculated as:

$$G_{st} = G_0 + \frac{a * f_w * A}{(C_s - \Gamma)(1 + D_s/D_0)} \tag{S11}$$

Where G_0 is stomatal conductance when A=0. a and D_0 are empirical constants, f_w is an empirical parameter describing the availability of soil water for plants. A is net assimilation rate in Eq. (S3). C_s is CO_2 mol fraction at the leaf surface. Γ is CO_2 compensation point of photosynthesis. D_s is vapour pressure deficit at the leaf surface.

Text 2. Mathematic derivations of big-leaf $\boldsymbol{\beta}$

Equation (S4) and (S5) can be simplified as:

$$A_c = v_{cmax,25} * f_{vcmax}(T_f) * \frac{C_i - \Gamma_*}{C_i + K_c(1 + C_o - K_O)} * S = a_c * S \tag{S12}$$

$$A_q = j_{cmax,25} * f_{jcmax}(T_f) * \frac{C_i - \Gamma_*}{C_i + 2\Gamma_*} * S = a_q * S \tag{S13}$$

Where a_c and a_q represent leaf-level Rubisco- and RuBP-limit photosynthesis rates respectively:

$$a_c = v_{cmax,25} * f_{vcmax}(T_f) * \frac{C_i - \Gamma_*}{C_i + K_c(1 + C_o - K_O)} \tag{S14}$$

$$a_q = j_{cmax,25} * f_{jcmax}(T_f) * \frac{C_i - \Gamma_*}{C_i + 2\Gamma_*} \tag{S15}$$

S is a function of LAI, indicating the scaling factor that scales fluxes at the single top leaf of the canopy to whole canopy fluxes. The formulations of S for sunlit leaves and shaded leaves are:

$$S_{sun} = \frac{1 - \exp[-\mathrm{LAI}(k_n + k_b)]}{k_n + k_b} \tag{S16}$$

$$S_{sha} = \frac{1 - \exp(-k_n \mathrm{LAI})}{k_n} - \frac{1 - \exp[-\mathrm{LAI}(k_n + k_b)]}{k_n + k_b} \tag{S17}$$

where subscripts "*sun*" and "*sha*" denote the sunlit and shaded components of the scaling factors.

Big-leaf $\beta_{\mathrm{GPP}_{sun}}$ (or $\beta_{\mathrm{GPP}_{sha}}$) can be decompossed as the sum of normalized sensitivity of photosynthesis rate: $\beta_{p_{sun}}$ (or $\beta_{p_{sha}}$) and leaf-to-canopy scaling factor: $\beta_{S_{sun}}$ (or $\beta_{S_{sha}}$) as shown in Eq. (S18) and Eq. (S19). Subscripts "*sun*" and "*sha*" denote the sunlit and shaded components of leaf-level photosynthesis and leaf-to-canopy scaling factors.

$$\beta_{\mathrm{GPP}_{sun}} = \frac{1}{\mathrm{GPP}_{sun}} * \frac{\mathrm{dGPP}_{sun}}{dC_a} = \frac{1}{p_{sun*}S_{sun}} * \frac{\mathrm{d}(p_{sun*}S_{sun})}{dC_a} = \frac{1}{p_{sun}} * \frac{\mathrm{d}p_{sun}}{\mathrm{d}C_a} + \frac{1}{S_{sun}} * \frac{\mathrm{d}S_{sun}}{\mathrm{d}C_a} = \mathcal{L}_{sun} * \frac{\mathrm{d}C_{isun}}{\mathrm{d}C_a} + \frac{1}{S_{sun}} * \frac{\mathrm{d}S_{sun}}{\mathrm{d}C_a} = \beta_{p_{sun}} + \beta_{S_{sun}} \quad \text{(S18)}$$

$$\beta_{\mathrm{GPP}_{sha}} = \frac{1}{\mathrm{GPP}_{sha}} * \frac{\mathrm{dGPP}_{sha}}{\mathrm{d}C_a} = \frac{1}{p_{sha*}S_{sha}} * \frac{\mathrm{d}\left(p_{sha*}S_{sha}\right)}{\mathrm{d}C_a} = \frac{1}{p_{sha}} * \frac{\mathrm{d}p_{sha}}{\mathrm{d}C_a} + \frac{1}{S_{sha}} * \frac{\mathrm{d}S_{sha}}{\mathrm{d}C_a} = \mathcal{L}_{sha} * \frac{\mathrm{d}C_{i\mathrm{sha}}}{\mathrm{d}C_a} + \frac{1}{S_{sha}} * \frac{\mathrm{d}S_{sha}}{\mathrm{d}C_a} = \beta_{p_{sha}} + \beta_{S_{sha}} \quad \text{(S19)}$$

Table S1. Prescribed minimum LAI and maximum LAI values for C_3 PFTs in CABLE. Abbreviations are the same as Fig. 1.

PFT	LAImin	LAImax
ENF	0.5	7
EBF	1	7
DNF	0.35	7
DBF	0.35	7
SHB	0.1	3
C3GRAS	0.1	3
TUN	0.1	3

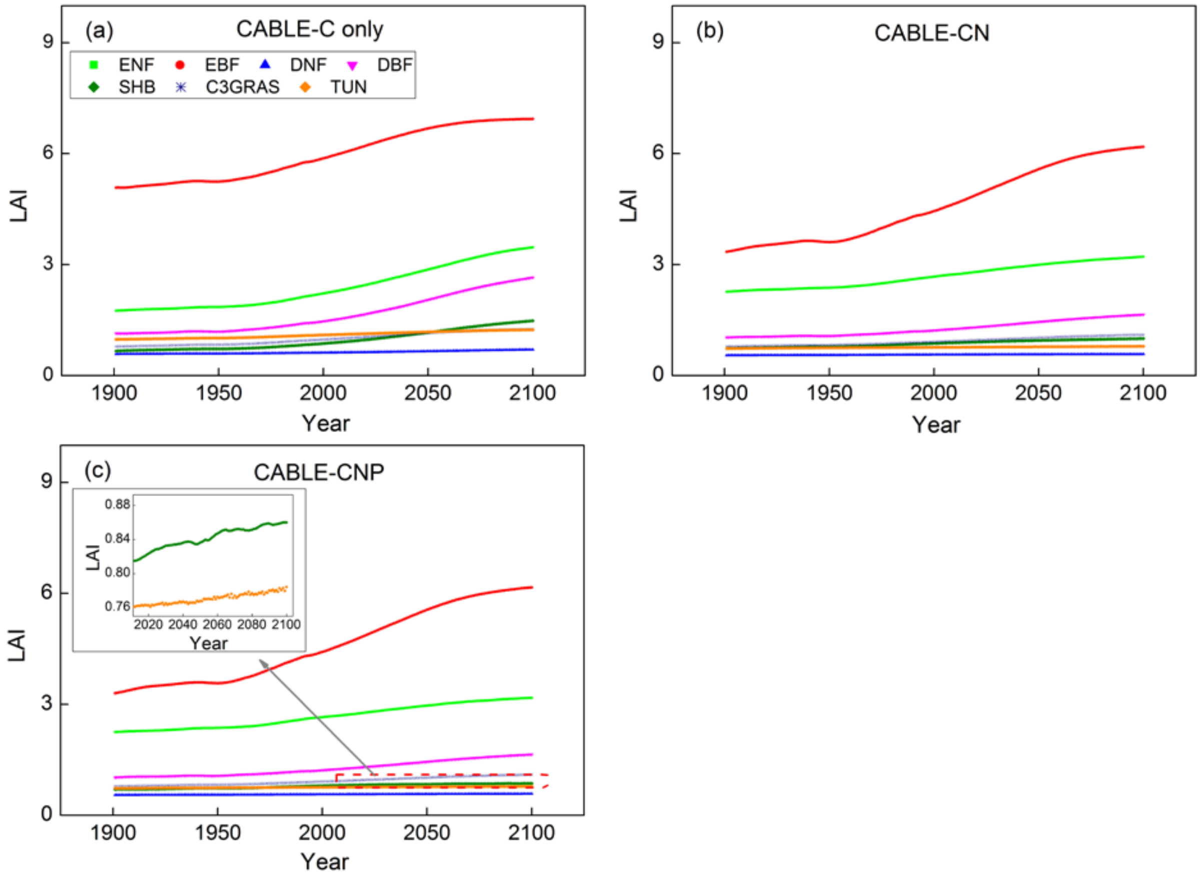

Figure S1. Temporal trends of yearly average LAI for C_3 PFTs from 1901 to 2100 from CABLE-C only (a), CABLE-CN (b), and CABLE-CNP (c) simulations. LAI value of evergreen broadleaf forest increases with time but gradually saturates at the prescribed maximum value from CABLE-C only simulation. LAI values of other plants also increase but are far below the prescribed maximum values at 2100 in all simulations. The inset in (c) is the enlarged view of LAI trends for shrub and tundra under RCP8.5 scenario in CABLE-CNP simulation, which show some oscillations. Abbreviations and symbols are the same as Fig. 1.

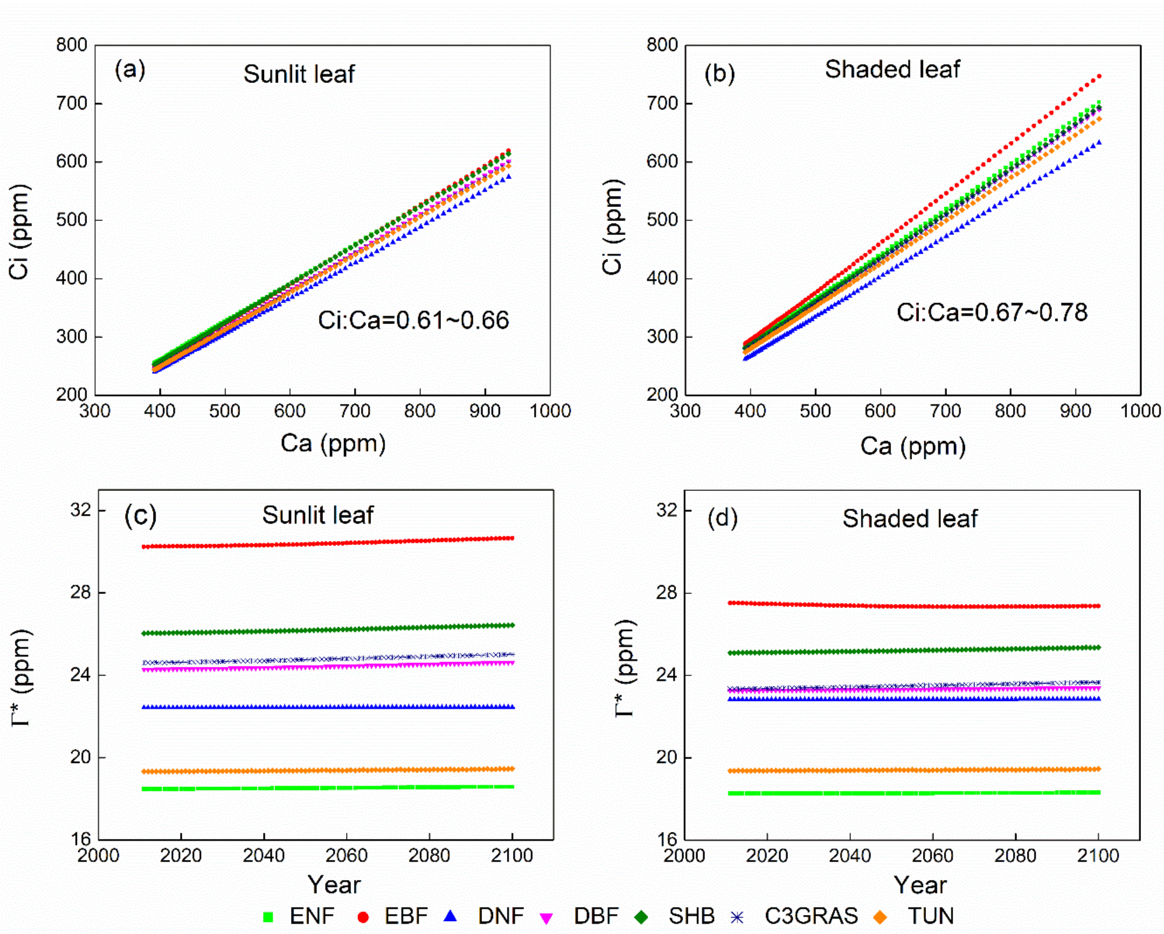

Figure S2. Responses of yearly intercellular CO_2 concentration (C_i) to eCO_2 of a single sunlit leaf (a) and shaded leaf (b) for C_3 PFTs from CABLE-CN simulation. Temporal trends of CO_2 compensation point in the absence of day respiration (Γ_*) for sunlit leaf (c) and shaded leaf (d) during 2011 to 2100 from CABLE-CN simulation. The ratio of C_i to C_a (C_i/C_a) is approximately constant with eCO_2 for each PFT and varies little across PFTs. Γ_* values vary across PFTs, but do not change over time for each PFT. Abbreviations and symbols are the same as Fig. 1.

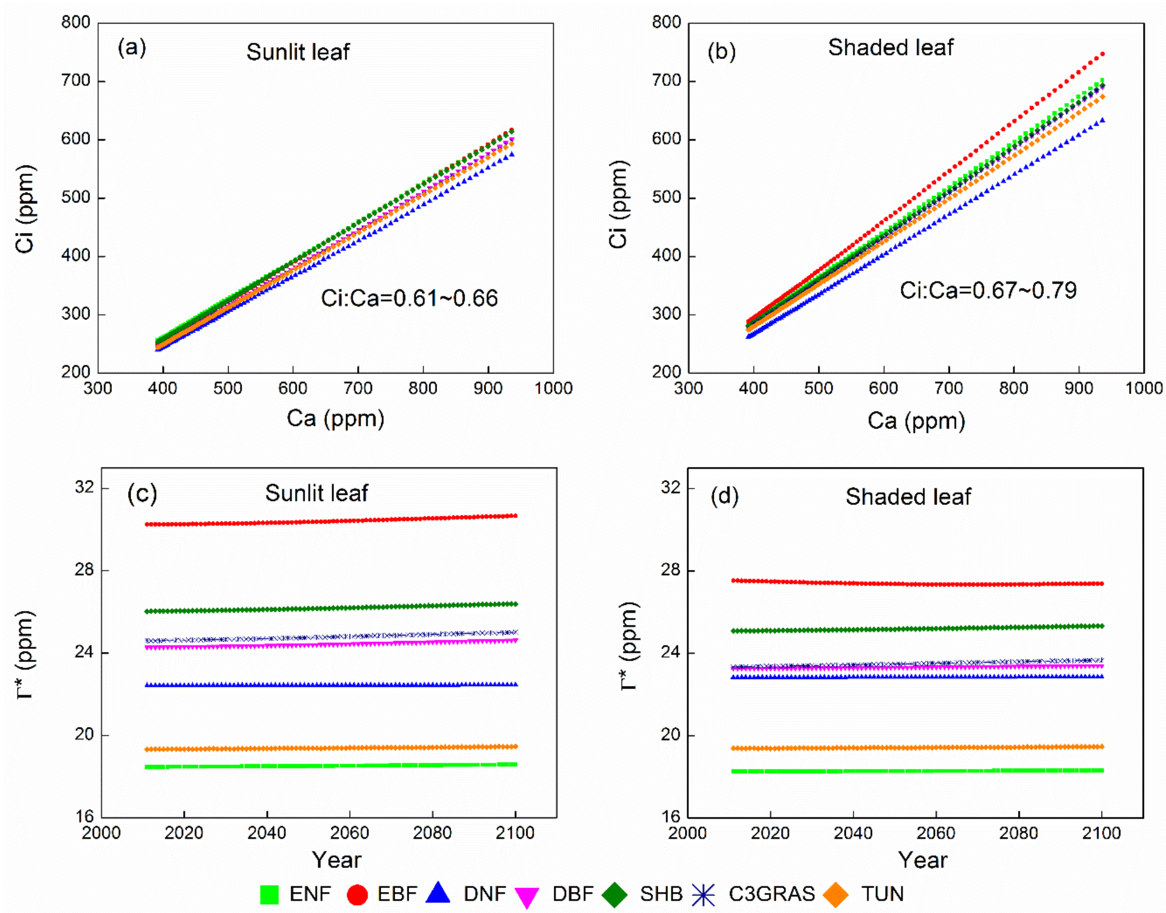

Figure S3. Responses of yearly intercellular CO_2 concentration (C_i) to eCO_2 of a single sunlit leaf (a) and shaded leaf (b) for C_3 PFTs from CABLE-CNP simulation. Temporal trends of CO_2 compensation point in the absence of day respiration (Γ_*) for sunlit leaf (c) and shaded leaf (d) during 2011 to 2100 from CABLE-CNP simulation. The ratio of C_i to C_a (C_i/C_a) is approximately constant with eCO_2 for each PFT and varies little across PFTs. Γ_* values vary across PFTs, but do not change over time for each PFT. Abbreviations and symbols are the same as Fig. 1.

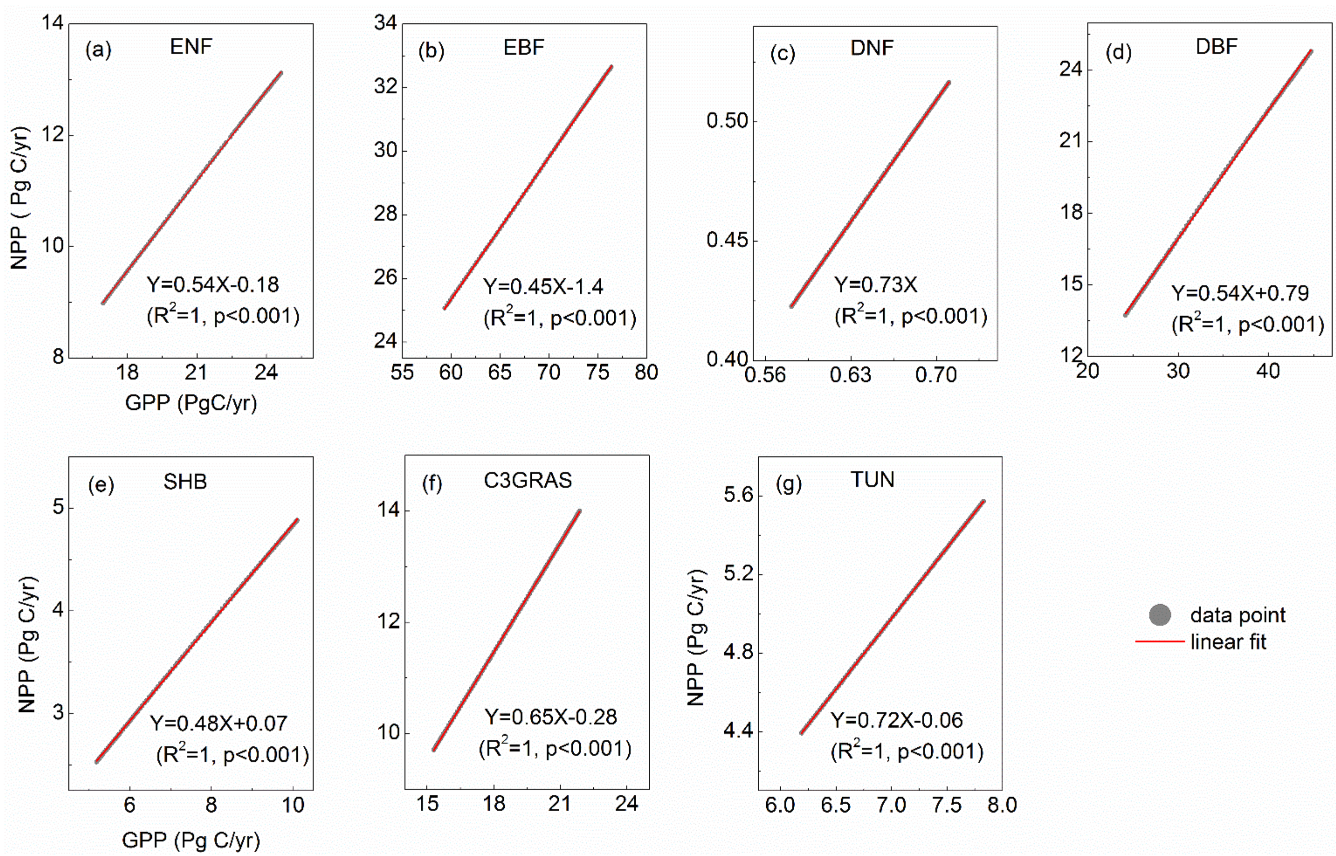

Figure S4. Correlations between NPP and GPP with eCO_2 from 2011 to 2100 for C_3 PFTs from CABLE-C only simulation. Abbreviations are the same as Fig. 1.

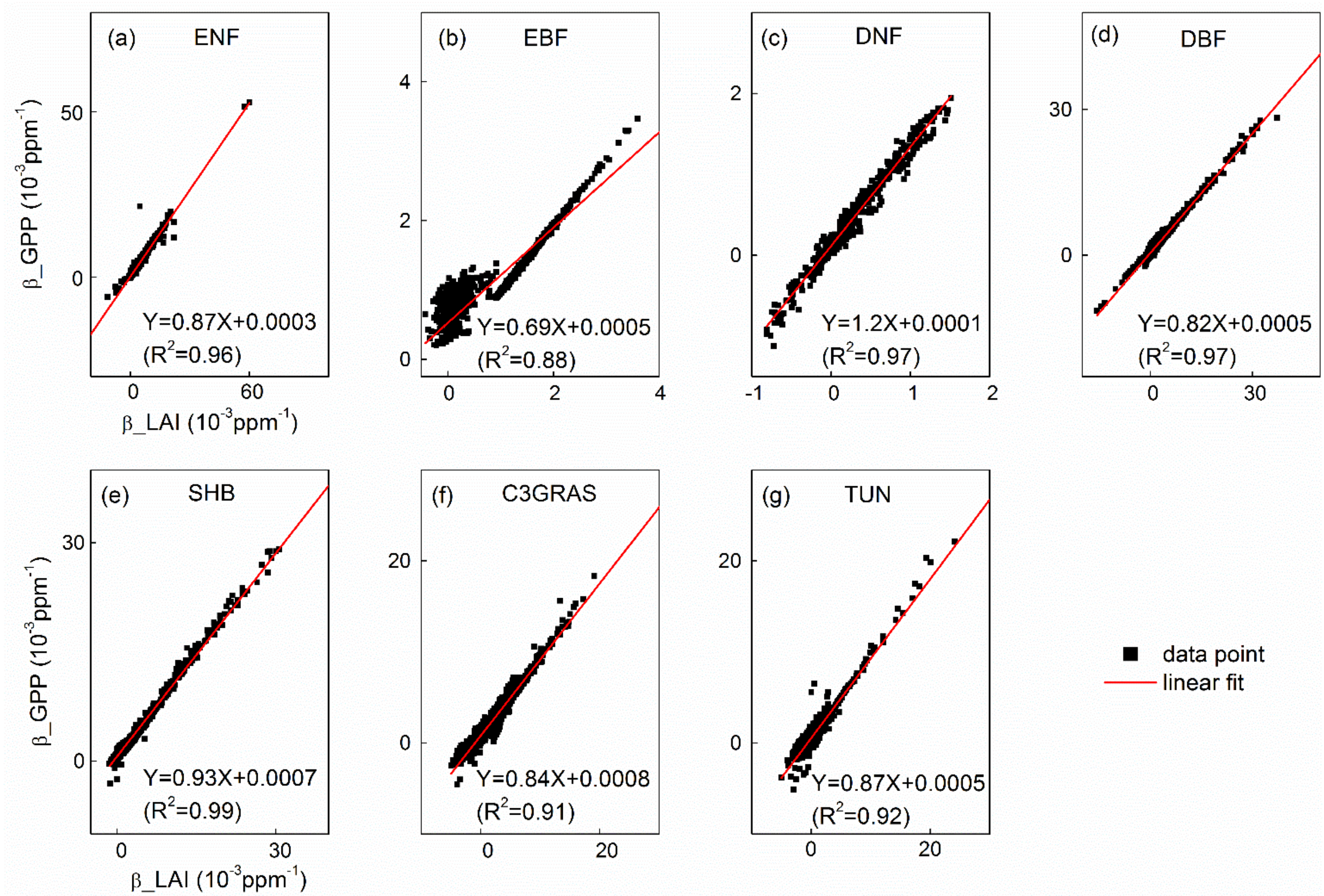

Figure S5. Correlations between β_{GPP} and β_{LAI} for patches within each C_3 PFT at the year 2023 from CABLE-C only simulation. Plants of the same type but at different locations show diverse responses of GPP primarily because the sensitivities of LAI vary. The relationships are all significant at the 0.001 level. Abbreviations are the same as Fig. 1.

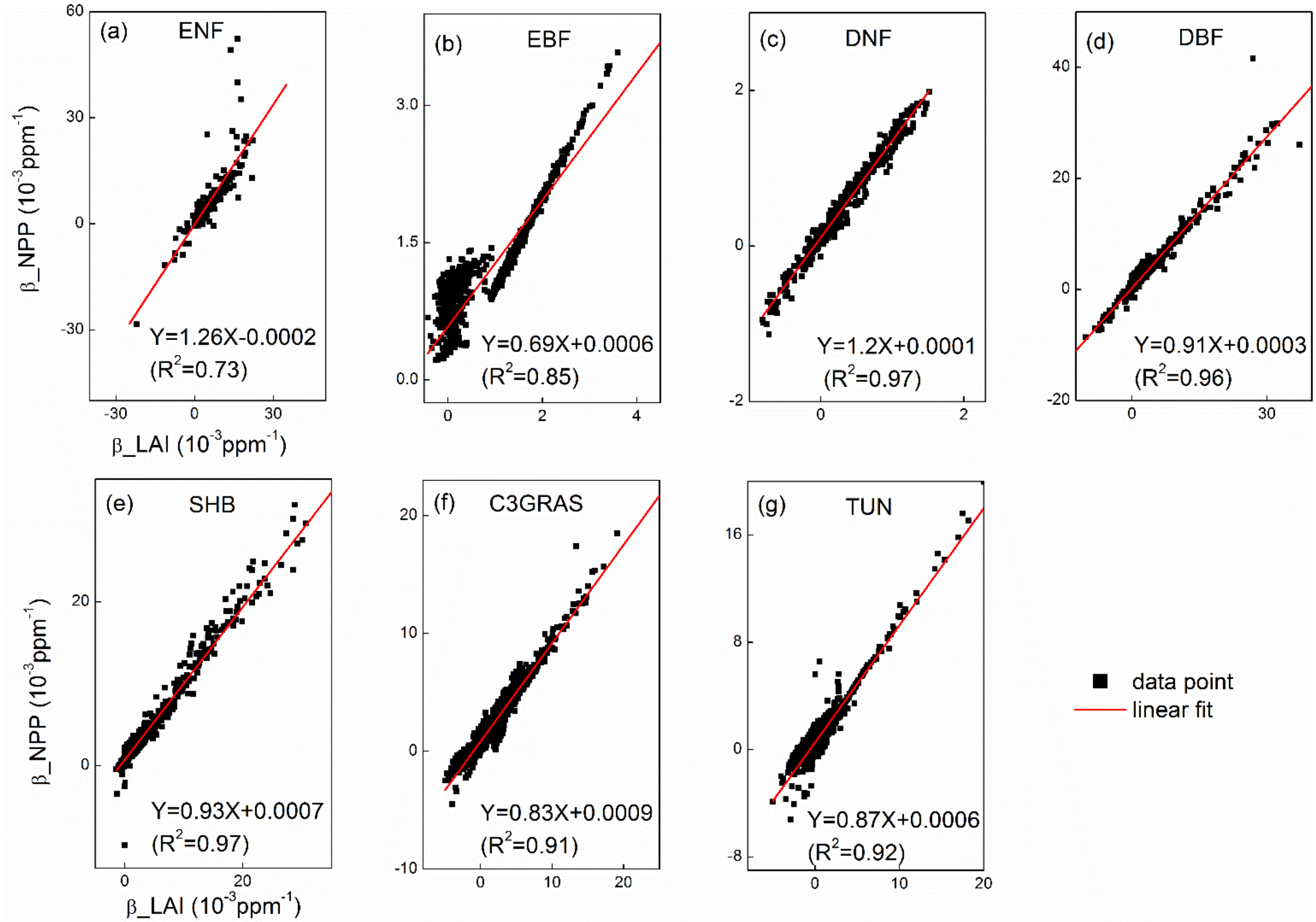

Figure S6. Correlations between $\boldsymbol{\beta}_{\mathbf{NPP}}$ and $\boldsymbol{\beta}_{\mathbf{LAI}}$ for patches within each C_3 PFT at the year 2023 from CABLE-C only simulation. Plants of the same type but at different locations show diverse responses of NPP primarily because the sensitivities of LAI vary. The relationships are all significant at the 0.001 level. Abbreviations are the same as Fig. 1.

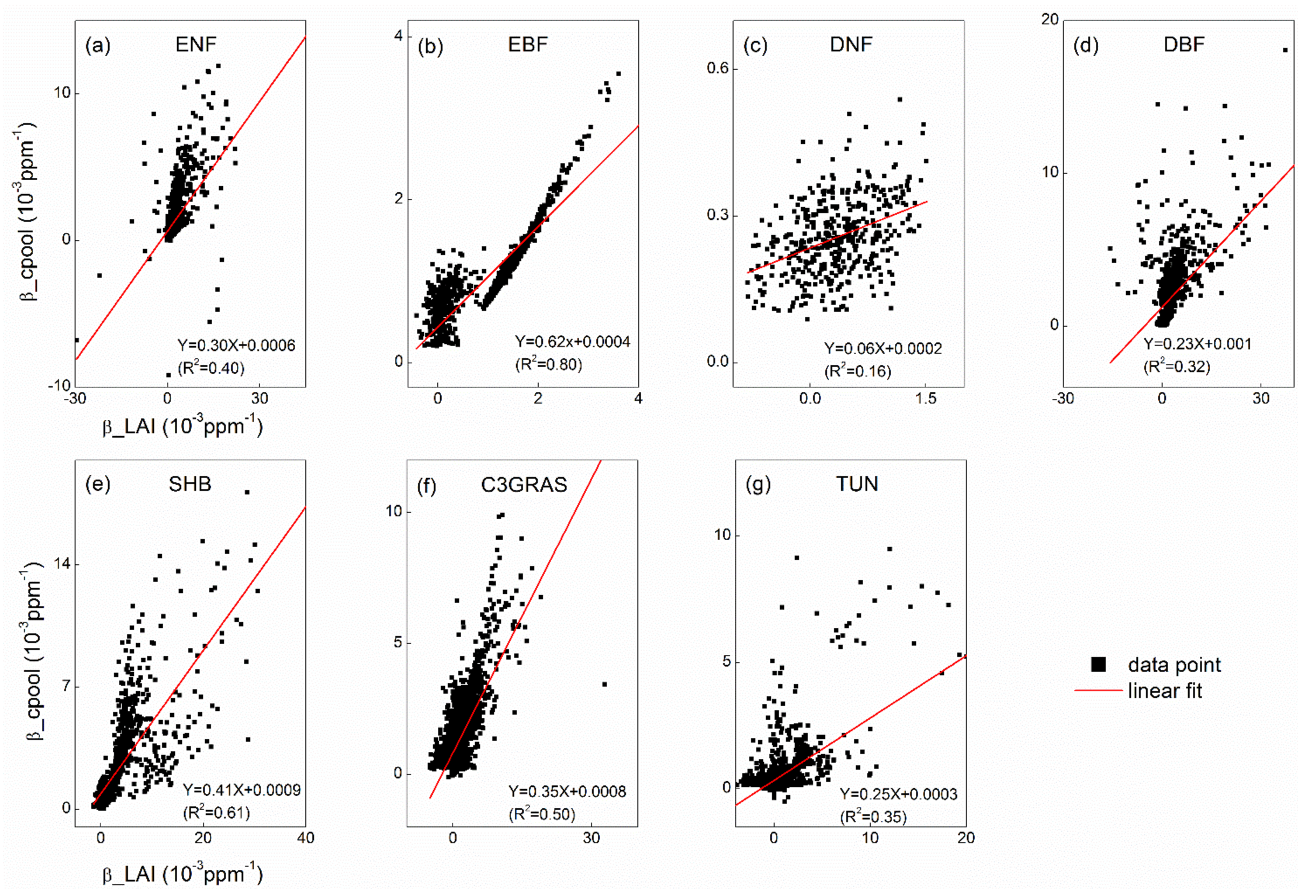

Figure S7. Correlations between β_{cpool} and β_{LAI} for patches within each C_3 PFT at the year 2023 from CABLE-C only simulation. The correlations between β_{cpool} and β_{LAI} are weaker than those between β_{NPP} and β_{LAI}. The relationships are all significant at the 0.001 level. Abbreviations are the same as Fig. 1.

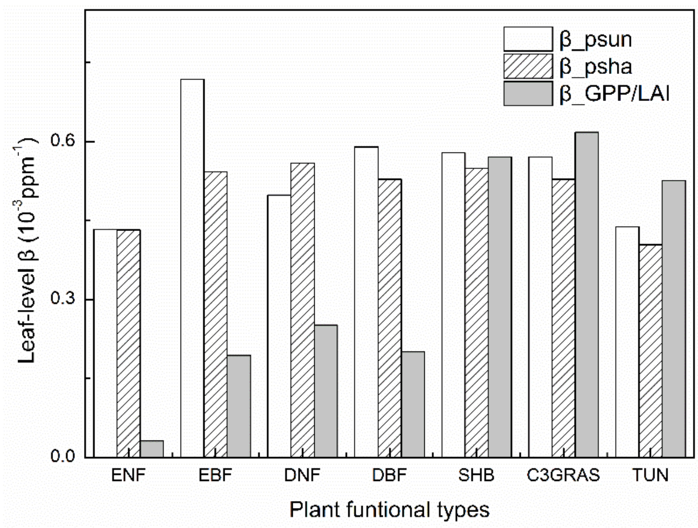

Figure S8. Comparision between leaf-level β calculated through biochemical parameters C_i and Γ_* for sunlit leaf (β_psun) and shaded leaf (β_psha) and sensitivities of GPP/LAI (β_GPP/LAI) for different C_3 PFTs at the year 2023 from CABLE-C only simulation. Abbreviations are the same as Fig. 1.

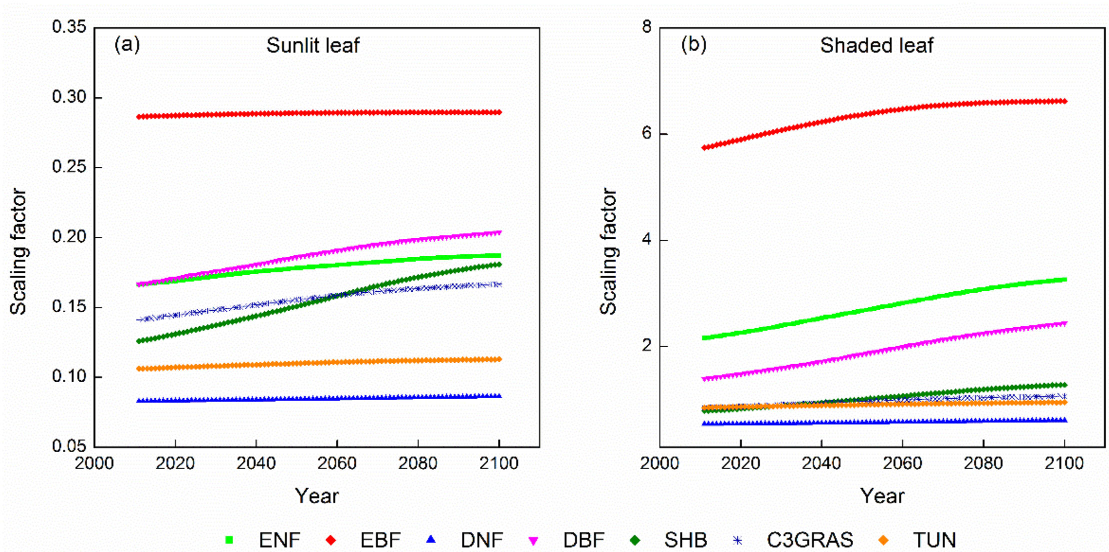

Figure S9. Temporal trends of the leaf-to-canopy scaling factors for sunlit leaves and shaded leaves of different C_3 PFTs from the CABLE-C only simulation from 2011 to 2100. The magnitudes of the scaling factors for shaded leaves are greatly larger than those for sunlit leaves for all C_3 PFTs. And the scaling factors for sunlit leaves of evergreen broadleaf forest, evergreen needleleaf forest and deciduous broadleaf forest gradually saturate with eCO_2. Abbreviations and symbols are the same as Fig. 1.