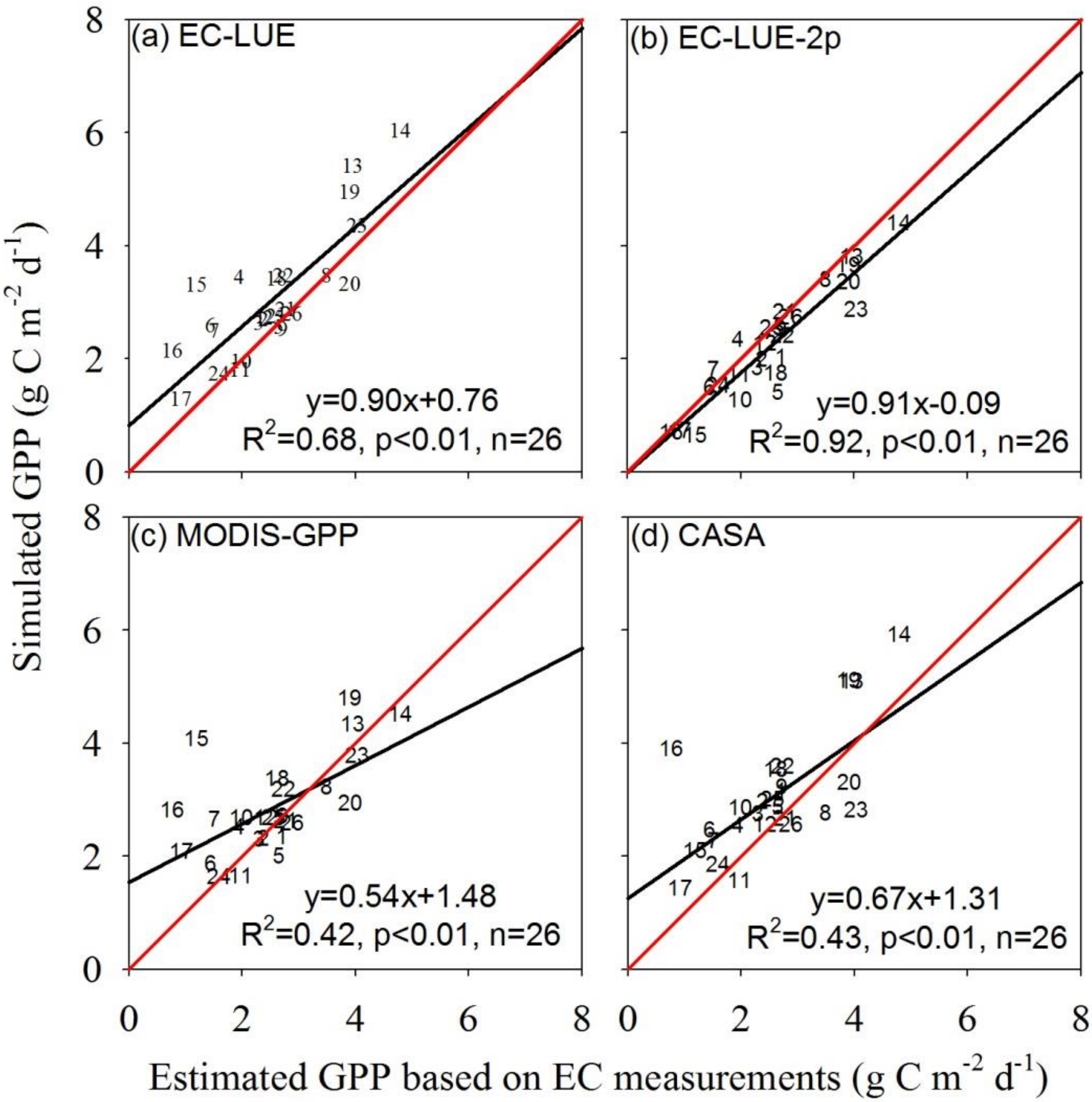
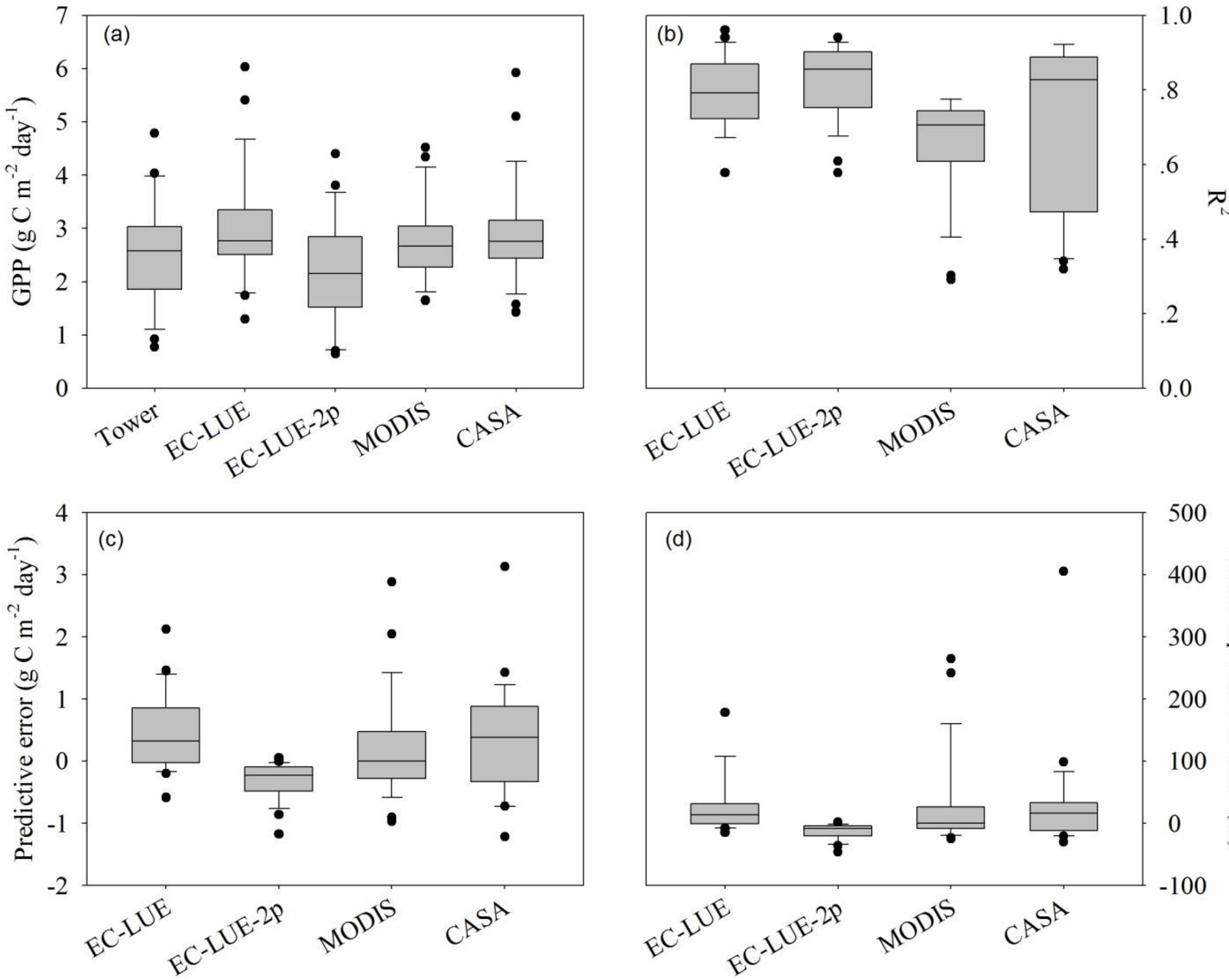
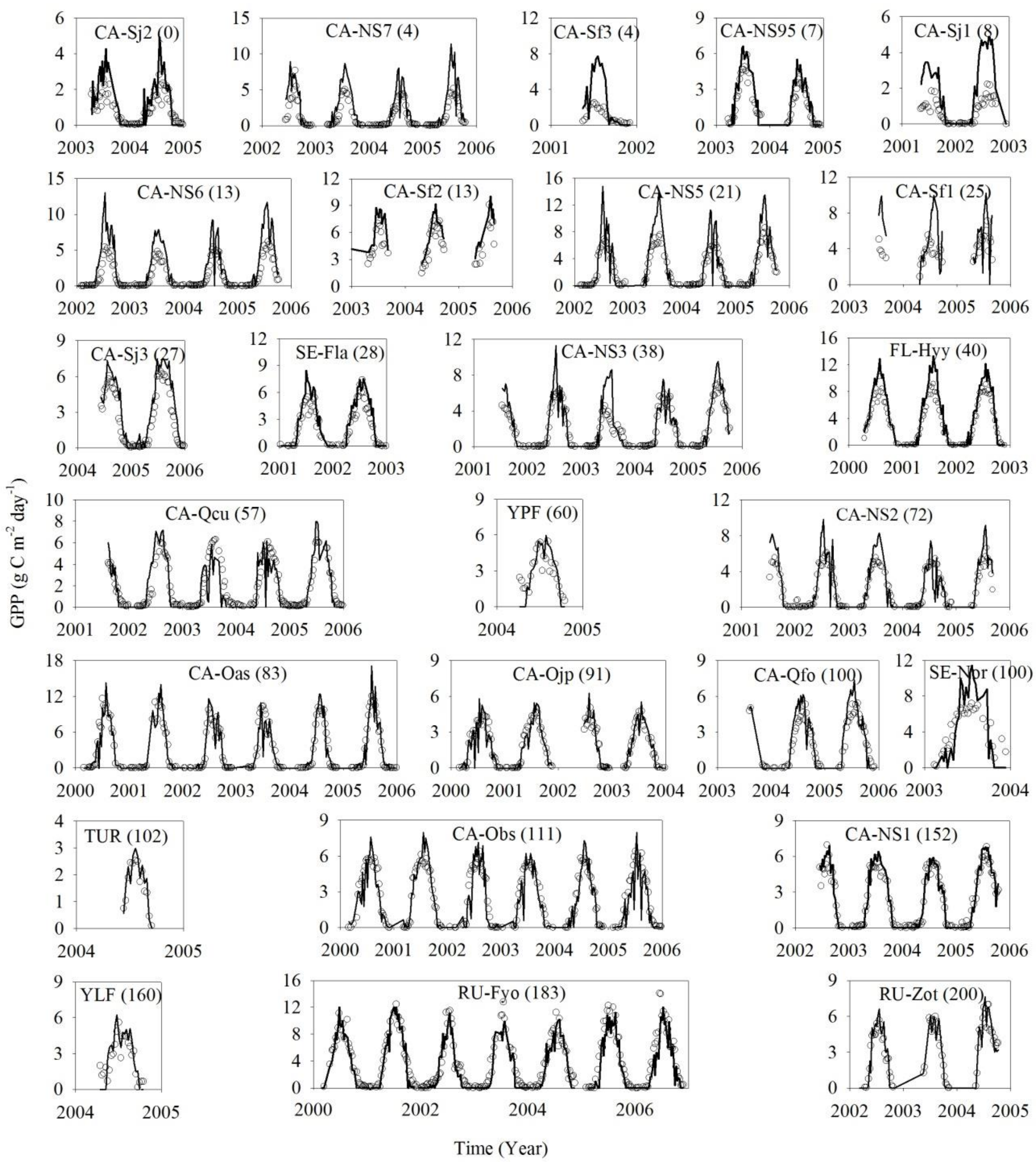


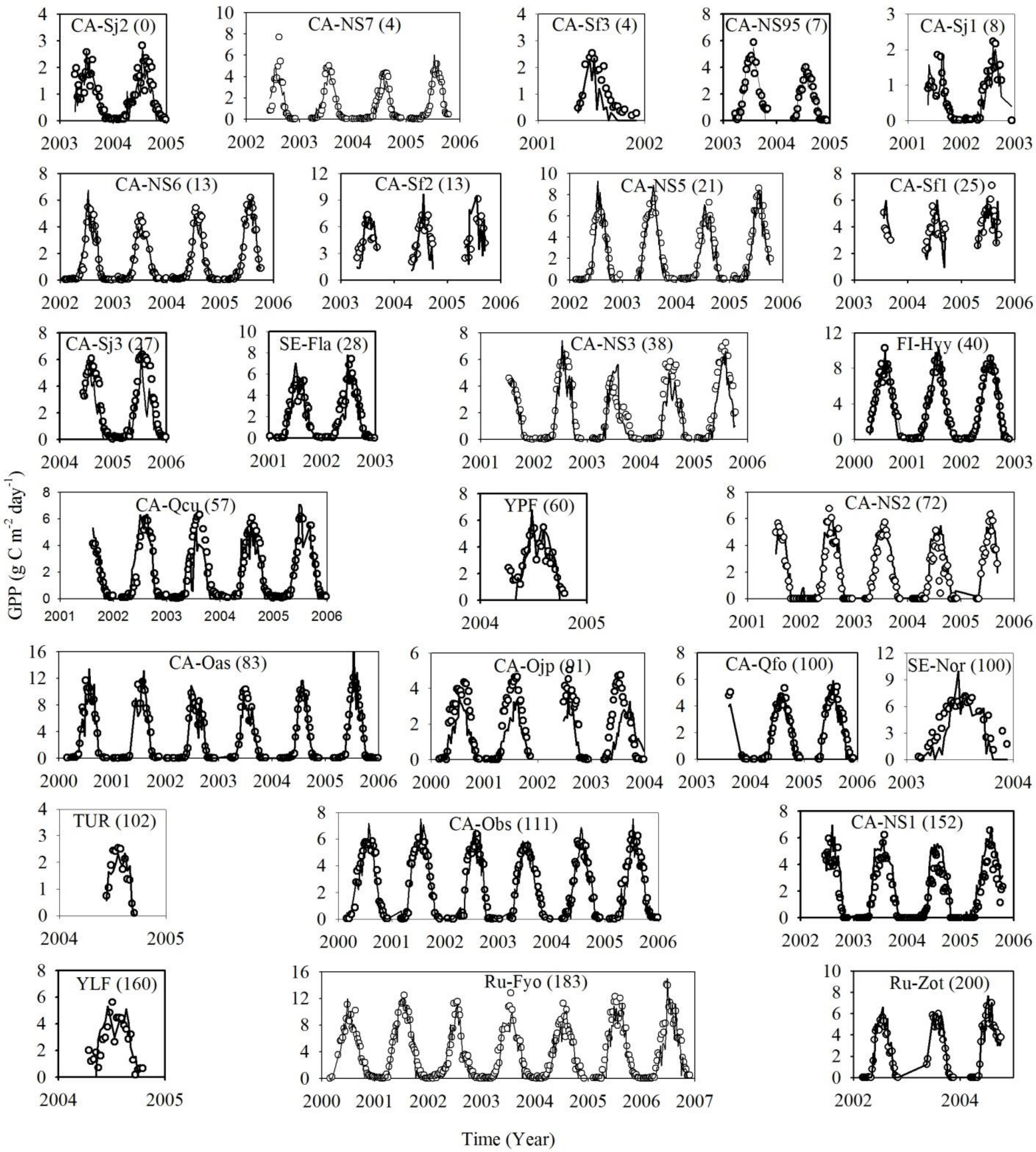
Supplementary Figure 1. The model performance of the EC-LUE model (a), EC-LUE-2p model (b), MODIS-GPP product (c) and CASA model (d) at all investigated sites. The values were site-averaged GPP over the study periods shown in Supplementary Table 1. The red lines are the 1:1 lines, and the black solid lines are the linear regression lines. The EC-LUE-2p model significantly improved GPP predictions by considering the impact of moss.



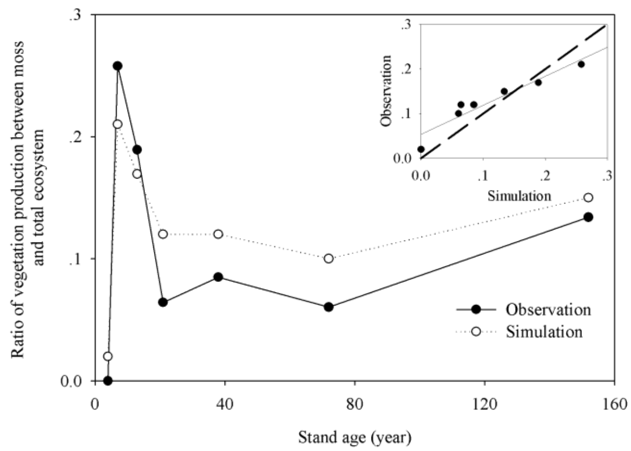
Supplementary Figure 2. Model comparison of simulated GPP values (a), coefficient of determination (R^2) (b), predictive error (PE) (c) and relative predictive error (RPE) (d) among the EC-LUE, EC-LUE-2p, MODIS-GPP, and CASA models. Boxplots with median, upper and lower quantiles, minimum and maximum or outliers (points).



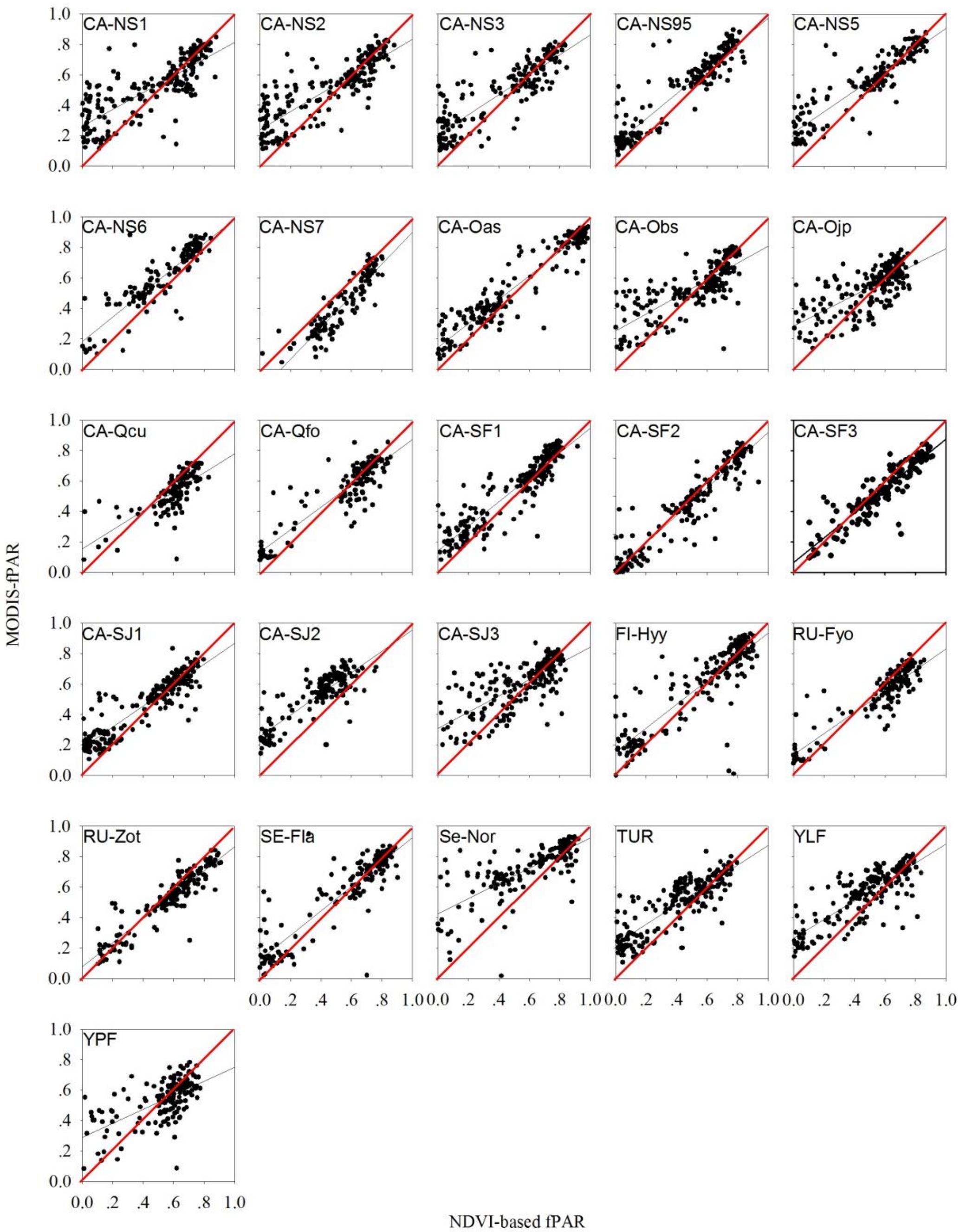
Supplementary Figure 3. Eight-day variation in estimated GPP from EC measurements (open circles) and predicted GPP using the EC-LUE model (black solid lines) at all sites. The numbers within parentheses are stand age.



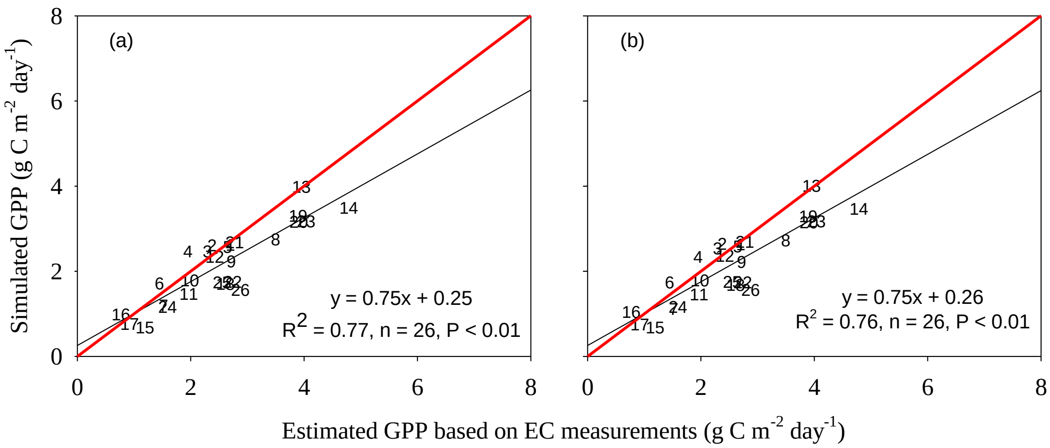
Supplementary Figure 4. Eight-day variation in estimated GPP from EC measurements (open circles) and predicted GPP using the EC-LUE-2p model (black solid lines) at all sites. The numbers within parentheses are stand age.



Supplementary Figure 5. Fractional contribution of moss to ecosystem GPP (simulated) and NPP (observed). Observations of mosses and vascular plants derived from the previous study[1]. Stand age for each site: CA-NS7 (4 year), CA-NS95 (7 year), CA-NS6 (13 year), CA-NS5 (21 year), CA-NS3 (38 year), CA-NS2 (72 year) and CA-NS1 (152 year). The insert shows the comparison of simulated and observed ratio. The dashed line is the 1:1 line, and the regression line is $y = 0.64x + 0.05$, $R^2 = 0.89$, $n = 7$, $p < 0.05$.



Supplementary Figure 6. The relationship between MODIS-fPAR product and the calculated fPAR using linear relationship of NDVI in this study. The red lines indicate the 1:1 line. The 8-day MODIS-fPAR product was used in this analysis.



Supplementary Figure 7. Model validation of EC-LUE-2p with calculated K_NDVI based on the relationship between K_NDVI and stand age. (a) Model validation for a given site using the relationship between K_NDVI and stand age, derived including all sites. (b) Model validation for a given site using the relationship based on other sites excluding this site. The 1:1 lines are red, and regression lines are black. The numbers in the figures indicate the site-averaged GPP values over the study period shown in Supplementary Table 1.

Supplementary Table 1 The eddy covariance sites used in this study

ID[1]	Site[2]	Lat[3]	Long[4]	Age[5]	AMT[6]	AP[7]	Period[8]	Reference
1	CA-NS1	55.88	-98.48	152	-2.89	500.29	2002-2005	2
2	CA-NS2	55.91	-98.52	72	-2.88	499.82	2001-2005	2
3	CA-NS3	55.91	-98.38	38	-2.87	502.22	2001-2005	2
4	CA-NS95	55.90	-98.21	7	-2.93	498.21	2001-2005	1
5	CA-NS5	55.86	-98.49	21	-2.87	500.34	2001-2005	2
6	CA-NS6	55.92	-98.96	13	-3.08	495.37	2001-2005	2
7	CA-NS7	56.63	-99.95	4	-3.52	483.27	2002-2005	2
8	CA-Oas	53.63	-106.19	83	0.34	428.53	2000-2005	3
9	CA-Obs	53.99	-105.12	111	0.79	405.60	2000-2005	4
10	CA-Ojp	53.92	-104.69	91	0.12	430.50	2000-2005	5
11	CA-Qcu	49.26	-74.04	57	0.13	949.00	2003-2005	6

12	CA-Qfo	49.69	-74.34	100	0.00	961.31	2003-2005	4
13	CA-Sf1	54.48	-105.82	25	-0.15	423.69	2003-2005	7
14	CA-Sf2	54.25	-105.88	13	-0.88	435.12	2001-2005	7
15	CA-Sf3	54.09	-106.01	4	0.08	441.78	2001-2005	7
16	CA-Sj1	53.91	-104.66	8	0.13	430.23	2001-2005	8
17	CA-Sj2	53.95	-104.65	0	0.11	430.33	2003-2005	9
18	CA-Sj3	53.87	-104.65	27	0.13	433.33	2003-2005	8
19	FI-Hyy	61.85	24.28	40	2.18	620.20	2000-2003	10
20	RU-Fyo	56.46	32.92	183	4.91	704.00	2000-2006	11
21	RU-Zot	60.80	89.35	200	-3.27	536.00	2002-2004	12, 13
22	SE-Fla	64.12	19.45	28	0.27	615.98	2001-2002	14
23	SE-Nor	60.08	17.47	100	5.45	561.02	2003	14
24	TUR	64.12	100.46	102	-9.17	317.00	2004	-
25	YLF	62.25	129.25	160	-10.40	259.00	2004	15
26	YPF	62.25	129.65	60	-10.40	259.00	2004	16

[1]Site label. [2]Abbreviation of EC site name. [3]Positive values indicate north latitude. [4]Negative values indicate west longitude, and positive values indicate east longitude. [5]Stand age in 2002. [6]Annual mean temperature (℃). [7]Total annual precipitation (mm). [8]The study period.

Supplementary Notes

Supplementary Note 1

Data at the EC sites

Data obtained at 26 EC sites in North America, Europe and Asia were used in this study to validate 4 LUE models and to calibrate the EC-LUE-2p model (Supplementary Table 1). They covered various stages of ecological successions in the boreal biome: deciduous broadleaf forests, mixed forests, evergreen needleleaf forests and grasslands. The EC data used in this study were obtained from the websites of AmeriFLUX (http://public.ornl.gov/ameriflux), CarboEuropeIP (http://gaia.agraria.unitus.it/database/carboeuropeip/), Canada-FLUXNET (http://www.fluxnet-canada.ca/) and AsiaFlux (http://www.asiaflux.net/). Supplementary information on the vegetation, climate, and soil at each site is available online. Half-hourly or hourly averaged PAR, T and friction velocity (u^*) were used with net ecosystem exchange of CO_2 (NEE) in this study. Datasets that were gap-filled by site investigators were used directly for this study (i.e., the LaThuile database)[17].

For the sites that were not in the LaThuile database (i.e., TUR, YLF, YPF; Supplementary Table 1), the following established procedures were used to process the data[18]. Nonlinear regression relationships between measured fluxes and controlling environmental variables (air temperature, PAR) were fit to fill the missing data using a 15-day moving window. The van't Hoff equation was used to fill the missing nighttime NEE ($F_{c,night}$)[19]:

$$F_{c,night} = A \times e^{(B \times T)} \qquad (1)$$

where A and B are estimated model coefficients, and T is air temperature. A Michaelis-Menten light response equation was used to fill the missing daytime NEE ($F_{c,day}$)[20]:

$$F_{c,day} = \frac{\alpha \times \mathrm{PAR} \times F_{GPP,sat}}{F_{GPP,sat} + \alpha \times \mathrm{PAR}} - F_{RE,day} \qquad (2)$$

where $F_{GPP,sat}$ (GPP at saturating light) and α (initial slope of the light response function) are empirically estimated coefficients, and $F_{RE,day}$ (ecosystem respiration) was estimated by extrapolation of Eq. (3) using the daytime air temperature. Daily NEE, ecosystem respiration (*Re*), and meteorological variables were synthesized based on half-hourly or hourly values, and the daily values were recorded as missing when more than 20% of the data from a given day was missing; otherwise, daily values were calculated by multiplying the averaged half-hourly or hourly rate by 24 hours[21]. GPP was calculated as the sum of NEE and Re. Based on the daily dataset, 8-day GPP mean value can be calculated. If more than 2 days of daily data were missing within a given 8-day period, the 8-day value was indicated as missing.

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