Ecosystem physio-phenology revealed using circular statistics
Supplementary information (I)

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1 Half-time sensitivity analysis (System memory to explain DOY_{GPPmax})

The optimum halftime parameter is estimated for each site showing that for most of the unimodal sites JS correlation is maximum when the halftime parameter takes values between 2 and 100 days. Per vegetation type Deciduous Broadleaf forest (DBF), Evergreen Needleleaf Forest (ENF) and Grassland (GRA) have similar values for the optimum half-time parameter (Figure A1.2). Evergreen Broadleaf Forest (EBF) presents a higher dispersion of half-time values between 12 to 146 days. Per climate classes, the Hot-summer Mediterranean ecosystem (Csa) has the highest variation. There are only 4 unimodal sites with an optimum half-time greater than 100 days: ZA-Kru, IT-Cpz, RU-Cok, and US-SRM. On the other hand, for the bimodal site (ES-LJu) the maximum JS coefficient is obtained with a half-time of 20 for the first growing season and 25 days for the second one (Table A1.2). Estimating the halftime of the drivers per site is a prerequisite for optimizing the predictions with the circular regressions in the next step. For most of the sites, the JS correlation coefficient is maximum between 0.98 and 0.85 (Figure A1.6), only 5 sites have a JS coefficient of less than 0.8: US-Ton, IT-MBo, IT-Ro2, US-Wkg, BR-Sa1. For ES-LJu the JS coefficient for the first growing season is 0.94 and 0.93 for the second one (Table A1.2).

Our results of the optimum halftime parameter between 2 and 100 days for all sites are similar to the time window length of 15 to 120 days required to explain the variations on the leaf unfolding for different tree species in Europe (Fu et al., 2015). Or, the time window length of 45 to 95 days to explain the flowering day of different plant species in Switzerland (Güsewell et al., 2017). No matter what phenological event is being analyzed all studies agree that phenological events are influenced by past climatic conditions in a cumulative form. Curiously, for the only bimodal site, the halftime parameter is similar between both growing seasons suggesting that the system memory does not change between growing seasons.

In our case, the use of a half-life decay function changes the interpretation of the optimum halftime day parameter indicating that half of the contribution is given before the halftime day in an exponential form and that the contribution of the rest of the days is low, but not equal to 0. Finally, we find that the optimum half-time is not necessarily related to the vegetation type or the predominant climate class in each site. We suggest that it could be more related to the species dominance and the spatial arrangement and the intraspecific climatic variability of each site.

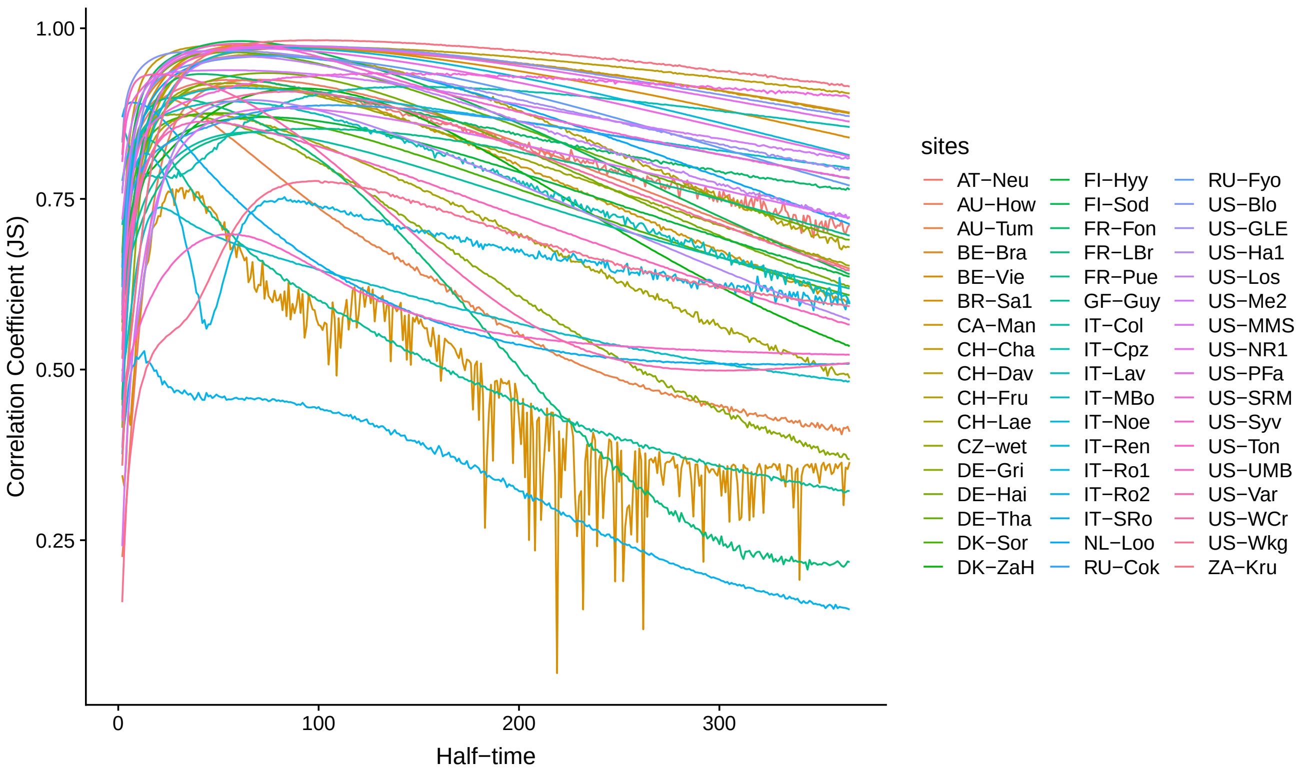

Figure S1. Half-time sensitivity analysis. The correlation coefficient (JS) between the observed and predicted DOY_{GPPmax} using different half-time values. Each FLUXNET site is represented with a color.

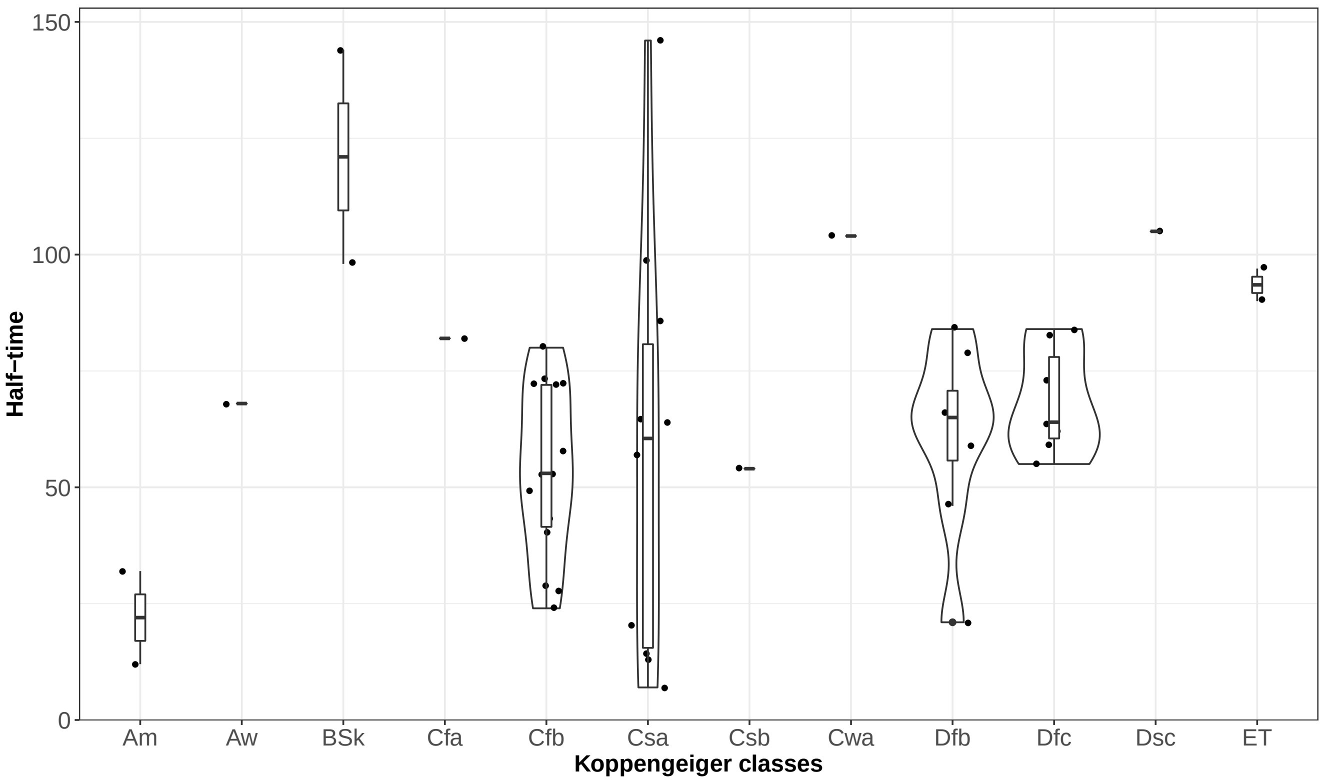

Figure S2. Half-time sensitivity analysis. Distribution of the half-time when the Jammalamanaka-Sarna (JS) coefficient is maximum for each FLUXNET site using as classification criterium the Koppen climate classes: Tropical monsoon climate (Am), Tropical savanna climate (Aw), Cold semi-arid climates (BSk), Humid subtropical climate (Cfa), Oceanic climate (Cfb), Hot-summer mediterranean climate (Csa), Warm-summer mediterranean climate (Csb), Humid subtropical climate (Cwa), humid continental climate (Dfb), Subarctic climate (Dfc, Dsc), and Tundra climate (ET)

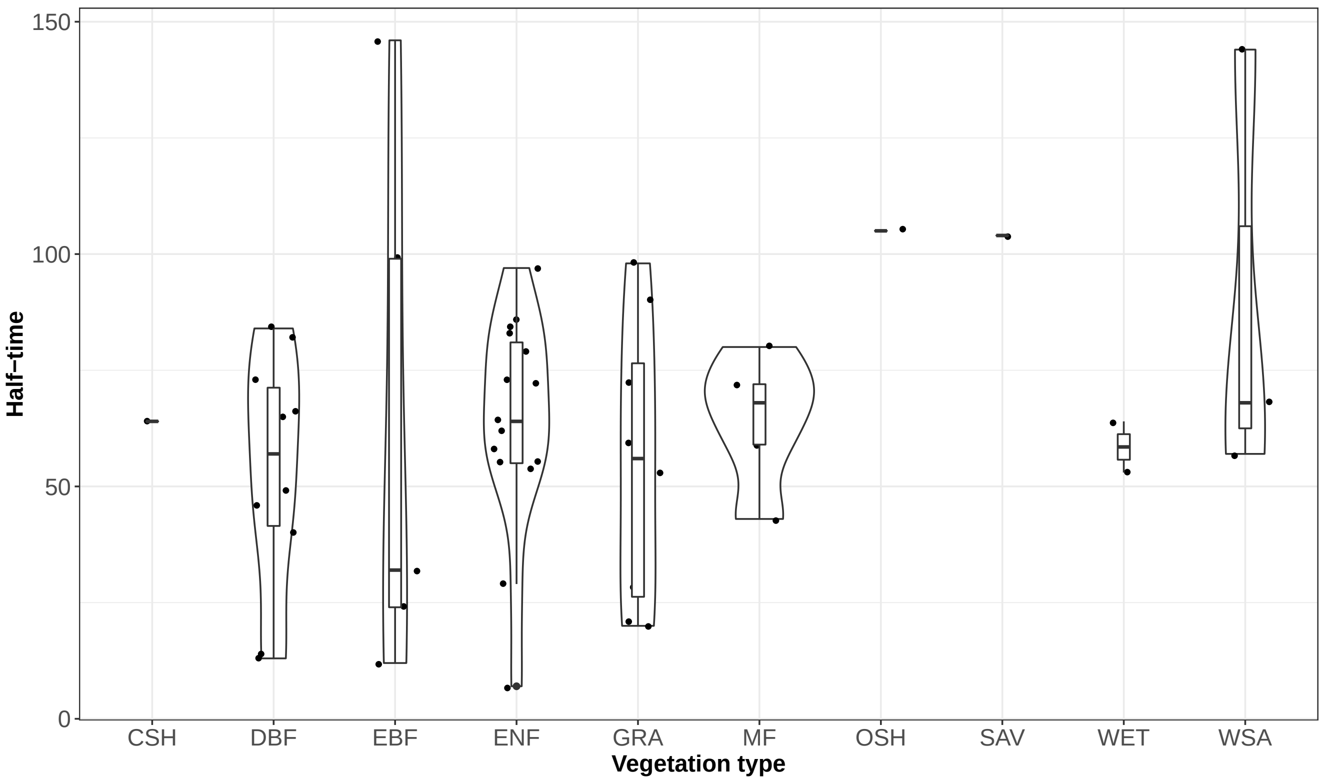

Figure S3. Half-time sensitivity analysis. Distribution of the optimum half-time parameter when the Jammalamadaka-Sarna (JS) coefficient is maximum per vegetation type. Closed Shrublands (CSH), Deciduous Broadleaf Forests (DBF), Evergreen Broadleaf Forests (EBF), Evergreen Needleleaf Forests (ENF), Grasslands (GRA), Mixed Forests (MF), Open Shrublands (SAV) Savannas, Permanent Wetlands (WET), Woody Savannas (WSA)

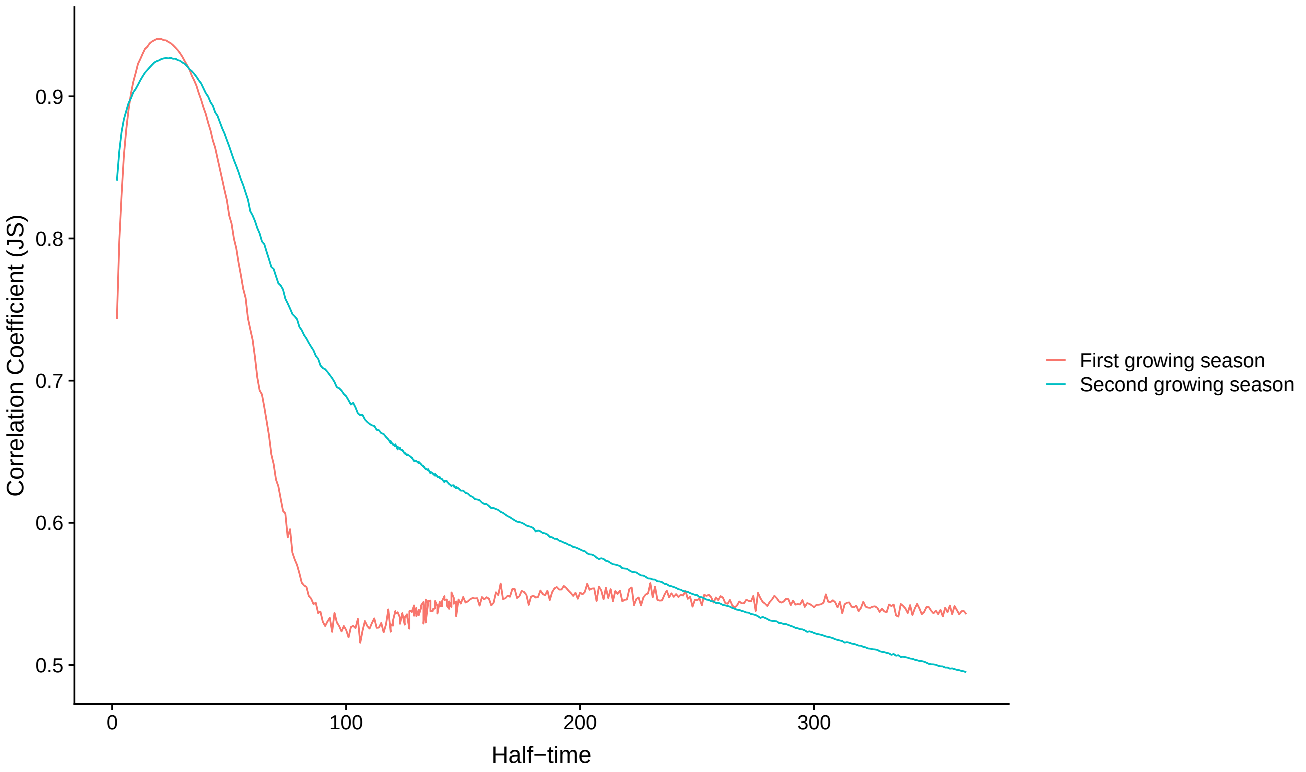

Figure S4. Half-time sensitivity analysis for ES-LJu the unique FLUXNET site analyzed with two growing seasons.

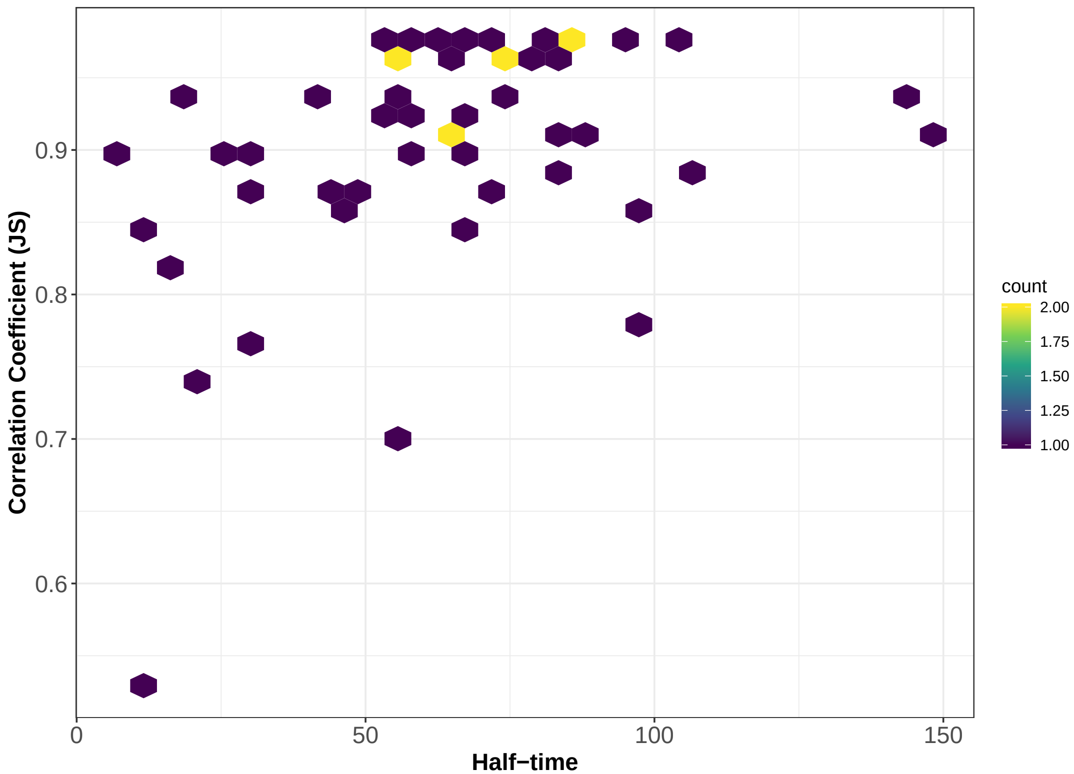

Figure S5. Distribution of the maximum correlation coefficient values when the optimum halftime has been used. Most of the sites have the maximum correlation coefficient when half-time is between 5 and 100 days.

Table S1: Optimum half-time coefficient and correlation coefficient per FLUXNET site. We report the name of sites, the climate class of the site following the Köppen-Geiger classification: Tropical monsoon climate (Am), Tropical savanna climate (Aw), Cold semi-arid climates (BSk), Humid subtropical climate (Cfa), Oceanic climate (Cfb), Hot-summer mediterranean climate (Csa), Warm-summer mediterranean climate (Csb), Humid subtropical climate (Cwa), humid continental climate (Dfb), Subarctic climate (Dfc, Dsc), and Tundra climate (ET). We also report the vegetation type where: We also report the Vegetation type: Closed Shrublands (CSH), Deciduous Broadleaf Forests (DBF), Evergreen Broadleaf Forest (EBF), Evergreen Needleleaf Forests (ENF), Grasslands (GRA), Mixed Forests (MF), Open Shrublands (OSH), Savannas (SAV), Permanent Wetlands (WET), Woody Savannas (WSA).

Site name	Köppen-Geiger class	Vegetation type	Optimum Half-time	Correlation coefficient (JS)
US-Ha1	Dfb	DBF	66	0.89
US-PFa	Dfb	MF	68	0.97
BE-Bra	Cfb	MF	80	0.97
BE-Vie	Cfb	MF	72	0.98
DE-Tha	Cfb	ENF	55	0.96
DK-Sor	Cfb	DBF	49	0.88
FI-Hyy	Dfc	ENF	73	0.87
IT-Col	Csa	DBF	65	0.85
NL-Loo	Cfb	ENF	72	0.96
CH-Dav	ET	ENF	97	0.97
RU-Fyo	Dfb	ENF	79	0.96
US-NR1	Dfc	ENF	84	0.97
IT-Ren	Dfc	ENF	83	0.97
US-MMS	Cfa	DBF	82	0.88
US-WCr	Dfb	DBF	84	0.91
CA-Man	Dfc	ENF	64	0.92
DK-ZaH	ET	GRA	90	0.91
FR-Pue	Csa	EBF	99	0.85
US-Los	Dfb	WET	64	0.96
US-UMB	Dfb	DBF	46	0.86
US-Var	Csa	GRA	20	0.93
AU-How	Aw	WSA	68	0.92
AU-Tum	Cfb	EBF	24	0.9
FI-Sod	Dfc	ENF	62	0.98

IT-SRo	Csa	ENF	7	0.89
US-Syv	Dfb	MF	59	0.98
US-Ton	Csa	WSA	57	0.7
ZA-Kru	Cwa	SAV	104	0.98
DE-Hai	Cfb	DBF	73	0.93
FR-LBr	Cfb	ENF	29	0.9
IT-Cpz	Csa	EBF	146	0.91
US-Me2	Csb	ENF	54	0.94
IT-Lav	Cfb	ENF	58	0.89
RU-Cok	Dsc	OSH	105	0.89
AT-Neu	Dfc	GRA	59	0.92
CH-Lae	Cfb	MF	43	0.88
DE-Gri	Cfb	GRA	28	0.87
GF-Guy	Am	EBF	12	0.84
IT-MBo	Dfb	GRA	21	0.74
IT-Noe	Csa	CSH	64	0.91
IT-Ro2	Csa	DBF	13	0.53
US-Blo	Csa	ENF	86	0.97
US-GLE	Dfc	ENF	55	0.97
US-SRM	BSk	WSA	144	0.93
US-Wkg	BSk	GRA	98	0.78
BR-Sa1	Am	EBF	32	0.77
CH-Cha	Cfb	GRA	53	0.98
CH-Fru	Cfb	GRA	72	0.96
FR-Fon	Cfb	DBF	40	0.93
CZ-wet	Cfb	WET	53	0.92
IT-Ro1	Csa	DBF	14	0.82

Table S2. Results of the optimum half-time and the maximum correlation coefficient for " Llano de los Juanes", Spain with Köppen-Geiger class: Hot-summer Mediterranean climate (Csa) and vegetation type: Open Shrublands (OSH)

			DOY_{GPPmax} (GS 1)		DOY_{GPPmax} (GS 2)	
Site name	Köppen-Geiger class	Vegetation type	Optimum Halftime	Correlation coefficient (JS)	Optimum Halftime	Correlation coefficient (JS)
ES-Lju	Csa	OSH	20	0.94	25	0.93

2 Phenological summary of the FLUXNET sites (Recovering DOY_{GPPmax})

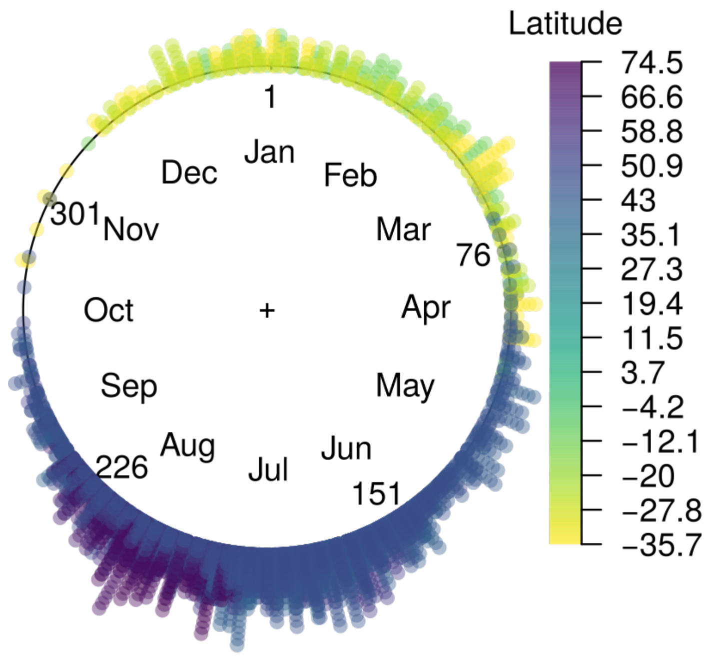

Figure S6. DOY_{GPPmax} distribution across the latitudinal gradient. Most of the DOY_{GPPmax} is reached at the middle of the year. This pattern is generated by the geographical trend of the location of the FLUXNET network in the Northern hemisphere.

Table S3: Mean angular direction and the standard deviation of DOY_{GPPmax} for ecosystems with one growing season per year.

Site name	Mean DOY_{GPPmax} (days)	SD DOY_{GPPmax} (days)
US-Ha1	195.2	19.5
US-PFa	196.6	21.6
BE-Bra	196.71	25.35
BE-Vie	192.28	29.9
DE-Tha	182.91	27.4
DK-Sor	169.96	13.96
FI-Hyy	199.93	17.74
IT-Col	187.75	23.84
NL-Loo	210.27	25.82
CH-Dav	180.99	38.69
RU-Fyo	192.14	23.17

US-NR1	201.98	28.79
IT-Ren	193.55	32.34
US-MMS	183.59	22.71
US-WCr	198.26	20.02
CA-Man	215.87	19.96
DK-ZaH	204.39	10.3
FR-Pue	159.97	34.07
US-Los	194.81	13.46
US-UMB	189.13	20.5
US-Var	95.95	21.82
AU-How	28.77	30.87
AU-Tum	24.29	46.9
FI-Sod	214.35	15.66
IT-SRo	142.6	28.3
US-Syv	194.9	25.65
US-Ton	114.63	20
ZA-Kru	15.35	37.09
DE-Hai	190.26	22.84
FR-LBr	177.35	23.83
IT-Cpz	154.5	46.04
US-Me2	182.5	26.15
IT-Lav	167.19	37.11
RU-Cok	209.61	11.48
AT-Neu	161.46	33.73
CH-Lae	185.32	30.71
DE-Gri	178.61	33.51
GF-Guy	214.86	41.17
IT-MBo	169.51	12.22
IT-Noe	120.71	28.96
IT-Ro2	155.48	18.69
US-Blo	199.04	33.38
US-GLE	209.55	17.46
US-SRM	227.65	17.66

US-Wkg	228.54	11.26
BR-Sa1	325.24	38.49
CH-Cha	201.24	38.2
CH-Fru	163.9	39.97
FR-Fon	179.49	24.11
CZ-wet	169.88	17.68
IT-Ro1	148.23	11.33

Table S4. Mean angular direction and standard deviation of DOY_{GPPmax} for ecosystems with two growing seasons

			DOY_{GPPmax} (GS 1)		DOY_{GPPmax} (GS 2)	
Site name	Koppen	Vegetation type	Mean (DOY)	SD (days)	Mean (DOY)	SD (days)
ES-Lju	Csa	OSH	143.62	17.84	302.63	19.18

3 Similarity of regression coefficients per vegetation type and climate classes

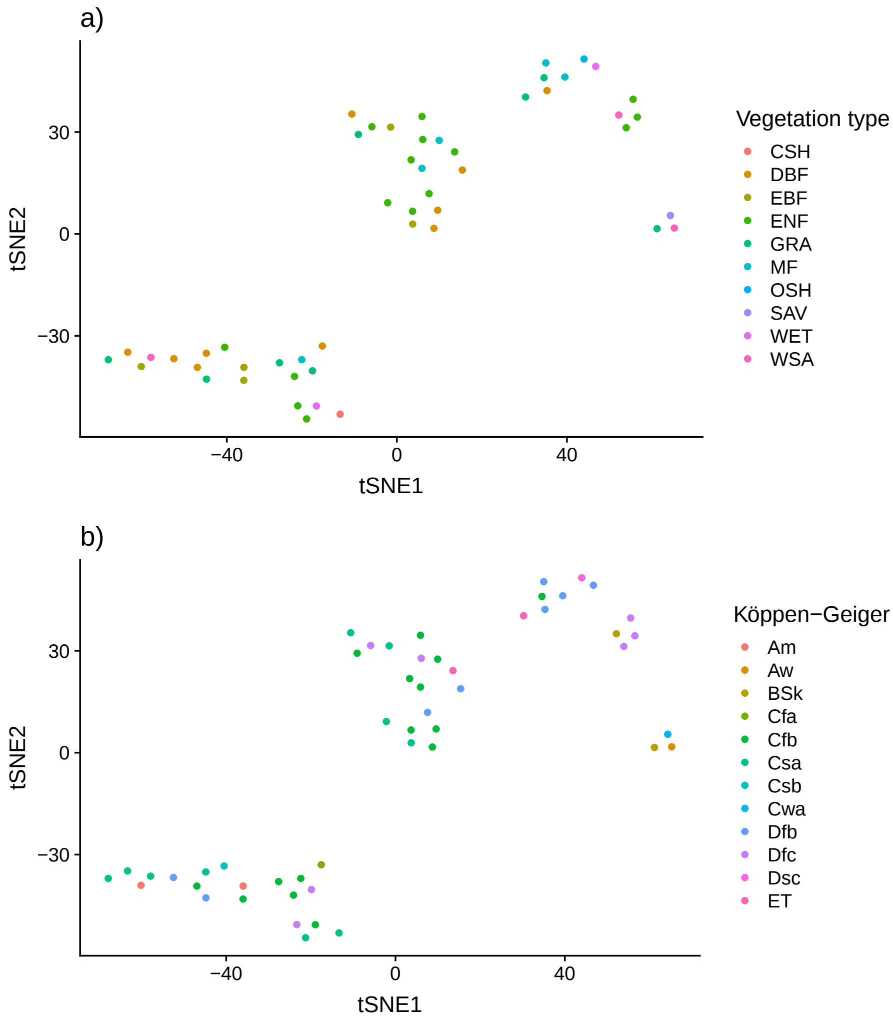

Figure S7. Similarity between the regression coefficients of air temperature, shortwave incoming radiation, precipitation and vapor pressure deficit of the circular regression for each FLUXNET site. t-Distributed Stochastic Neighbor Embedding (t-SNE) analysis was performed using perplexity = 5. a). Colors per the vegetation: Closed Shrublands (CSH), Deciduous Broadleaf Forests (DBF), Evergreen Broadleaf Forest (EBF), Evergreen Needleleaf Forests (ENF), Grasslands (GRA), Mixed Forests (MF), Open Shrublands (OSH), Savannas (SAV), Permanent Wetlands (WET), Woody Savannas (WSA). c) Colors per Köppen-Geiger climate classes: Tropical monsoon climate (Am), Tropical savanna climate (Aw), Cold semi-arid climates (BSk), Humid subtropical climate (Cfa), Oceanic climate (Cfb), Hot-summer mediterranean climate (Csa), Warm-summer mediterranean climate (Csb), Humid subtropical climate (Cwa), humid continental climate (Dfb), Subarctic climate (Dfc, Dsc), and Tundra climate (ET)

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