Supplementary Information: Global patterns of forest autotrophic carbon fluxes

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Table S1. Climate variable definitions, sources, and abbreviations

Abbreviation	Climate variable	Units	Definition	Time span	Source
MAT	Mean annual temperature	°C	Annual mean temperature, from primary literature or WorldClim if not reported	1970 - 2000	Primary literature; WorldClim[1]
MAP	Mean annual precipitation	mm yr^{-1}	Annual mean precipitation, from primary literature or WorldClim if not reported	1970 - 2000	Primary literature; WorldClim[1]
T Seas	Temperature seasonality	°C	Standard deviation (variation) of monthly temperature averages	1970 - 2000	WorldClim[1]
P Seas	Precipitation seasonality	%	Coefficient of variation of mean monthly precipitation x 100	1970 - 2000	WorldClim[1]
ATR	Annual temperature range	°C	Maximum temperature of warmest month - minimum temperature of coldest month	1970 - 2000	WorldClim[1]
Solar R	Solar radiation	kJ m^{-2} yr^{-1}	Solar radiation	1970 - 2000	WorldClim2[2]
Cloud	Cloud cover	%	Cloud percentage cover	1901 - 2014	CRU time-series dataset v 4.03[3]
AFD	Annual frost days	days yr^{-1}	Number of freeze days annually	1901 - 2014	CRU time-series dataset v 4.03[3]
AWD	Annual wet days	days yr^{-1}	Number of days with precipitation >0.1 mm annually	1901 - 2014	CRU time-series dataset v 4.03[3]
PET	Potential evapotranspiration	mm yr^{-1}	Mean annual potential evapotranspiration	1950 - 2000	Global Aridity Index and Potential Evapotranspiration Climate Database[4]
AI	Aridity		MAP/mean annual PET	1950 - 2000	Global Aridity Index and Potential Evapotranspiration Climate Database[4]
VPD	Vapour pressure deficit	kPa	Mean monthly vapour pressure deficit	1958 - 2015	TerraClimate[5]
Max VPD	Maximum vapour pressure deficit	kPa	Maximum monthly vapour pressure deficit	1958 - 2017	Derived from TerraClimate data
WSM	Water stress months	months yr^{-1}	Number of months annually with MAP < PET	1970 - 2000	Derived from WorldClim data
LGS	Length of growing season	months yr^{-1}	Number of months annually with mean minimum temperature > 0.5°C	1901 - 2014	Derived from CRU data
gsT	Growing season temperature	°C	Mean growing season temperature	1901 - 2014	Derived from CRU data
gsP	Growing season precipitation	mm month^{-1}	Mean monthly precipitation during growing season months	1901 - 2014	Derived from CRU data
gsPET	Growing season PET	mm month^{-1}	Mean monthly potential evapotranspiration during growing season months	1901 - 2014	Derived from CRU data
gsR	Growing season solar radiation	mm month^{-1}	Mean monthly solar radiation during growing season	1901 - 2014	Derived from CRU data

[*] The WorldClim version used was the most recent available at the time of analysis
[1] Hijmans et al. (2005) [2] Fick et al. (2017) [3] Harris et al. (2017) [4] Abatzoglou et al. (2018)

Table S2. Model form, ΔAIC, and R^2 for each climate variables as a single fixed effect in models for each C flux. Model forms include first-order linear (Lin), second-order polynomial (Poly), and logarithmic (Log).

	Latitude			MAT			MAP			T Seas			P Seas			ATR			Solar R			AI		
Carbon Flux	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R-sq	dAIC
GPP	Lin	0.64	54.9	Lin	0.61	52.5	Lin	0.18	33.3	Poly	0.71	69.5	-	-	-	Poly	0.69	63.0	Log	0.16	8.9	-	-	-
NPP	Log	0.50	44.3	Lin	0.42	41.5	Poly	0.21	16.7	Log	0.52	44.3	-	-	-	Log	0.49	42.3	Poly	0.16	12.5	Lin	0.04	2.8
ANPP	Lin	0.44	63.4	Lin	0.44	80.5	Poly	0.16	19.7	Log	0.41	58.7	-	-	-	Log	0.37	51.9	Lin	0.11	12.3	Lin	0.05	2.1
ANPP stem	Lin	0.18	22.2	Lin	0.24	38.5	Log	0.05	7.3	Lin	0.14	17.6	Poly	0.05	5	Lin	0.12	13.6	Log	0.06	6.8	Lin	0.07	4
ANPP foliage	Lin	0.50	37.7	Lin	0.58	52.9	Poly	0.25	13.3	Lin	0.48	34.1	-	-	-	Lin	0.50	36.1	Log	0.17	10.1	Lin	0.11	6.8
BNPP root	Lin	0.34	22.9	Log	0.31	21.0	Poly	0.15	6.2	Log	0.36	26.6	-	-	-	Log	0.33	23.6	Poly	0.29	18.8	-	-	-
BNPP fine root	Lin	0.17	8.0	Lin	0.15	7.2	Log	0.11	5.4	Lin	0.17	8.4	-	-	-	Log	0.19	10.9	Log	0.14	7.2	Log	0.06	2.4
R auto	Lin	0.65	13.1	Lin	0.59	10.9	Poly	0.60	8.6	Log	0.65	13.1	-	-	-	Log	0.60	11.5	Log	0.27	2.4	Poly	0.48	3.7
R root	Log	0.22	8.8	Lin	0.24	8.3	Lin	0.15	6.8	Log	0.24	9.5	-	-	-	Log	0.22	8.8	-	-	-	Lin	0.16	7.3

	Cloud			AFD			AWD			PET			VPD			Max VPD			WSM			LGS		
Carbon Flux	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC	Model	R^2	Δ AIC
GPP	-	-	-	Log	0.54	50.0	Lin	0.11	5.7	Poly	0.36	19.7	Poly	0.31	15.9	-	-	-	-	-	-	Lin	0.53	38.2
NPP	Lin	0.06	3.6	Lin	0.40	38.5	Lin	0.11	7.3	Poly	0.32	24.3	Poly	0.18	15.3	-	-	-	Lin	0.04	4	Lin	0.38	28.4
ANPP	Poly	0.09	7.1	Log	0.41	61.6	Lin	0.17	18.7	Poly	0.27	24.5	Poly	0.23	21.4	Poly	0.06	2.2	Poly	0.06	3	Lin	0.34	44.0
ANPP stem	Poly	0.09	5.4	Log	0.17	22.3	-	-	-	Poly	0.20	14.0	Poly	0.21	17.7	Log	0.14	7.5	-	-	-	Log	0.11	12.6
ANPP foliage	-	-	-	Lin	0.53	43.4	Lin	0.15	7	Log	0.32	24.2	Log	0.35	30.0	Poly	0.07	4.9	Poly	0.17	7.8	Log	0.46	32.9
BNPP root	-	-	-	Lin	0.28	19.1	Poly	0.11	3.4	Poly	0.36	23.2	Poly	0.26	13.9	-	-	-	-	-	-	Lin	0.26	14.7
BNPP fine root	-	-	-	Lin	0.16	9.2	Lin	0.08	2.7	Log	0.14	7.1	Log	0.06	1.9	-	-	-	-	-	-	Lin	0.13	5.8
R auto	-	-	-	Log	0.57	9.4	Null	0.26	0.6	Log	0.36	4.8	Log	0.35	4.3	-	-	-	Null	0.3	1.5	Lin	0.47	5.8
R root	Log	0.16	1.9	Log	0.19	7.3	Lin	0.17	3.5	Poly	0.19	1.7	Poly	0.27	6.7	-	-	-	Lin	0.14	6.1	Lin	0.19	5.9

Table S3. Joint effects of MAT and MAP on forest C fluxes

Carbon flux	MAT	MAT + MAP	MAT x MAP	R^2
GPP	<0.0001	<0.0001	NS	0.66
NPP	<0.0001	NS	0.018	0.48
ANPP	<0.0001	0.035	NS	0.45
ANPP stem	<0.0001	NS	0.021	0.26
ANPP foliage	<0.0001	NS	NS	0.59
BNPP root	<0.0001	NS	NS	0.29
BNPP fine root	0.0021	NS	NS	0.15
R auto	0.00016	0.041	NS	0.71
R root	0.0011	NS	NS	0.25

Table S4. Comparison of growing season length and MAT as predictors of forest C fluxes

Fixed effect	AIC value	Δ AIC	Marginal R^2
GPP			
MAT	126.43	0.00	0.62
Growing season length	140.81	14.38	0.54
None	178.96	52.54	0.00
NPP			
MAT	174.88	0.00	0.52
Growing season length	191.54	16.65	0.40
None	216.17	41.29	0.00
ANPP			
MAT	249.51	0.00	0.29
Growing season length	254.21	4.70	0.26
None	268.94	19.43	0.00
ANPP stem			
MAT	235.96	0.00	0.15
Growing season length	237.29	1.33	0.14
None	243.14	7.18	0.00
ANPP foliage			
MAT	484.88	0.00	0.45
Growing season length	520.96	36.09	0.35
None	560.35	75.47	0.00
BNPP root			
MAT	184.54	0.00	0.59
Growing season length	204.93	20.38	0.46
None	237.47	52.92	0.00
BNPP fine root			
MAT	540.19	0.00	0.24
Growing season length	566.37	26.18	0.11
None	578.66	38.46	0.00
R auto			
MAT	45.26	0.00	0.63
Growing season length	50.36	5.10	0.50
None	56.17	10.91	0.00
R root			
MAT	133.54	0.00	0.25
Growing season length	135.93	2.39	0.20
None	141.79	8.25	0.00

Table S5. Best models by carbon flux. Where ΔAIC values </= 2 all models with a ΔAIC value </= 2 are presented

Carbon flux	Climate variable	Model type	ΔAIC relative to null model	ΔAIC relative to next best model	R^2
GPP	T Seas	Poly	69.5	6.55	0.71
NPP	MAT	Lin	41.5	0.21	0.42
	T Seas	Log	44.3	-	0.52
ANPP	MAT	Lin	80.5	21.4	0.44
ANPP stem	MAT	Lin	38.5	15.87	0.24
ANPP foliage	MAT	Lin	52.9	11.05	0.58
BNPP root	T Seas	Log	26.6	3.01	0.36
BNPP fine root	ATR	Log	10.9	2.11	0.19
R auto	T Seas	Log	13.1	1.62	0.65
	ATR	Log	11.5	-	0.60
R root	T Seas	Log	9.5	0.76	0.24
	ATR	Log	8.8	-	0.22
	MAT	Lin	8.3	-	0.24

Table S6. Pairwise comparisons between carbon fluxes

C flux variable 1	C flux variable 2	Climate variable	R^2 variable 1	R^2 variable 2	Model type variable 1	Model type variable 2	Number of plots	Variable with higher R^2
GPP	NPP	Latitude	0.62	0.66	Lin	Lin	37	NPP
		MAT	0.62	0.70	Log	Lin	37	NPP
		T Seas	0.65	0.70	Log	Log	37	NPP
NPP	ANPP	Latitude	0.52	0.48	Log	Log	158	NPP
		MAT	0.30	0.44	Log	Lin	158	ANPP
		T Seas	0.47	0.43	Lin	Lin	158	NPP
	BNPP	Latitude	0.49	0.34	Log	Lin	116	NPP
		MAT	0.41	0.22	Log	Log	116	NPP
		T Seas	0.49	0.41	Log	Log	116	NPP
ANPP	ANPP stem	Latitude	0.35	0.13	Lin	Lin	176	ANPP
		MAT	0.42	0.17	Lin	Lin	176	ANPP
		T Seas	0.29	0.09	Lin	Lin	176	ANPP
	ANPP foliage	Latitude	0.32	0.45	Log	Log	96	ANPP foliage
		MAT	0.36	0.50	Lin	Lin	96	ANPP foliage
		T Seas	0.27	0.42	Lin	Lin	96	ANPP foliage
GPP	R auto	Latitude	0.64	0.34	Null	Null	11	GPP
		MAT	0.69	0.34	Null	Null	11	GPP
		T Seas	0.64	0.32	Null	Null	11	GPP
BNPP	R root	Latitude	0.01	0.39	Null	Null	9	R root
		MAT	0.08	0.35	Null	Null	9	R root
		T Seas	0.01	0.63	Null	Null	9	R root

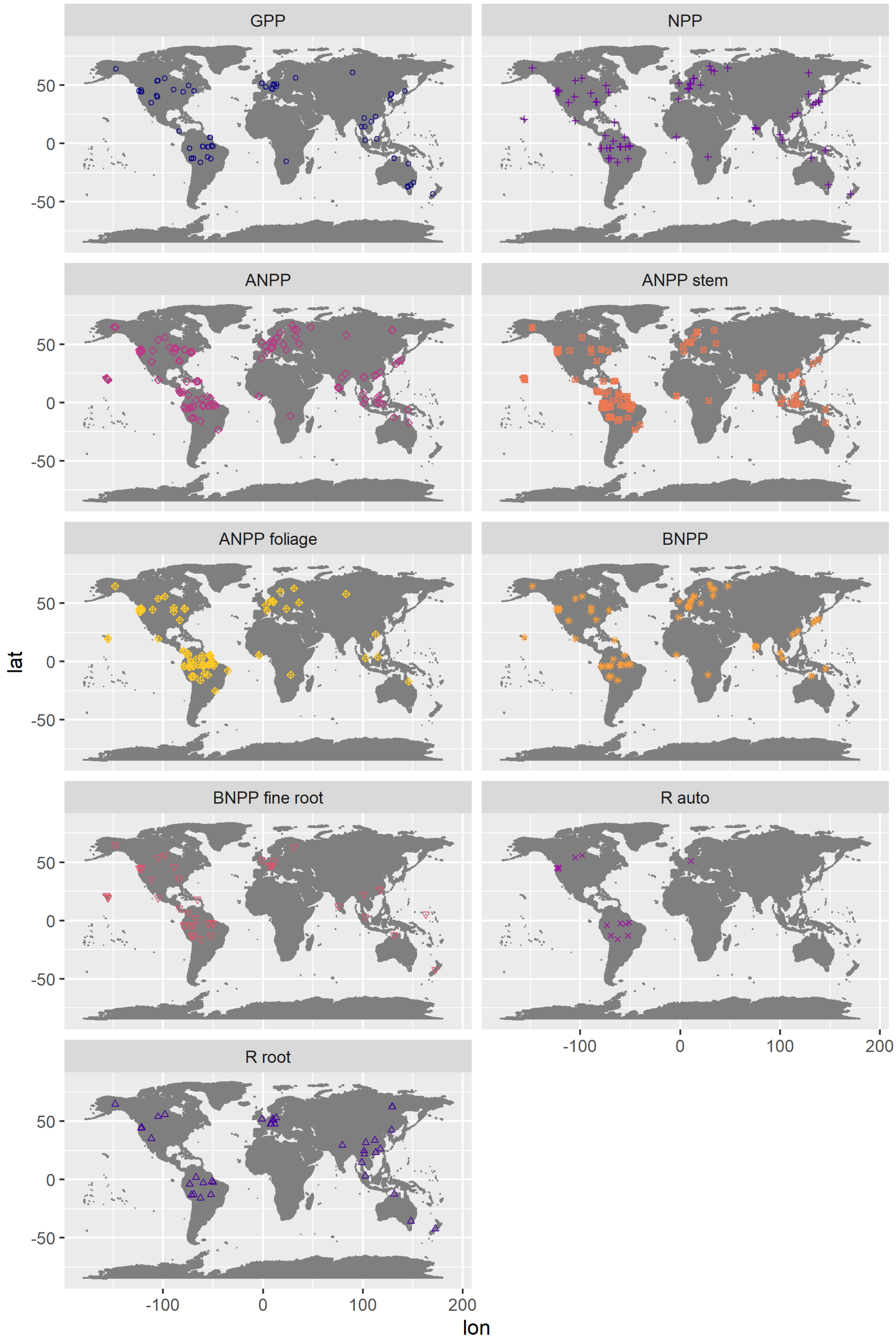

Figure S1: Maps showing distribution of samples for the nine forest C fluxes analyzed here

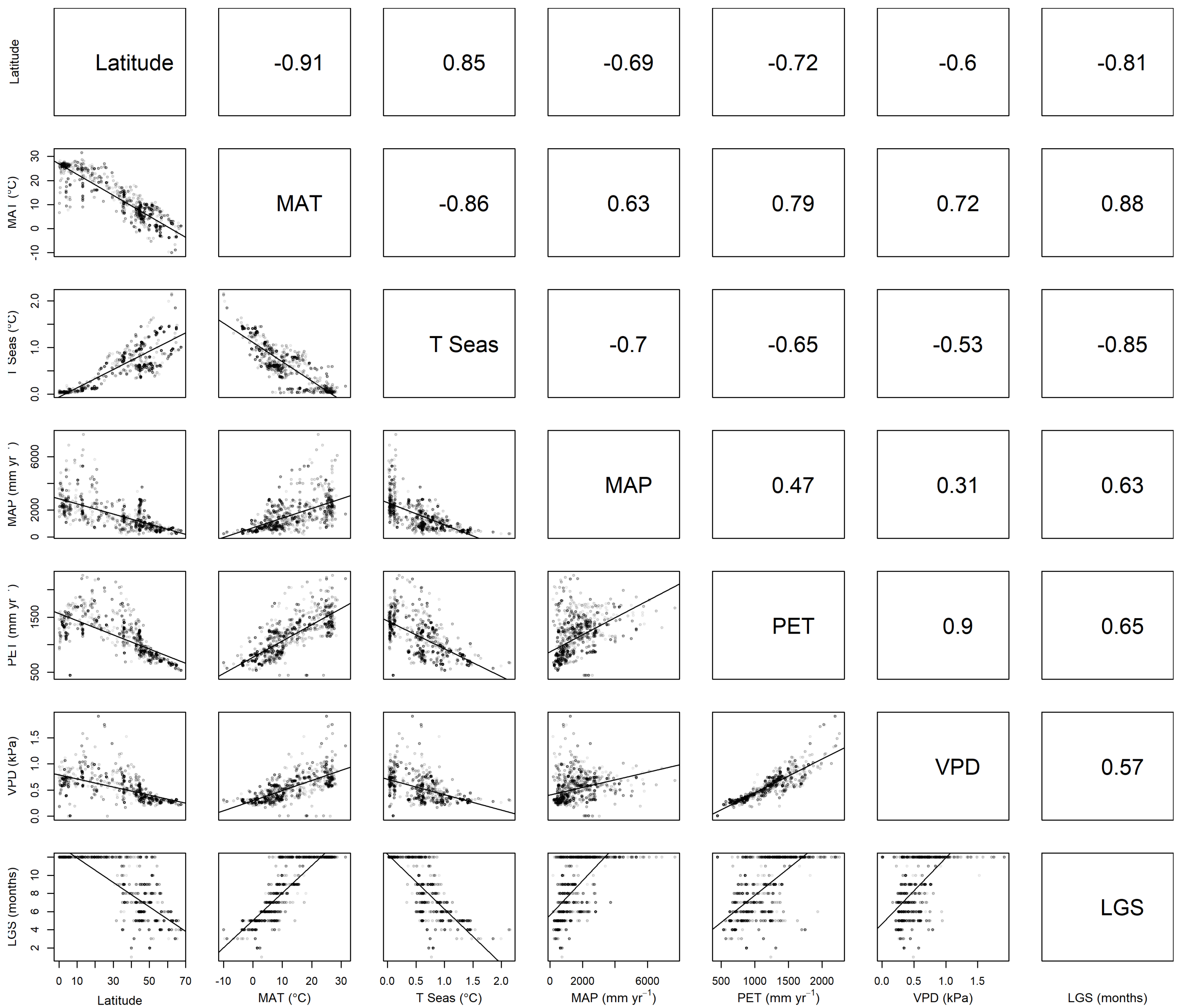

Figure S2: Scatterplots and Pearson's R values for relationships between latitude and climate variables

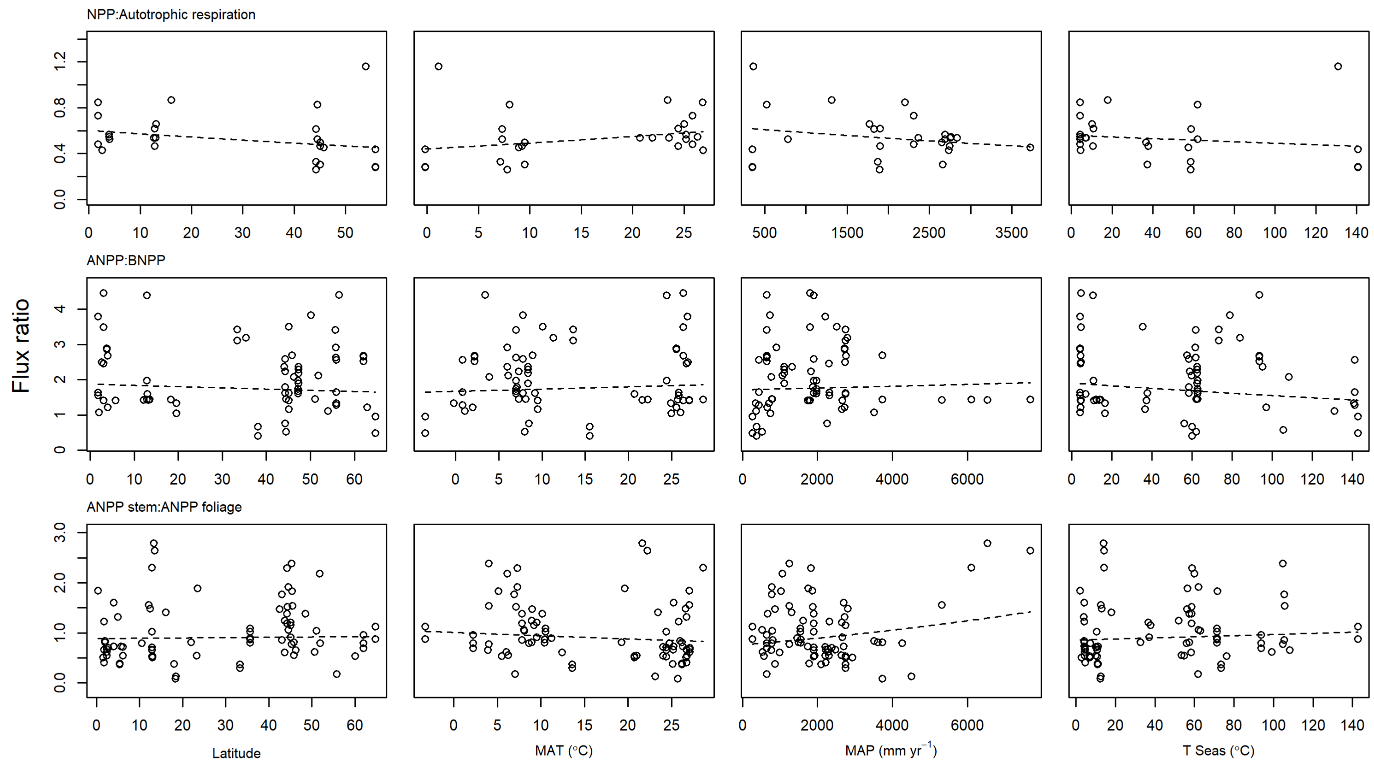

Figure S3: Ratios among forest C fluxes as a function of latitude and climate variables

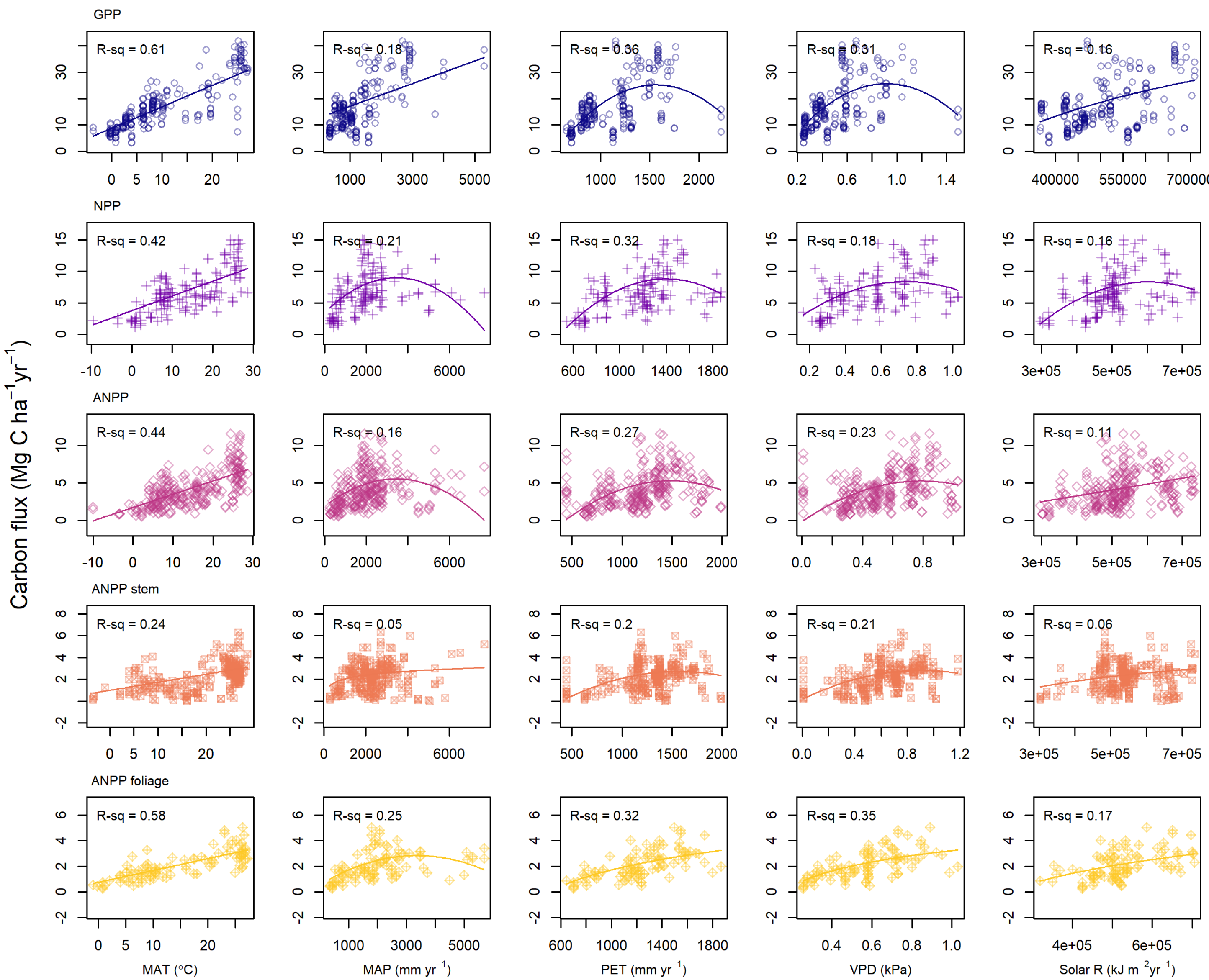

Figure S4: Individual plots of forest C fluxes in relation to mean annual climate, part 1.

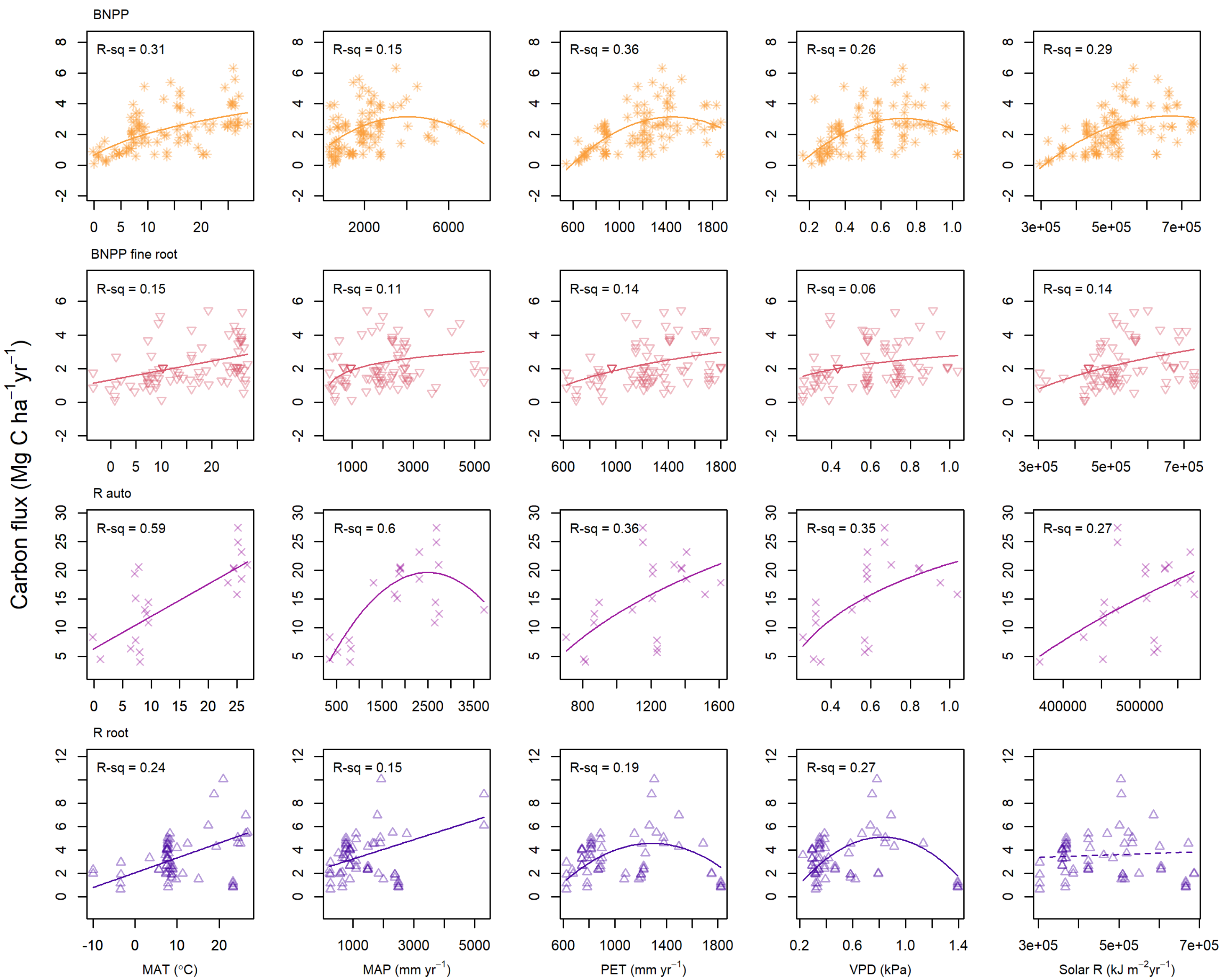

Figure S5: Individual plots of forest C fluxes in relation to mean annual climate, part 2.

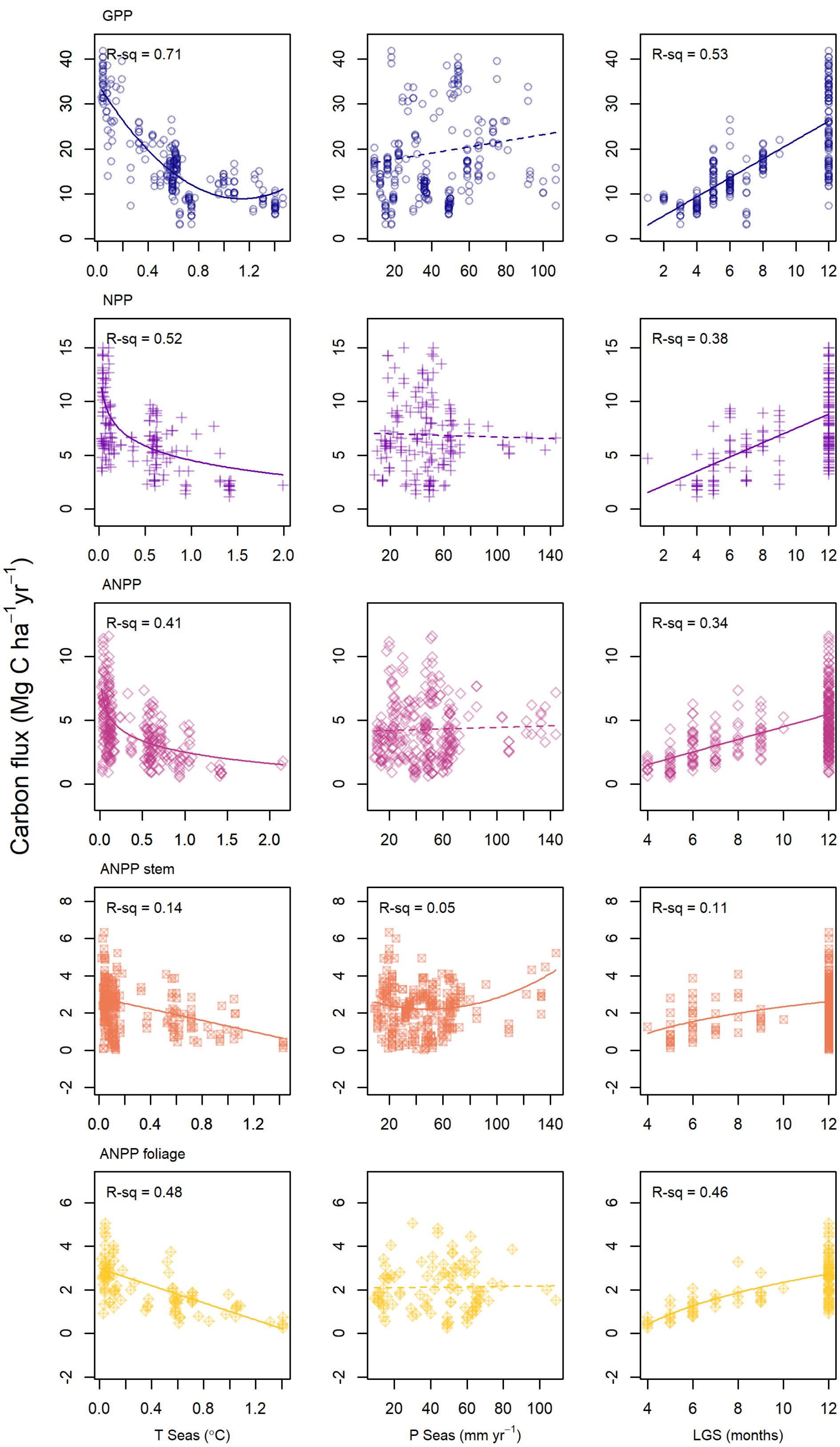

Figure S6: Individual plots of forest C fluxes in relation to mean climate seasonality, part 1.

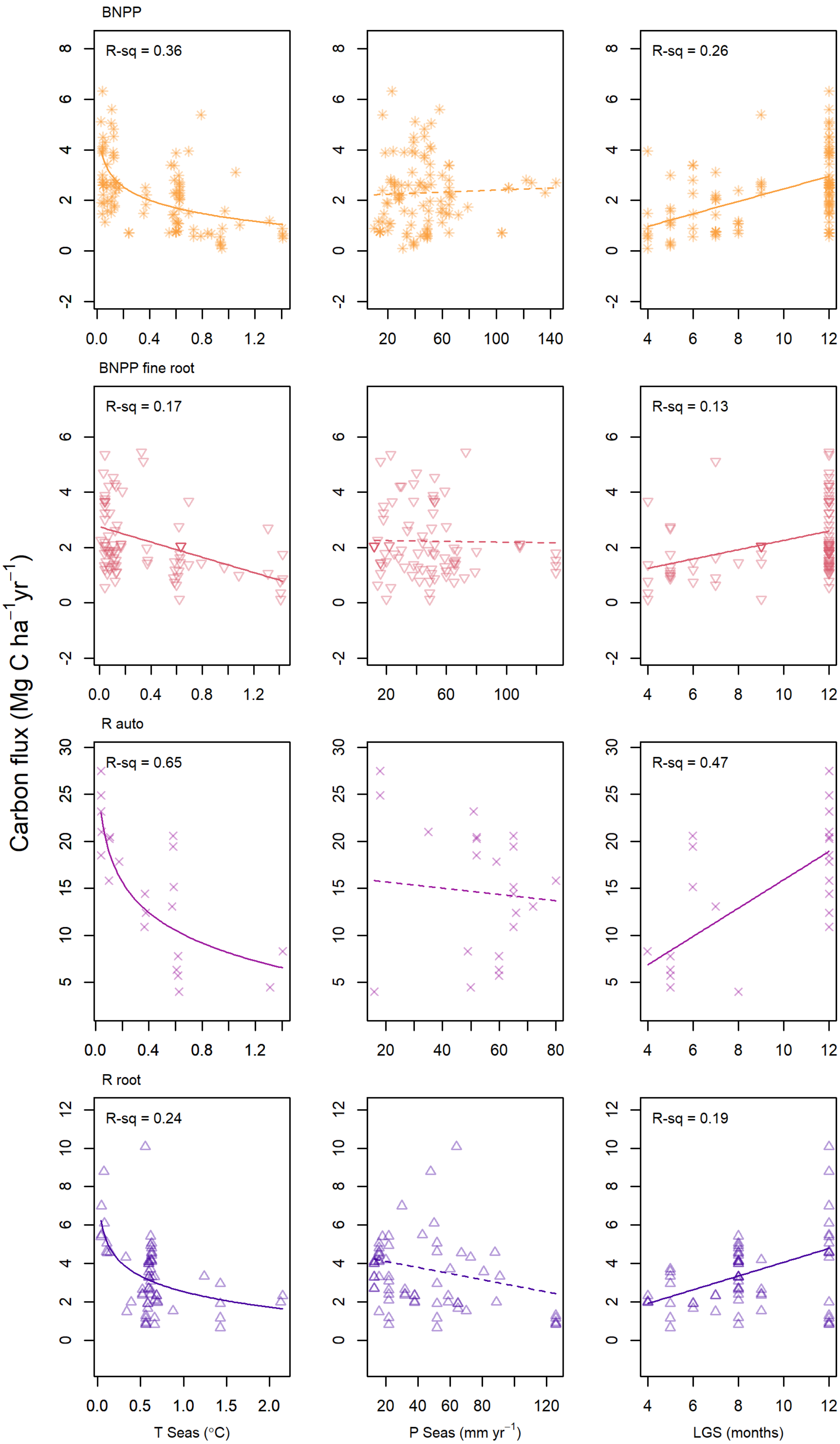

Figure S7: Individual plots of forest C fluxes in relation to mean climate seasonality, part 2.

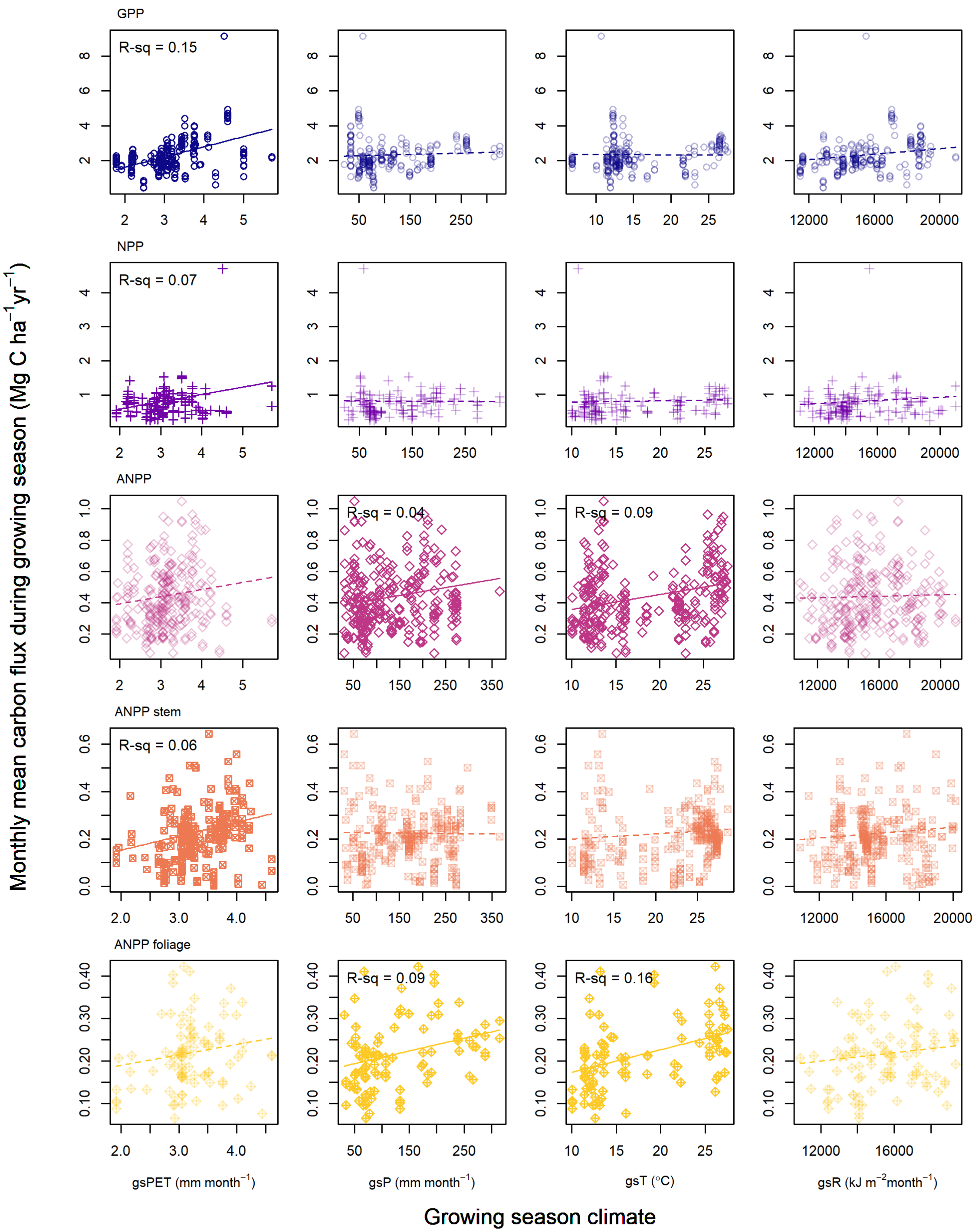

Figure S8: Growing season length-standardized forest C fluxes in relation to mean growing season climate, part 1.

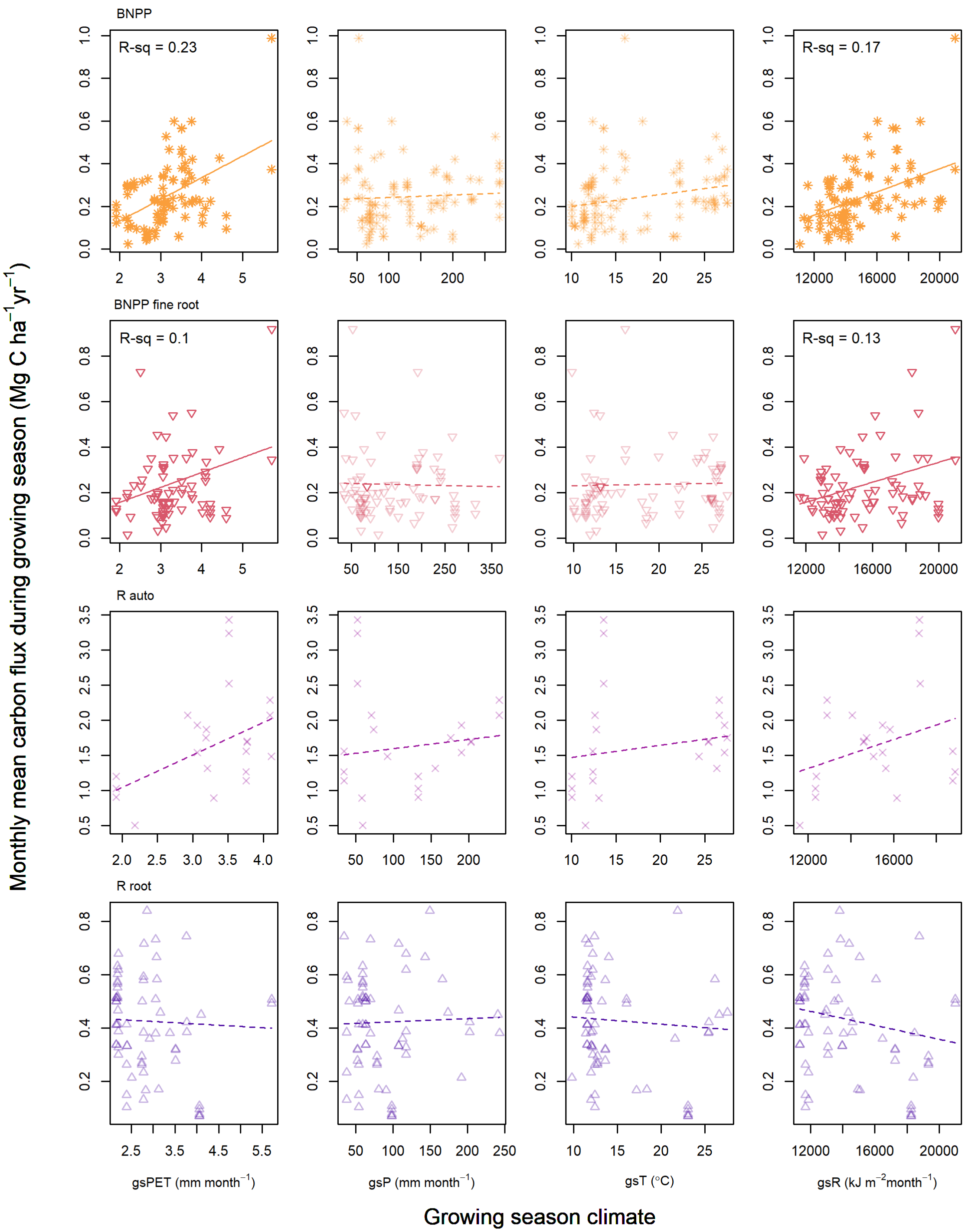

Figure S9: Growing season length-standardized forest C fluxes in relation to mean growing season climate, part 2.

References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*, 170191. https://doi.org/10.1038/sdata.2017.191

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset: *International Journal of Climatology*, *34*(3), 623–642. https://doi.org/10.1002/joc.3711

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, *25*(15), 1965–1978. https://doi.org/10.1002/joc.1276