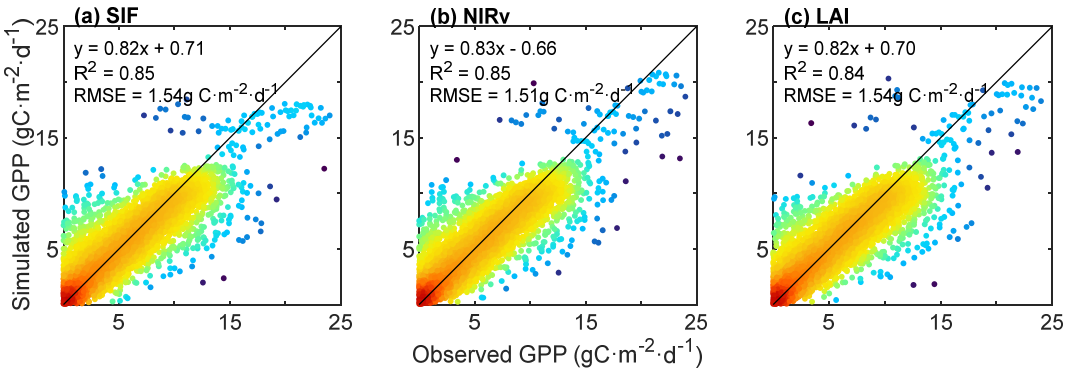

Figure S1. Evaluation of the simulated GPP against flux tower measurements. The predictions were based on the universal models using the Random Forest (RF) method.

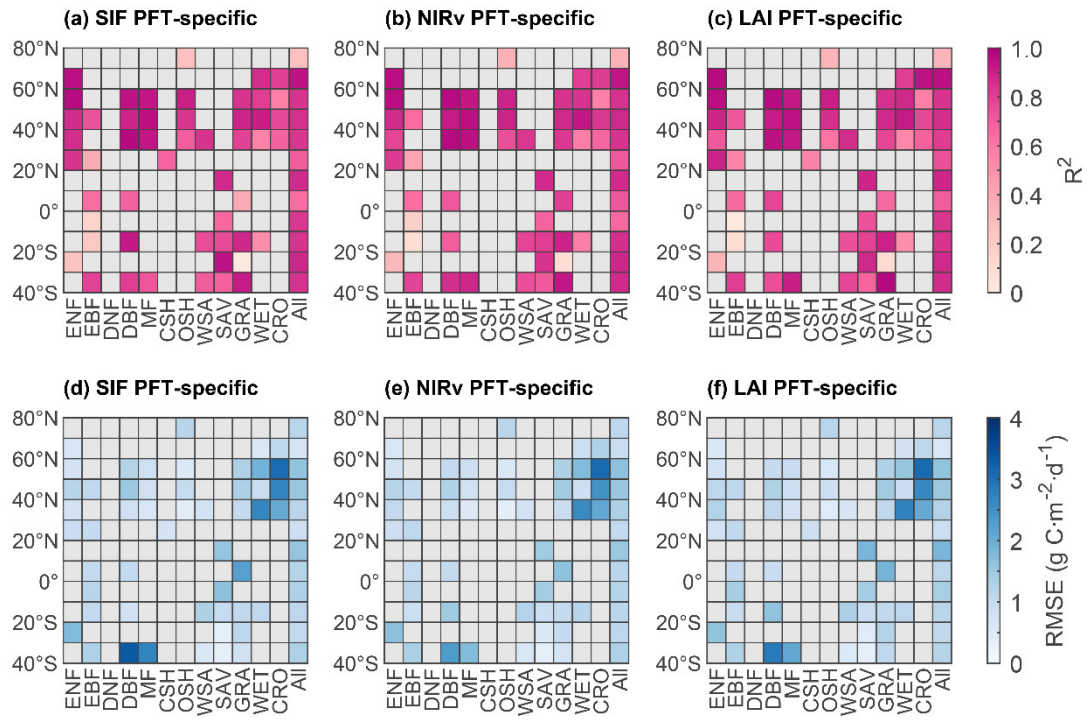

Figure S2. PFT-specific models performance for each PFT along latitude gradient using the RF method. (a)-(c) The R^2 of universal models that each vegetation index used as one of the model predictors. (d)-(f) The RMSE of universal models that each vegetation index used as one of the model predictors. The gray squares represent that there is no flux tower for the corresponding PFT and latitudinal bands.

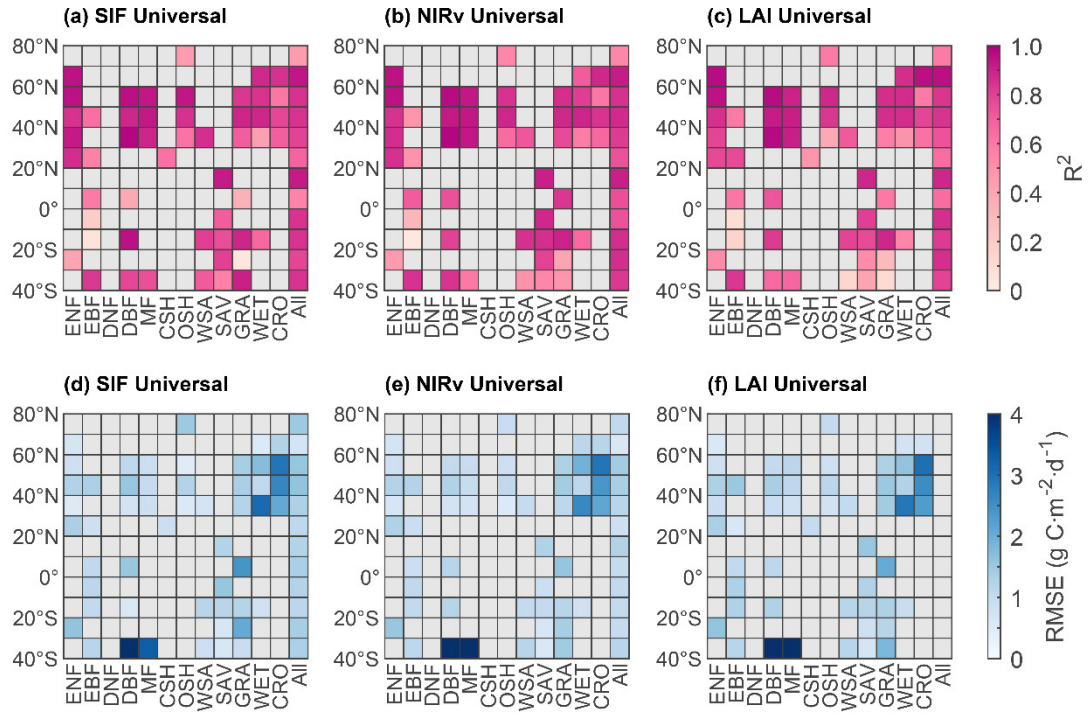

Figure S3. Universal models performance for each PFT along latitude gradient using the Back Propagation Neural Network (BPNN) method. (a)-(c) The R^2 of universal models that each vegetation index used as one of the model predictors. (d)-(f) The RMSE of universal models that each vegetation index used as one of the model predictors. The gray squares represent that there is no flux tower for the corresponding PFT and latitudinal bands.

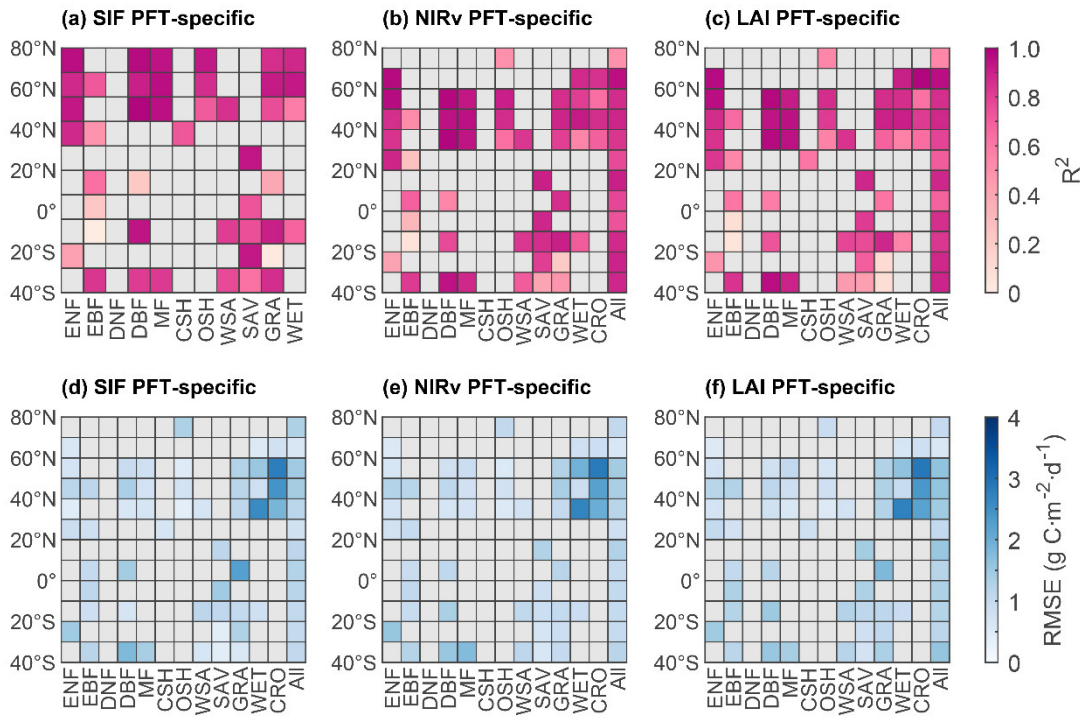

Figure S4. PFT-Specific models performance for each PFT along latitude gradient using the BPNN method.(a)-(c) The R^2 of universal models that each vegetation index used as one of the model predictors. (d)-(f) The RMSE of universal models that each vegetation index used as one of the model predictors. The gray squares represent that there is no flux tower for the corresponding PFT and latitudinal bands.

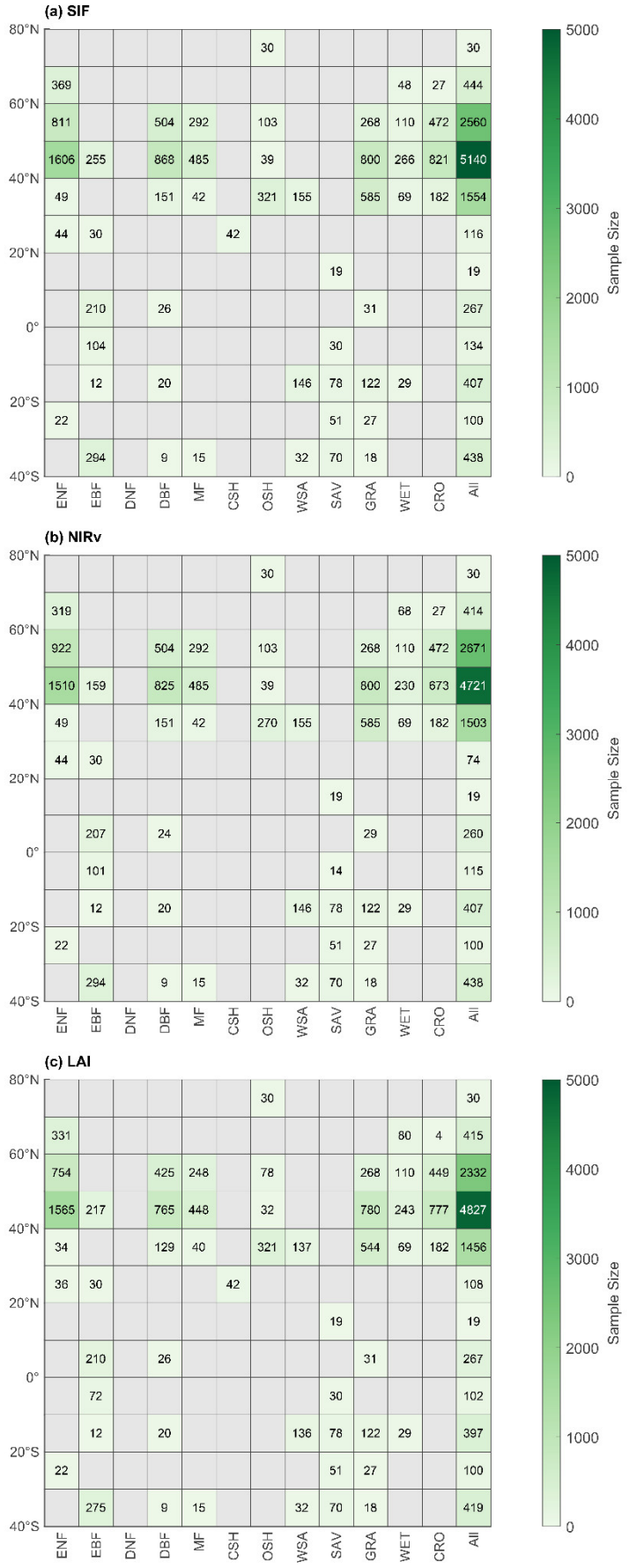

Figure S5. The sample size for each PFT along latitude gradient.

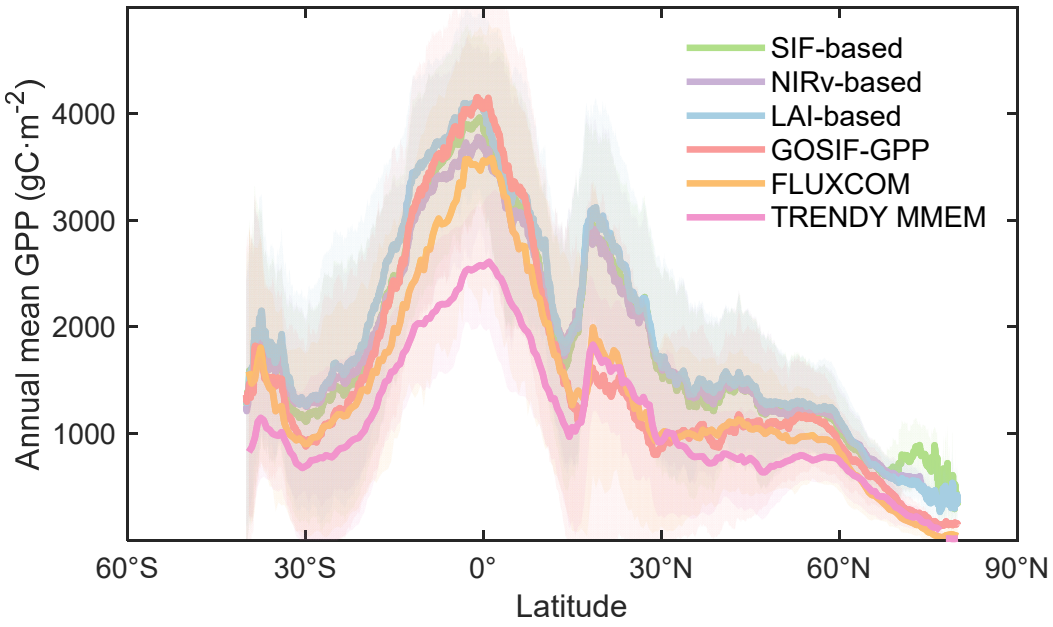

Figure S6. Latitudinal profiles of annual mean GPP during 2003-2018. The shaded areas represent the standard deviations of the GPP.

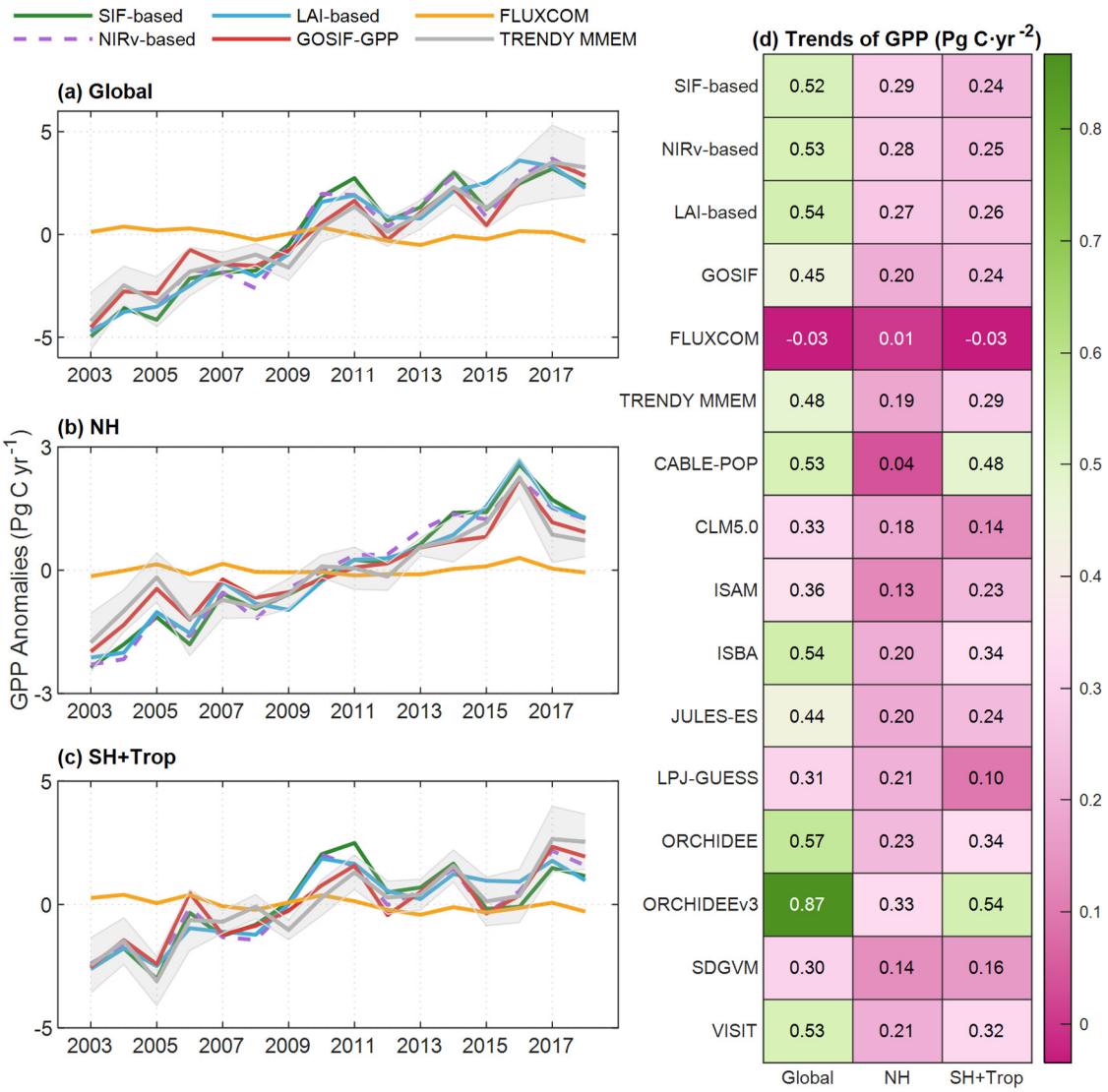

Figure S7. Interannual variability and trends for the period of 2003-2018. (a-c) Interannual changes in anomalies of GPP. The global land is divided into the northern hemisphere (NH: 30°N–90°N) and the tropical and southern hemisphere (SH+Trop: 90°S–30°N). SIF-based (green), NIRv-based (blue), and LAI-based (orange) represent the universal models constructed in this study using random forest based on three VIs (i.e., SIF, NIRv, and LAI), respectively. TRENDY MMEM (gray) represents the average of the multi-model ensemble mean. The shaded areas represent the standard deviations (SD) of the ten processed models in the TRENDY group. (d) Global and regional GPP trends in individual models and products.

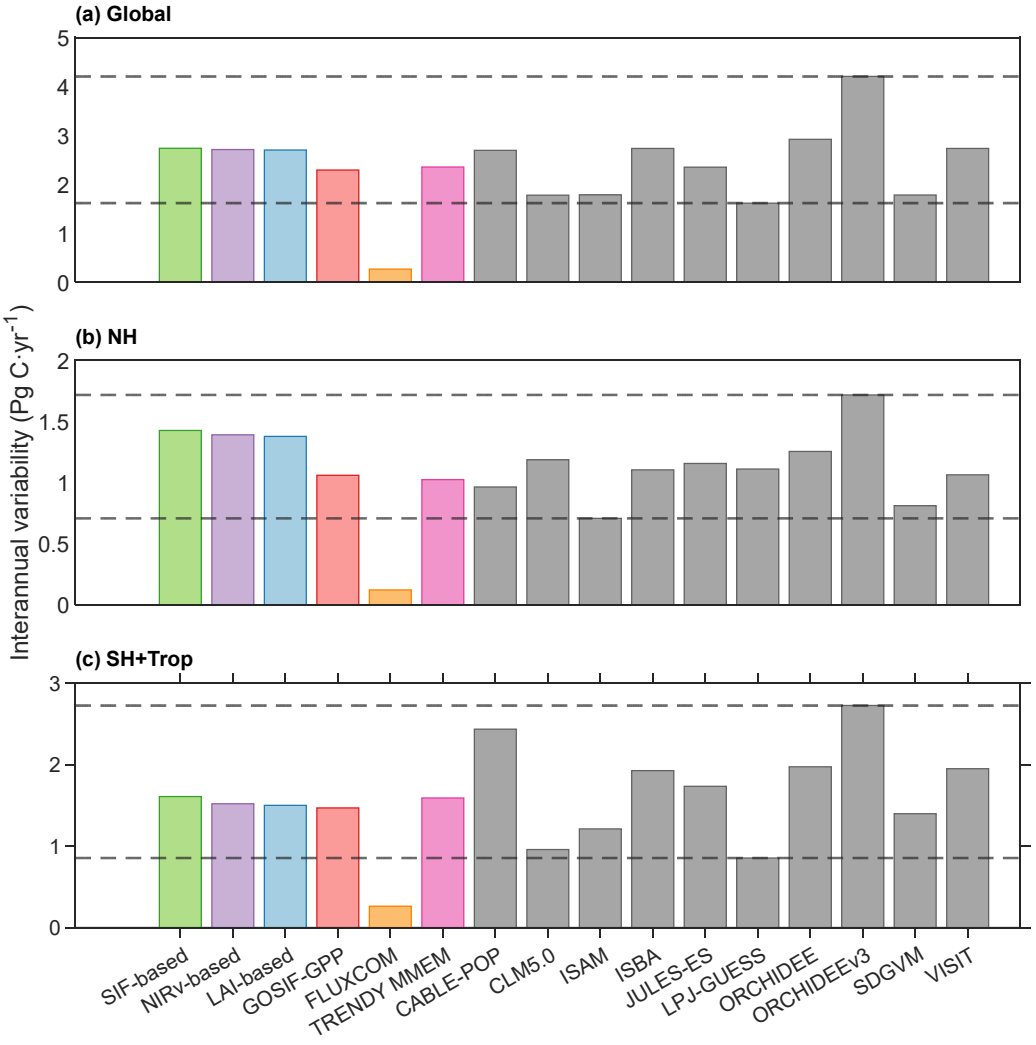

Figure S8. Comparisons of the interannual variability of GPP among different GPP products. The global land is divided into the northern hemisphere (NH: 30°N–90°N) and the tropical plus southern hemisphere (SH+Trop: 90°S–30°N). SIF-based, NIRv-based, and LAI-based represent the universal models constructed in this study using random forest based on three VIs (i.e., SIF, NIRv, and LAI), respectively. The dashed lines represent the maximum and minimum values of the ten processed models in the TRENDY group ('S3' scenarios). TRENDY MMEM represents the average of the multi-model ensemble mean.

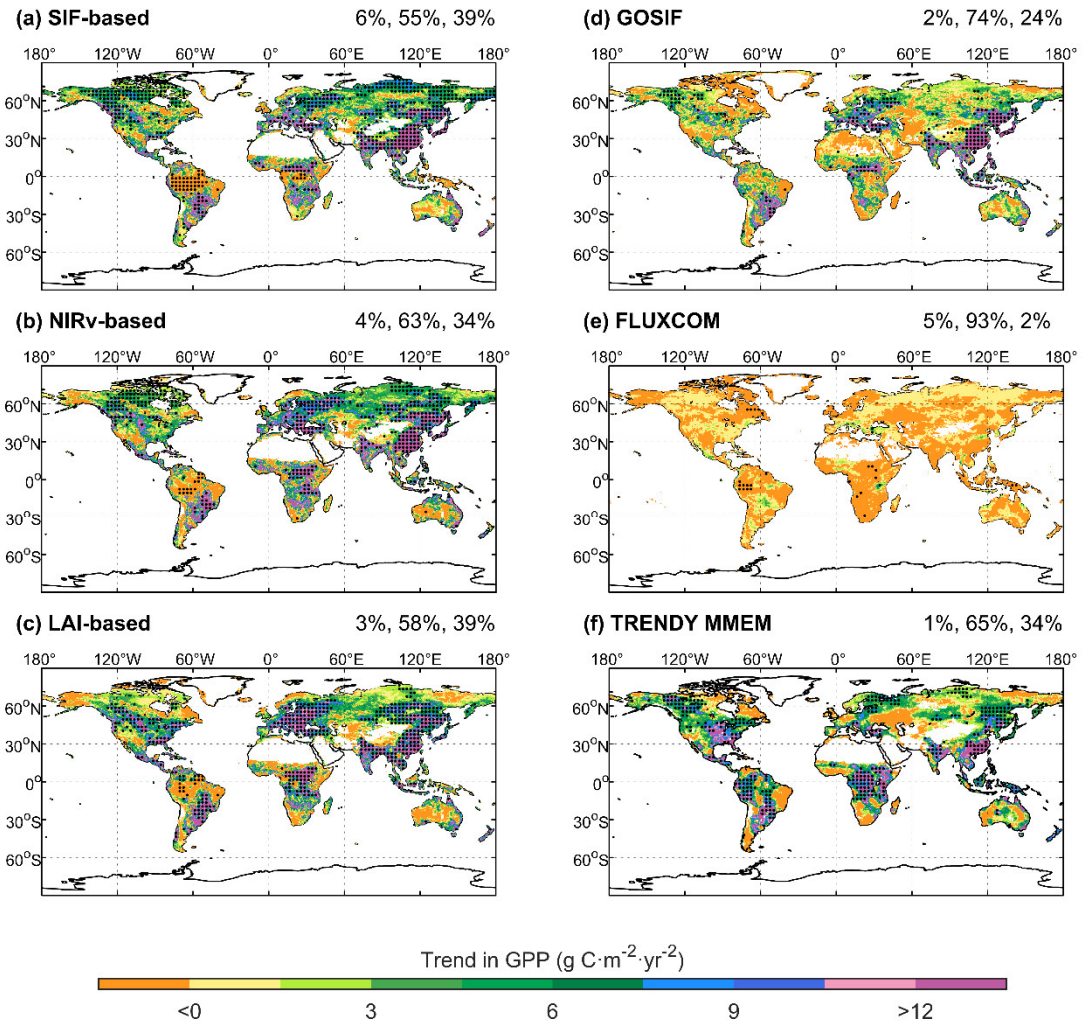

Figure S9. Spatial patterns of global GPP trends during 2003-2019. Black dots indicate trends that are statistically significant (Mann-Kendall test; $p<0.05$). The three numbers at the top of each subplot represent the percentages of the area with significant negative trends, insignificant trends, and significant positive trends in the global vegetated lands.

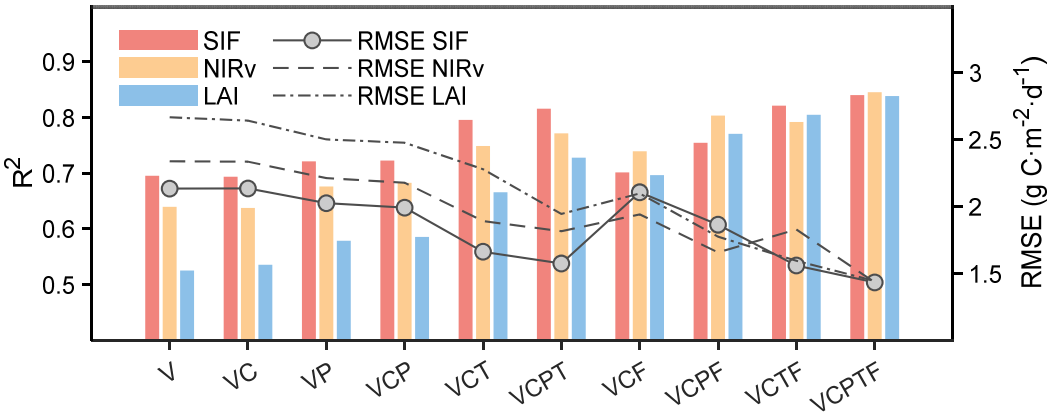

Figure S10. The performance of BPNN models using different combinations of predictors. The hyper-parameters of the models using other combinations of inputs were consistent with the optimal model. The left and right axes respectively represent the mean predicted R^2 and RMSE of the models repeated 50 times, with negligible differences each time. The variables used to develop the GPP estimation models were represented by the combination of their abbreviations, i.e., VIs (V), CO_2 (C), PFT (P), plant traits (T), and climate factors (F) (Table S2). For example, 'VCT' denotes the RF GPP model that used VIs, CO_2, and plant traits as input.

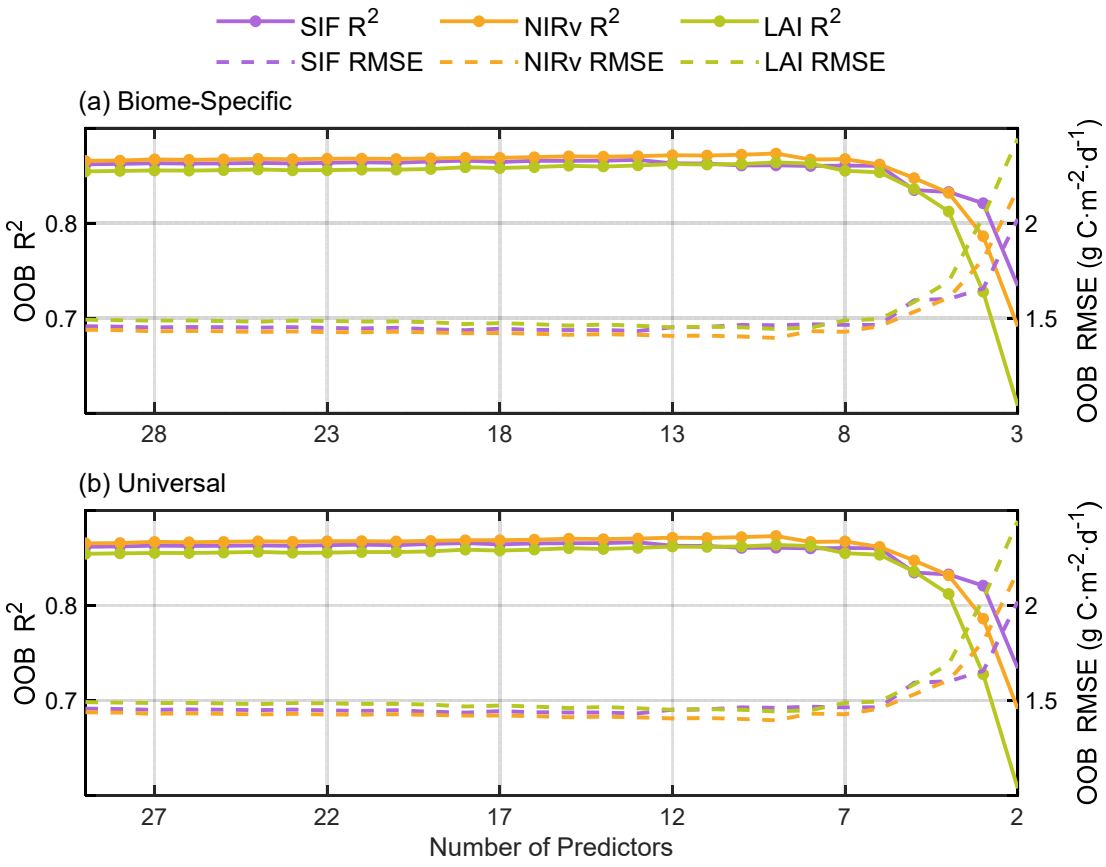

Figure S11. The relationship between the number of features selected and the performance of the random forest models. (a) PFT-specific models. (b) Universal models that the PFT is not considered. All solid lines represent the Out-Of-Bag (OOB) R^2 of models, and dashed lines represent the OOB RMSE of models.

Table S1. FLUXNET2015 Tier1 sites used in this study. ENF: evergreen needleleaf forests, EBF: evergreen broadleaf forests, DNF: deciduous needleleaf forests, DBF: deciduous broadleaf forests, MF: mixed forests, OSH: open shrublands, WSA: woody savannas, SAV: savannas, GRA: grasslands, CRO: croplands, and WET: wetlands.

Site ID	IGBP	Temporal coverage	Latitude (°)	Longitude (°)
AR-SLu	MF	2009-2011	-33.46	-66.46
AR-Vir	ENF	2009-2012	-28.24	-56.19
AT-Neu	GRA	2002-2012	47.12	11.32
AU-ASM	SAV	2010-2014	-22.28	133.25
AU-Cpr	SAV	2010-2014	-34.00	140.59
AU-Cum	EBF	2012-2014	-33.62	150.72
AU-DaP	GRA	2007-2013	-14.06	131.32
AU-DaS	SAV	2008-2014	-14.16	131.39
AU-Emr	GRA	2011-2013	-23.86	148.47
AU-Fog	WET	2006-2008	-12.55	131.31
AU-Gin	WSA	2011-2014	-31.38	115.71
AU-GWW	SAV	2013-2014	-30.19	120.65
AU-How	WSA	2001-2014	-12.49	131.15
AU-Lox	DBF	2008-2009	-34.47	140.66
AU-RDF	WSA	2011-2013	-14.56	132.48
AU-Rob	EBF	2014-2014	-17.12	145.63
AU-Stp	GRA	2008-2014	-17.15	133.35
AU-Tum	EBF	2001-2014	-35.66	148.15
AU-Wac	EBF	2005-2008	-37.43	145.19
AU-Whr	EBF	2011-2014	-36.67	145.03
AU-Wom	EBF	2010-2014	-37.42	144.09
AU-Ync	GRA	2012-2014	-34.99	146.29
BE-Bra	MF	1996-2014	51.31	4.52
BE-Lon	CRO	2004-2014	50.55	4.75
BE-Vie	MF	1996-2014	50.30	6.00
BR-Sa1	EBF	2002-2011	-2.86	-54.96
BR-Sa3	EBF	2000-2004	-3.02	-54.97
CA-Gro	MF	2003-2014	48.22	-82.16
CA-Man	ENF	1994-2008	55.88	-98.48
CA-NS1	ENF	2001-2005	55.88	-98.48
CA-NS2	ENF	2001-2005	55.91	-98.52
CA-NS3	ENF	2001-2005	55.91	-98.38
CA-NS4	ENF	2002-2005	55.91	-98.38
CA-NS5	ENF	2001-2005	55.86	-98.49
CA-NS6	OSH	2001-2005	55.92	-98.96
CA-NS7	OSH	2002-2005	56.64	-99.95

CA-Oas	DBF	1996-2010	53.63	-106.20
CA-Obs	ENF	1997-2010	53.99	-105.12
CA-Qfo	ENF	2003-2010	49.69	-74.34
CA-SF1	ENF	2003-2006	54.49	-105.82
CA-SF2	ENF	2001-2005	54.25	-105.88
CA-SF3	OSH	2001-2006	54.09	-106.01
CA-TP1	ENF	2002-2014	42.66	-80.56
CA-TP2	ENF	2002-2007	42.77	-80.46
CA-TP3	ENF	2002-2014	42.71	-80.35
CA-TP4	ENF	2002-2014	42.71	-80.36
CA-TPD	DBF	2012-2014	42.64	-80.56
CG-Tch	SAV	2006-2009	-4.29	11.66
CH-Cha	GRA	2005-2014	47.21	8.41
CH-Dav	ENF	1997-2014	46.82	9.86
CH-Fru	GRA	2005-2014	47.12	8.54
CH-Lae	MF	2004-2014	47.48	8.36
CH-Oe1	GRA	2002-2008	47.29	7.73
CH-Oe2	CRO	2004-2014	47.29	7.73
CN-Cha	MF	2003-2005	42.40	128.10
CN-Cng	GRA	2007-2010	44.59	123.51
CN-Dan	GRA	2004-2005	30.50	91.07
CN-Din	EBF	2003-2005	23.17	112.54
CN-Du2	GRA	2006-2008	42.05	116.28
CN-Du3	GRA	2009-2010	42.06	116.28
CN-HaM	GRA	2002-2004	37.37	101.18
CN-Qia	ENF	2003-2005	26.74	115.06
CZ-BK1	ENF	2004-2014	49.50	18.54
CZ-BK2	GRA	2004-2012	49.49	18.54
CZ-wet	WET	2006-2014	49.02	14.77
DE-Akm	WET	2009-2014	53.87	13.68
DE-Geb	CRO	2001-2014	51.10	10.91
DE-Gri	GRA	2004-2014	50.95	13.51
DE-Hai	DBF	2000-2012	51.08	10.45
DE-Kli	CRO	2004-2014	50.89	13.52
DE-Lkb	ENF	2009-2013	49.10	13.30
DE-Lnf	DBF	2002-2012	51.33	10.37
DE-Obe	ENF	2008-2014	50.79	13.72
DE-RuR	GRA	2011-2014	50.62	6.30
DE-RuS	CRO	2011-2014	50.87	6.45
DE-Seh	CRO	2007-2010	50.87	6.45
DE-SfN	WET	2012-2014	47.81	11.33
DE-Spw	WET	2010-2014	51.89	14.03
DE-Tha	ENF	1996-2014	50.96	13.57
DE-Zrk	WET	2013-2014	53.88	12.89

DK-Eng	GRA	2005-2008	55.69	12.19
DK-Fou	CRO	2005-2005	56.48	9.59
DK-Sor	DBF	1996-2014	55.49	11.64
ES-Amo	OSH	2007-2012	36.83	-2.25
ES-LgS	OSH	2007-2009	37.10	-2.97
ES-LJu	OSH	2004-2013	36.93	-2.75
ES-Ln2	OSH	2009-2009	36.97	-3.48
FI-Hyy	ENF	1996-2014	61.85	24.29
FI-Jok	CRO	2000-2003	60.90	23.51
FI-Let	ENF	2009-2012	60.64	23.96
FI-Lom	WET	2007-2009	68.00	24.21
FI-Sod	ENF	2001-2014	67.36	26.64
FR-Fon	DBF	2005-2014	48.48	2.78
FR-Gri	CRO	2004-2014	48.84	1.95
FR-LBr	ENF	1996-2008	44.72	-0.77
FR-Pue	EBF	2000-2014	43.74	3.60
GF-Guy	EBF	2004-2014	5.28	-52.92
GH-Ank	EBF	2011-2014	5.27	-2.69
IT-BCi	CRO	2004-2014	40.52	14.96
IT-CA1	DBF	2011-2014	42.38	12.03
IT-CA2	CRO	2011-2014	42.38	12.03
IT-CA3	DBF	2011-2014	42.38	12.02
IT-Col	DBF	1996-2014	41.85	13.59
IT-Cp2	EBF	2012-2014	41.70	12.36
IT-Cpz	EBF	1997-2009	41.71	12.38
IT-Isp	DBF	2013-2014	45.81	8.63
IT-La2	ENF	2000-2002	45.95	11.29
IT-Lav	ENF	2003-2014	45.96	11.28
IT-MBo	GRA	2003-2013	46.01	11.05
IT-PT1	DBF	2002-2004	45.20	9.06
IT-Ren	ENF	1998-2013	46.59	11.43
IT-Ro1	DBF	2000-2008	42.41	11.93
IT-Ro2	DBF	2002-2012	42.39	11.92
IT-SR2	ENF	2013-2014	43.73	10.29
IT-SRo	ENF	1999-2012	43.73	10.28
IT-Tor	GRA	2008-2014	45.84	7.58
JP-MBF	DBF	2003-2005	44.39	142.32
JP-SMF	MF	2002-2006	35.26	137.08
MY-PSO	EBF	2003-2009	2.97	102.31
NL-Hor	GRA	2004-2011	52.24	5.07
NL-Loo	ENF	1996-2014	52.17	5.74
PA-SPn	DBF	2007-2009	9.32	-79.63
PA-SPs	GRA	2007-2009	9.31	-79.63
RU-Che	WET	2002-2005	68.61	161.34

RU-Cok	OSH	2003-2014	70.83	147.49
RU-Fyo	ENF	1998-2014	56.46	32.92
SN-Dhr	SAV	2010-2013	15.40	-15.43
US-AR1	GRA	2009-2012	36.43	-99.42
US-AR2	GRA	2009-2012	36.64	-99.60
US-ARb	GRA	2005-2006	35.55	-98.04
US-ARc	GRA	2005-2006	35.55	-98.04
US-ARM	CRO	2003-2012	36.61	-97.49
US-Blo	ENF	1997-2007	38.90	-120.63
US-CRT	CRO	2011-2013	41.63	-83.35
US-GBT	ENF	1999-2006	41.37	-106.24
US-GLE	ENF	2004-2014	41.37	-106.24
US-Goo	GRA	2002-2006	34.25	-89.87
US-Ha1	DBF	1991-2012	42.54	-72.17
US-IB2	GRA	2004-2011	41.84	-88.24
US-Ivo	WET	2004-2007	68.49	-155.75
US-KS1	ENF	2002-2002	28.46	-80.67
US-KS2	CSH	2003-2006	28.61	-80.67
US-Lin	CRO	2009-2010	36.36	-119.09
US-Los	WET	2000-2014	46.08	-89.98
US-Me1	ENF	2004-2005	44.58	-121.50
US-Me2	ENF	2002-2014	44.45	-121.56
US-Me3	ENF	2004-2009	44.32	-121.61
US-Me5	ENF	2000-2002	44.44	-121.57
US-Me6	ENF	2010-2014	44.32	-121.61
US-MMS	DBF	1999-2014	39.32	-86.41
US-Myb	WET	2010-2014	38.05	-121.77
US-Ne1	CRO	2001-2013	41.17	-96.48
US-Ne2	CRO	2001-2013	41.16	-96.47
US-Ne3	CRO	2001-2013	41.18	-96.44
US-NR1	ENF	1998-2014	40.03	-105.55
US-Oho	DBF	2004-2013	41.55	-83.84
US-ORv	WET	2011-2011	40.02	-83.02
US-PFa	MF	1995-2014	45.95	-90.27
US-Prr	ENF	2010-2014	65.12	-147.49
US-SRC	OSH	2008-2014	31.91	-110.84
US-SRG	GRA	2008-2014	31.79	-110.83
US-Sta	OSH	2005-2009	41.40	-106.80
US-Syv	MF	2001-2014	46.24	-89.35
US-Ton	WSA	2001-2014	38.43	-120.97
US-Tw1	WET	2012-2014	38.11	-121.65
US-Tw3	CRO	2013-2014	38.12	-121.65
US-Tw4	WET	2013-2014	38.10	-121.64
US-Twt	CRO	2009-2014	38.11	-121.65

US-Var	GRA	2000-2014	38.41	-120.95
US-WCr	DBF	1999-2014	45.81	-90.08
US-Whs	OSH	2007-2014	31.74	-110.05
US-Wi0	ENF	2002-2002	46.62	-91.08
US-Wi1	DBF	2003-2003	46.73	-91.23
US-Wi3	DBF	2002-2004	46.63	-91.10
US-Wi4	ENF	2002-2005	46.74	-91.17
US-Wi5	ENF	2004-2004	46.65	-91.09
US-Wi6	OSH	2002-2003	46.62	-91.30
US-Wi7	OSH	2005-2005	46.65	-91.07
US-Wi8	DBF	2002-2002	46.72	-91.25
US-Wi9	ENF	2004-2005	46.74	-91.07
US-Wkg	GRA	2004-2014	31.74	-109.94
US-WPT	WET	2011-2013	41.46	-83.00
ZM-Mon	DBF	2000-2009	-15.44	23.25

Table S2. Model codes and their corresponding predictors.

Model Code	VIs	CO_2	PFT	Plant Traits	Climate Factors
V	√				
VC	√	√			
VP	√		√		
VCP	√	√	√		
VCT	√	√		√	
VCPT	√	√	√	√	
VCF	√	√			√
VCPF	√	√	√		√
VCTF	√	√		√	√
VCPTF	√	√	√	√	√