Supplementary Material

S1. Additional photosynthesis equations

In JULES, leaf-level photosynthesis (Collatz et al 1991:1992) is calculated based on the limiting factor of three potential photosynthesis rates.

1. A light-limited rate, W_l:

$$W_l = \alpha(1-\omega)I_{par}\left(\frac{c_i-\Gamma}{c_i+2\Gamma}\right) \quad for\ C3\ plants \tag{A.1}$$

$$W_l = \alpha(1-\omega)I_{par} \quad for\ C4\ plants \tag{A.2}$$

where α is the quantum efficiency of photosynthesis (mol CO_2 mol PAR^{-1}) and ω is the leaf scattering coefficient for PAR. I_{par} is the photosynthetically active radiation hitting the leaf (mol m^{-2} s^{-1}), Γ is the CO_2 compensation point in the absence of mitochondrial respiration (Pa), and c_i is the internal CO_2 concentration (Pa).

2. A Rubisco-limited rate, W_c:

$$W_c = V_{cmax}\left(\frac{c_i-\Gamma}{c_i+K_c\left(1+{}^{O_a}/_{K_o}\right)}\right) for\ C3\ plants \tag{A.3}$$

$$W_c = V_{cmax} \quad for\ C4\ plants \tag{A.4}$$

where K_O and K_C are the Michaelis-Menten parameters for O_2 and CO_2, respectively, and V_{cmax} is the maximum rate of carboxylation of Rubisco (μmol CO_2 m^{-2} s^{-1}).

3. A rate of transport of photosynthetic products for C3 plants, and PEPCarboxylase limitation for C4 plants, W_e:

$$W_e = 0.5V_{cmax} \quad for\ C3\ plants \tag{A.5}$$

$$W_e = 2x10^4\ V_{cmax}\frac{c_i}{P_*} \quad for\ C4\ plants \tag{A.6}$$

where P_* is the surface air pressure (Pa).

S2. Data for N_{mass}, LMA, and LL. The table shows the data sources for the TRY data used in this study. For each source, the number of measurements for each source is provided for N_{mass}/specific leaf area (SLA) pairs and for leaf lifespan.

Ref.	Contact	N_{mass} + SLA	Leaf lifespan
Atkin et al., 1997; Campbell et al., 2007	Owen Atkin	218	
Xu and Baldocchi, 2003	Dennis Baldocchi	468	
Cavender-Bares et al., 2006	Jeannine Cavender-Bares	x	
unpublished	F. Stuart III Chapin	50	48
Cornelissen et al., 2004; Cornelissen et al., 2003, 1996; Diaz et al., 2004; Quested et al., 2003	Johannes Cornelissen	690	161
	Will Cornwell (+David Ackerly)	53	
Díaz et al., 2004 (maybe didn't use); Diaz et al. 2010 (definitely used)	Sandra Díaz	70	
Han et al., 2005; He et al., 2006, 2007	Jingyun Fang	148	
Freschet and Cornelissen, 2010; Freschet et al., 2010	Gregoire Freschet (+Hans Cornelissen)	40	
	Eric Garnier (+ Sandra Lavorel)	966	
Kattge et al., 2009	Jens Kattge*	1326	204
Kurokawa and Nakashizuka, 2008	Hiroko Kurokawa	399	89
	Daniel Laughlin	139	
Niinemets, 1999; Niinemets, 2001	Ülo Niinemets	264	33
Ordoñez et al., 2010; Ordoñez et al., 2010	Jenny Ordoñez (+Peter van Bodegom)	282	
Ogaya and Peñuelas, 2007a, 2007b, 2003; Ogaya, 2006; Sardans et al., 2008	Josep Peñuelas	808	
Poorter et al., 2009; 2006	Lourens Poorter		x
Reich et al., 2008, 2009	Peter Reich	720	199
Cornwell et al., 2007	Lawren Sack	30	
Shipley and Lechowicz 2000, Ecoscience, 7:183-	Bill Shipley	603	

194 2. Meziane and Shipley, 1999, Plant Cell and Environment			
	Enio Sosinski	66	
Soudzilovskaia et al, 2013, PNAS	Nadia Soudzilovskaia	155	
	Peter van Bodegom	x	x
Wright et al., 2011	S. Joseph (Joe) Wright	204	
Wright et al., 2006, 2004	Ian Wright	1673	442

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S3. Energy and respiration results at the Fluxnet sites

The TRY-based parameters give a lower N_{root} and N_{stem} for all PFTs, and a lower N_{leaf} for all PFTs except for C_3 grass and BET-Te (Fig. S2). For C_3 grass, the simulated N_{leaf} in JULES9 is higher during the winter than in JULES5, since a moderate LAI is maintained due to the new phenology. N_{leaf} is higher for BET-Te due to thicker leaves than previously. The respiration fluxes at BR-Ma2 provide a good example of the impacts of the new PFT parameters (Fig. SM3). The lower N_{stem} and N_{root} in JULES9 compared to JULES5 (Fig. SM2) reduced simulated R_{pm} (Eqn. 8). As a result, the average increase in plant respiration (46 g C m^{-2} yr^{-1}) was much smaller than the increase in GPP (377 g C m^{-2} yr^{-1}), and NPP increased from 867 g C m^{-2} yr^{-1} in JULES5 to 1198 g C m^{-2} yr^{-1} in JULES9, which was higher than the observed value at Manaus of 1011±140 g C m^{-2} yr^{-1} (Mahli et al., 2009). At Santarem, NPP also increased, but it was lower than the observed value of 1440 g C m^{-2} yr^{-1}.

The higher ecosystem respiration in JULES9 compared to JULES5 that accompanied the increased GPP was less realistic (in terms of RMSE), with 3 exceptions (Fig. SM3), but the

seasonal cycle of total respiration was improved at 8 sites. The RMSE decreased at ES-ES1, where lower GPP and R in the fall and winter were more realistic, at JP-Tom, where the switch from generic needle leaf to deciduous needle leaf improved all aspects of the simulation, and at FI-Kaa, where the new phenology of grass also improved the simulation.

In JULES, latent heat flux (LE) is due to evaporation from water stored on the canopy, evaporation of water from the top layer of soil, transpiration through the stomata, and sublimation of snow. The seasonal cycle of LE was improved at nine sites, however r decreased (by <0.03) at BR-Sa1, ES-ES1, BR-Sa3, US-Bo1, and US-FPe, comparing $JULES9_{ALL}$ to JULES5. The RMSE increased by >4 W m^{-2} in $JULES9_{TRY}$ compared to JULES5 at DE-Tha and FI-Hyy, and RMSE increased by a further 4 W m^{-2} at DE-Tha when the photosynthesis/respiration parameters were added due to the higher GPP and stomatal conductance. However, the correlation was >0.91 for both sites. At some forest sites, simulated LE (SH) was too high (low) during the winter and spring (DE-Tha, US-Ha1, and US-MMS), however the LE component contributing to the high bias is site-dependent. For example, from Jan.-Mar. the largest source of LE is evaporation from snow/ice (E_i) at Harvard, canopy evaporation and E_i at Tharandt, and soil evaporation/transpiration at Morgan Monroe. These springtime errors were not affected by the new PFTs. Another consistent bias in the forests was high mid-summer LE (De-Tha, FI-Hyy, US-Ha1, and US-MMS), which in this case always results from the soil evaporation/transpiration. Because the new PFTs tend to increase GPP and stomatal conductance, the errors in summer LE are higher.

Table S1. List of parameters and symbols in the text.

Symbol	Units	Equation	Description	Default Value[a]
A_l	kg C m^{-2} s^{-1}	5	Leaf-level photosynthesis	
a_{wl}	kg C m^{-2}	24	Allometric coefficient	
a_{ws}	--	24	Ratio of total to respiring stem carbon	
b_{wl}	--	24	Allometric exponent	1.667
C_i	Pa	6	Internal leaf CO_2 concentration	
C_{mass}	kg C [kg biomass]$^{-1}$	23	Leaf carbon concentration per unit mass	0.5 for this study
C_s	Pa	6	Leaf surface CO_2 concentration	
D_{crit}	kg kg^{-1}	7	Critical humidity deficit	
d_T	--	16	Rate of change of leaf turnover with temperature	
f_0	--	7	Stomatal conductance parameter	
f_d	--	4	Leaf dark respiration coefficient	
g_s	m s^{-1}	6	Leaf-level stomatal conductance	
i_v	μmol CO_2 m^{-2} s^{-1}	19	Intercept for relationship between N_{area} and $V_{cmax,25}$	
k_n	--	3, 20	Extinction coefficient for nitrogen	0.78
h	m	13, 23, 24	Canopy height	
L_{bal}	m^2 m^{-2}	12, 13, 22-24	Balanced leaf area index (maximum LAI given the plant's height)	
L_{max}	m^2 m^{-2}		Maximum LAI	
L_{min}	m^2 m^{-2}		Minimum LAI	
LMA	kg m^{-2}	18, 21, 22	Leaf mass per unit area (new parameter)	
N_a	kg N m^{-2}	18	Leaf nitrogen per unit area	
n_{eff}	mol CO_2 m^{-2} s^{-1} kg C [kg N]$^{-1}$	3	Constant relating leaf nitrogen to Rubisco carboxylation capacity	
N_{l0}	kg N [kg C]$^{-1}$	3	Top leaf nitrogen concentration (old parameter, mass basis)	
N_m	kg N kg^{-1}	18, 21-23	Top leaf nitrogen concentration (new parameter)	
N_l	kg N m^{-2}	11, 21	Total leaf nitrogen concentration	
N_r	kg N m^{-2}	12, 22	Total root nitrogen concentration	
N_s	kg N m^{-2}	13, 23	Total stem nitrogen concentration	
p	--	17	Phenological state (LAI/L_{bal})	
$Q_{10,leaf}$	--	2	Constant for exponential term in temperature function of V_{cmax}	2
R_a	kg C m^{-2} s^{-1}	8	Total plant autotrophic respiration	
R_d	kg C m^{-2} s^{-1}	4, 5	Leaf dark respiraiton	
r_g	--	10	Growth respiration coefficient	0.25
$rootd$	m		e-folding root depth	
s_v	μmol CO_2 g N^{-1} s^{-1}	19	Slope between N_{area} and $V_{cmax,25}$	
T_{low}	°C	1	Upper temperature parameter for V_{cmax}	
T_{off}	°C	16	Threshold temperature for phenology	
T_{opt}[b]	°C		Optimal temperature for V_{cmax}	
T_{upp}	°C	1	Upper temperature parameter for V_{cmax}	
$V_{cmax,25}$	μmol m^{-2} s^{-1}	1, 9	The maximum rate of carboxylation of Rubisco at 25°C	
W	kg C m^{-2} s^{-1}	5	Smoothed minimum of the potential limiting rates of phososynthesis	
α	mol CO_2 [mol PAR photons]$^{-1}$		Quantum efficiency	

β	--	5	Soil moisture stress factor	
Γ^*	Pa	7	CO_2 compensation point	
γ_0	[360 days]$^{-1}$	16	Minimum leaf turnover rate	
γ_{lm}	[360 days]$^{-1}$	16	Leaf turnover rate	
γ_p	[360 days]$^{-1}$	17	Leaf growth rate	20
μ_{rl}	--	12, 22	Ratio of nitrogen concentration in roots and leaves	
μ_{sl}	--	13, 23	Ratio of nitrogen concentration in stems and leaves	
η_{sl}	kg C m^{-2} LAI^{-1}	13, 23	Live stemwood coefficient	0.01
σ_L	kg C m^{-2} LAI^{-1}	11, 12	Specific leaf density (old parameter)	

[a]Default values only provided for non-PFT-dependent parameters.

Table S2. New trait-based parameters for 5 PFTs that are consistent with TRY data.

	BT	NT	C3	C4	SH
N_m	0.021	0.0115	0.0219	0.0113	0.0136
LMA	0.0823	0.2263	0.0498	0.1370	0.1515
s_v	29.81	18.15	37.75	20.48	23.15
i_v	5.73	6.32	5.93	0.00	14.71
$V_{cmax,25}$	57.25	53.55	47.10	31.71	62.41
T_{off}	5	-40	5	5	5
d_T	9	9	0	0	9
γ_0	0.25	0.25	3.0	3.0	0.66
γ_p	20	15	20	20	15
L_{min}	1	1	1	1	1
L_{max}	9	7	3	3	4

Table S3. Relationship between WWF ecoregions and the eight biomes used in this study.

WWF ecoregion	Biome for this study
Tropical & Subtropical Moist Broadleaf Forests	Tropical forests
Tropical & Subtropical Dry Broadleaf Forests	Tropical forests
Tropical & Subtropical Coniferous Forests	Tropical forests
Temperate Broadleaf & Mixed Forests	Extratropical mixed forests
Temperate Conifer Forests	Boreal and coniferous forests
Boreal Forests/Taiga	Boreal and coniferous forests
Tropical & Subtropical Grasslands, Savannas & Shrublands	Tropical savannas
Temperate Grasslands, Savannas & Shrublands	Temperate grasslands
Flooded Grasslands & Savannas	Temperate grasslands
Montane Grasslands & Shrublands	Temperate grasslands
Tundra	Tundra
Mediterranean Forests, Woodlands & Scrub	Mediterranean woodlands
Deserts & Xeric Shrublands	Desert
Mangroves	Tropical forests

Supplemental Material: Figures

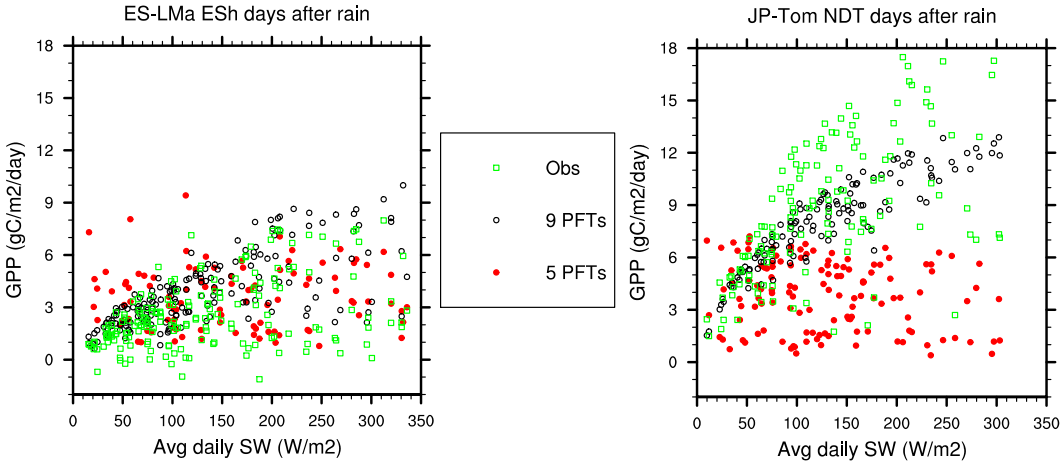


Figure S1. Daily average GPP versus shortwave radiation on days following rainfall when leaf area index is at or near its seasonal maximum.

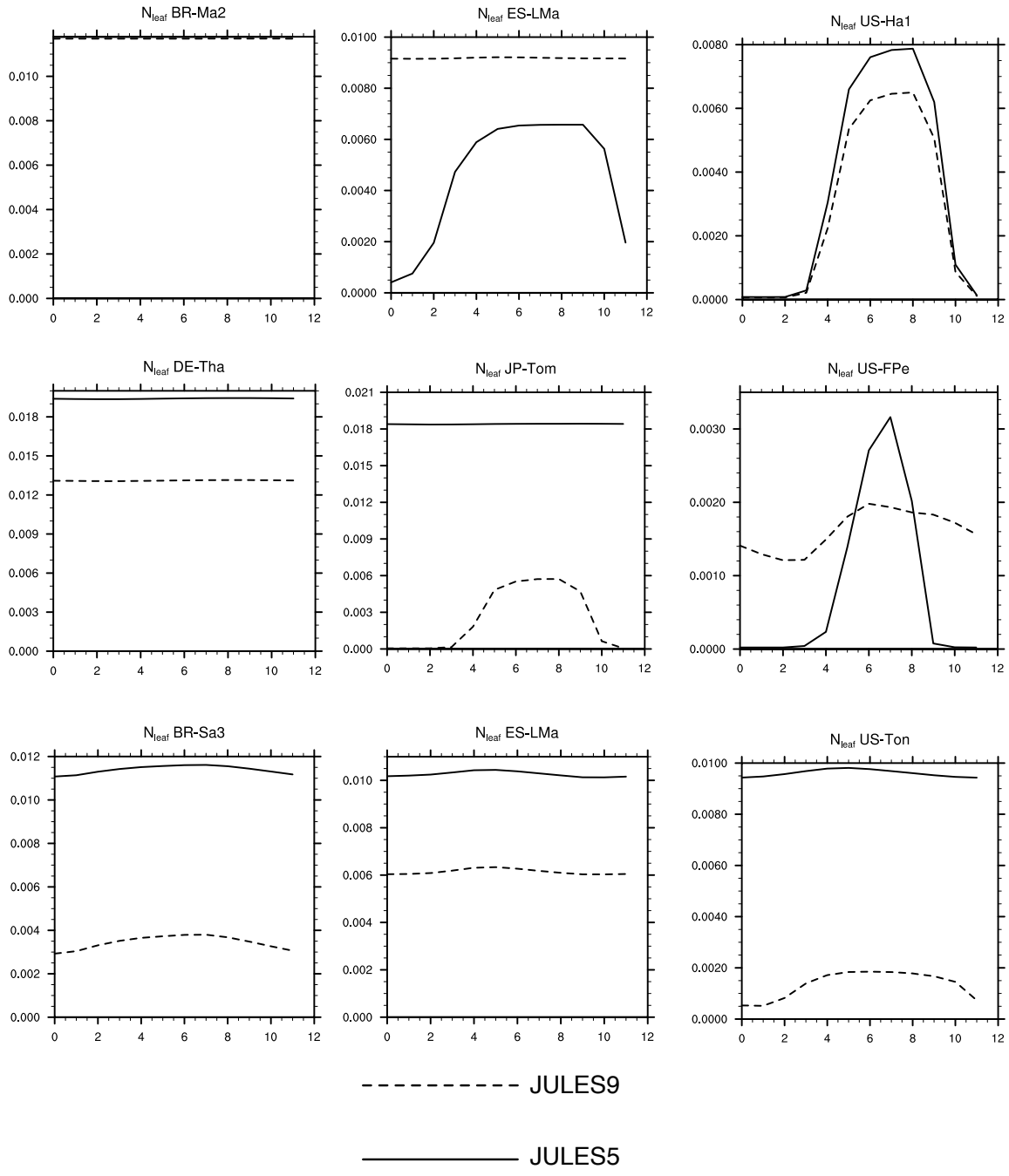


Figure S2. Monthly mean leaf nitrogen content (scaled by LAI) at nine sites representative of each of the new PFTs.

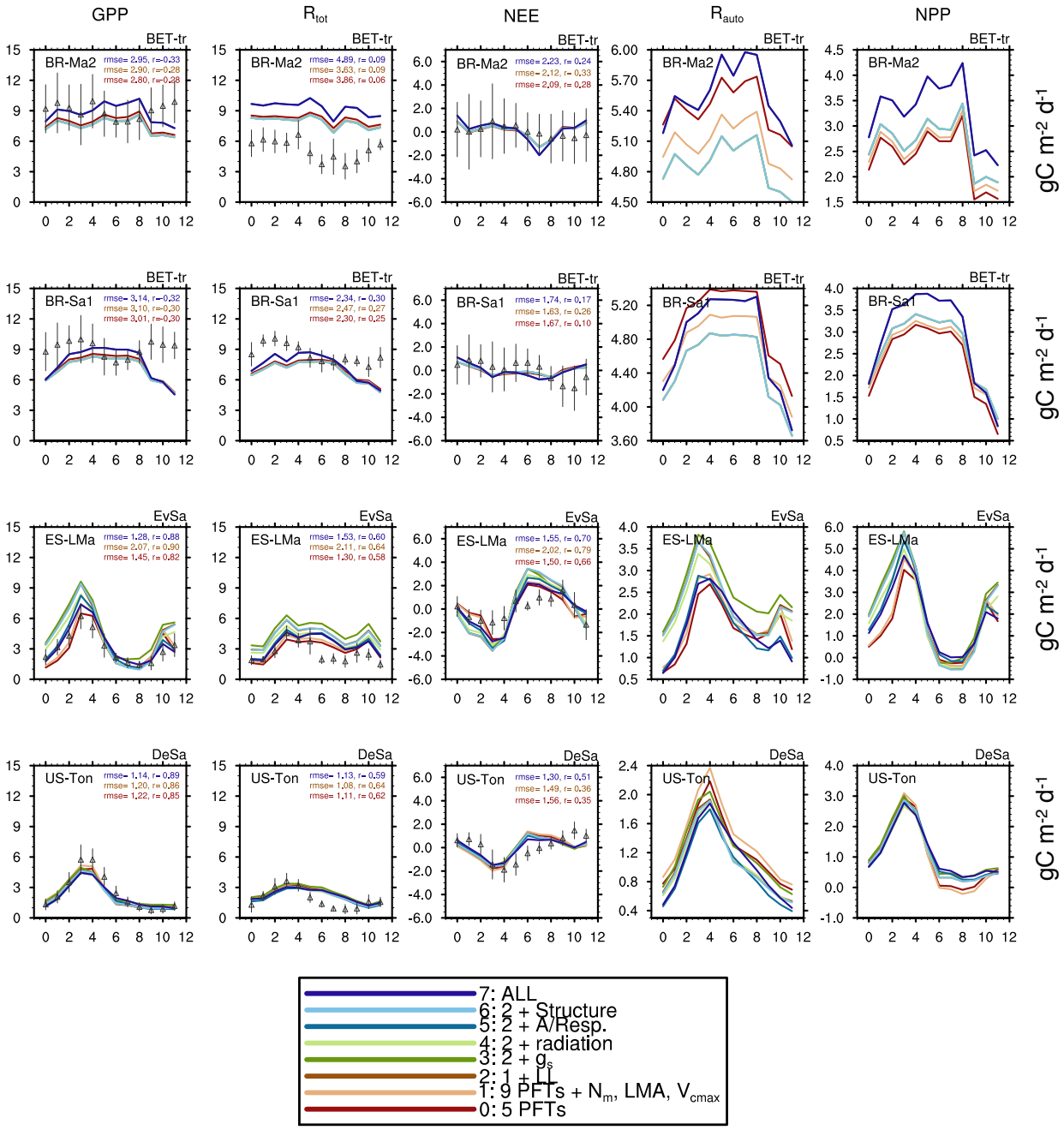
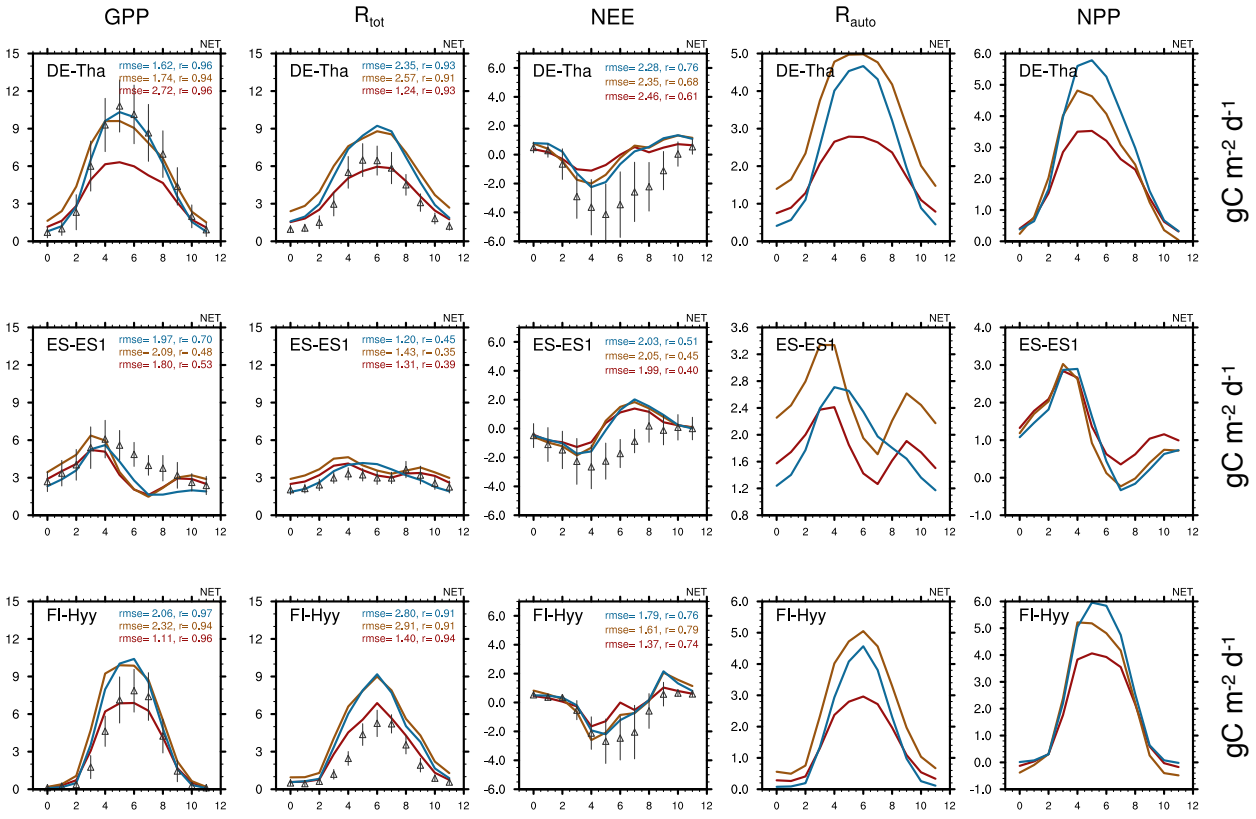


Figure S3a. Monthly mean fluxes of GPP, total ecosystem respiration, NEE, autotrophic respiration, and NPP at two tropical forest sites (BET-tr) and two savannah sites (EvSa=Evergreen Savannah, DeSa=Deciduous Savannah). Observations ± standard deviation from Fluxnet are shown with triangles and vertical lines. All simulations in Table 4 in the main text are shown. Also shown are the daily root mean square error (rmse) based on daily fluxes and the correlation coefficient (r) based on monthly mean fluxes for all years of the simulations. All units are in gC m^{-2} d^{-1}.



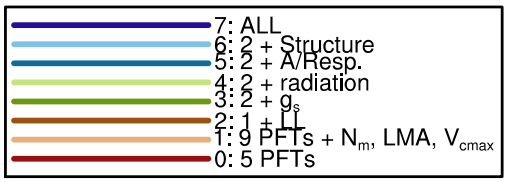


Figure S3b. As in SM3a but for three needleleaf evergreen (NET) sites.

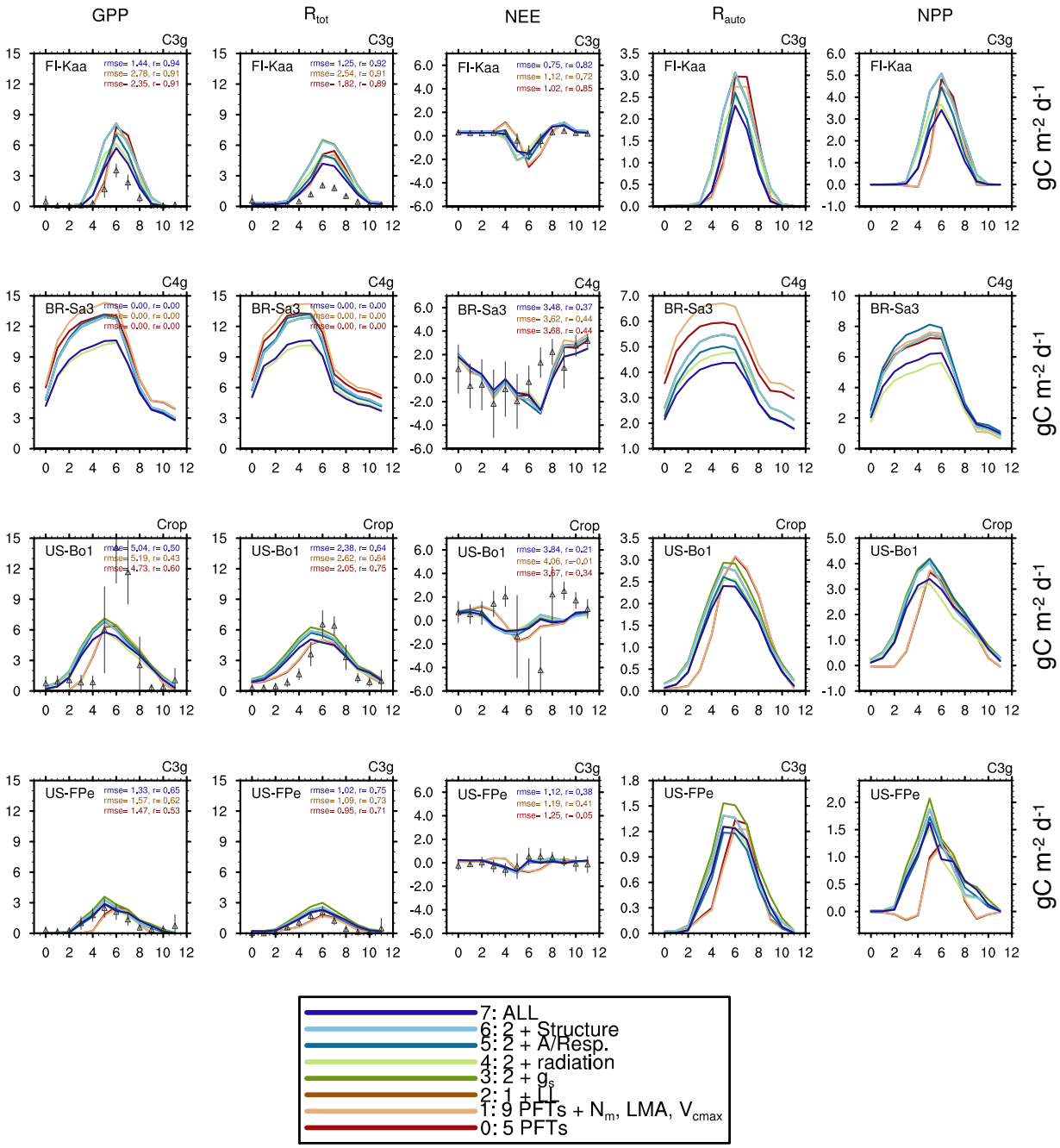


Figure S3c. As in SM3a but for four grass sites.

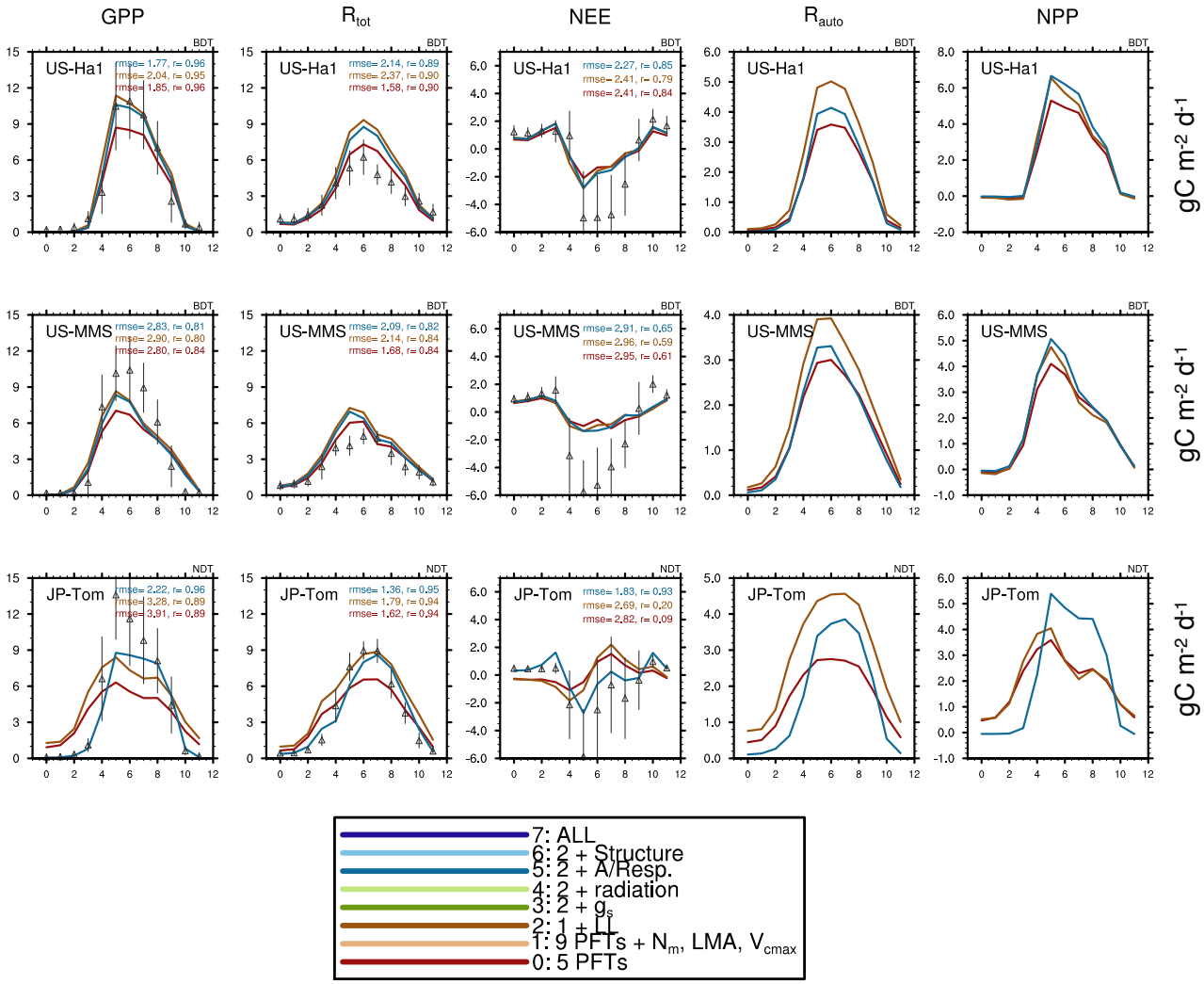


Figure S3d. As in SM3a but for two broadleaf deciduous (BDT) sites and one needleleaf deciduous (NDT) site.

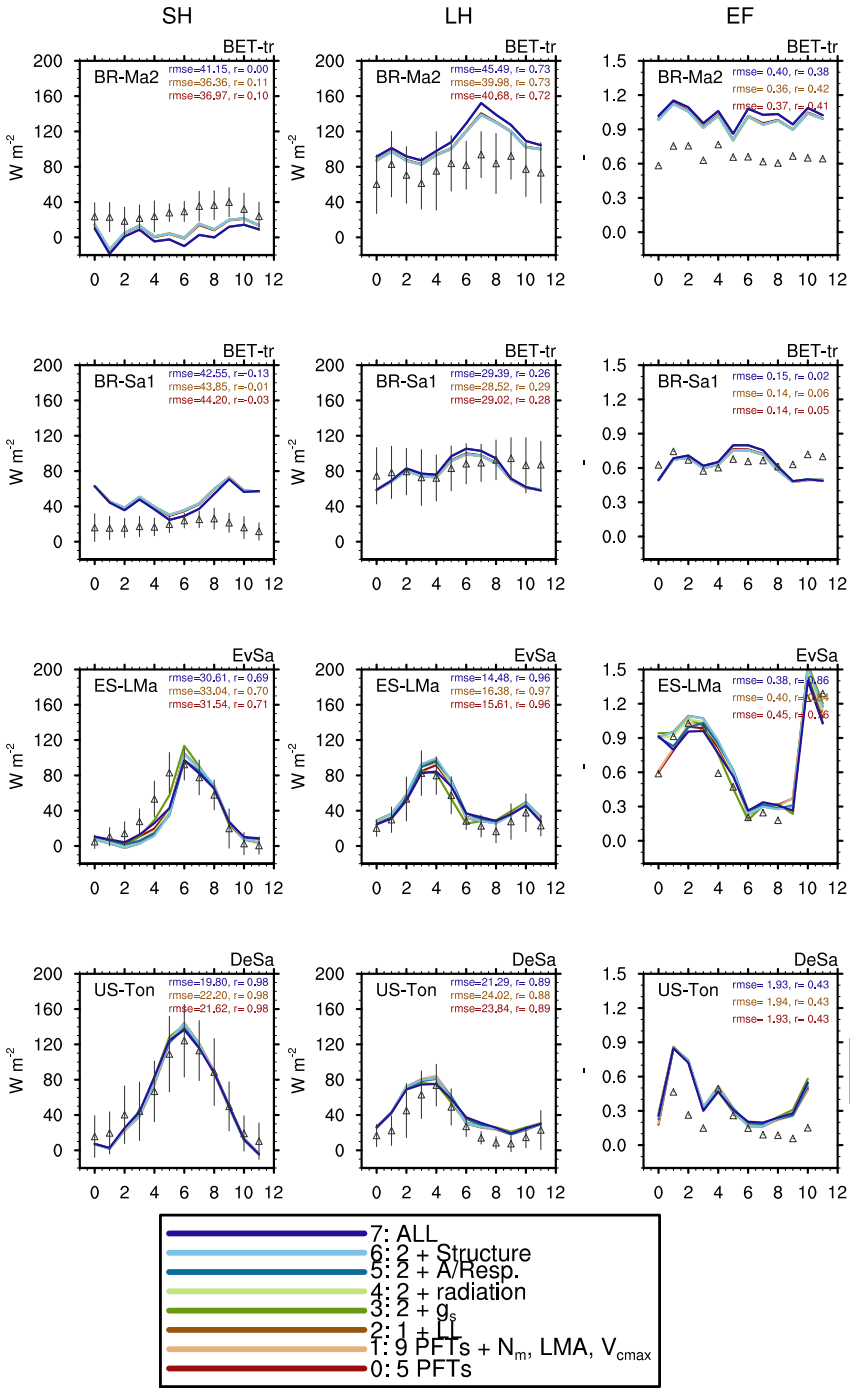


Figure S4a. Monthly mean fluxes of latent heat, sensible heat, and evaporative fraction (=LE/(SH +LE) at two tropical forest sites (BET-tr) and two savannah sites (EvSa=Evergreen Savannah, DeSa=Deciduous Savannah). Observations ± standard deviation from Fluxnet are shown with triangles and vertical lines.

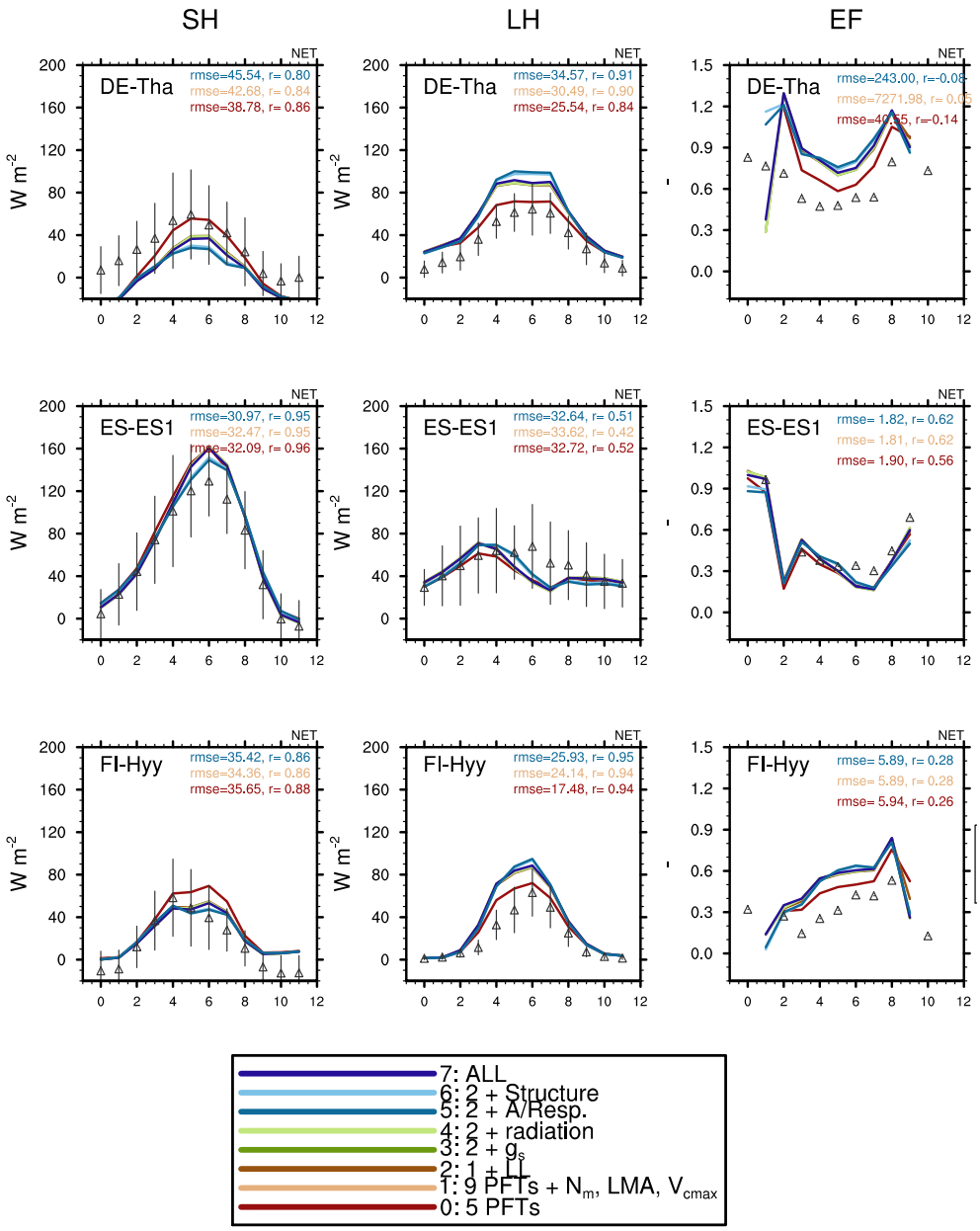


Figure S4b. As in Fig. S4a but for the NET sites.

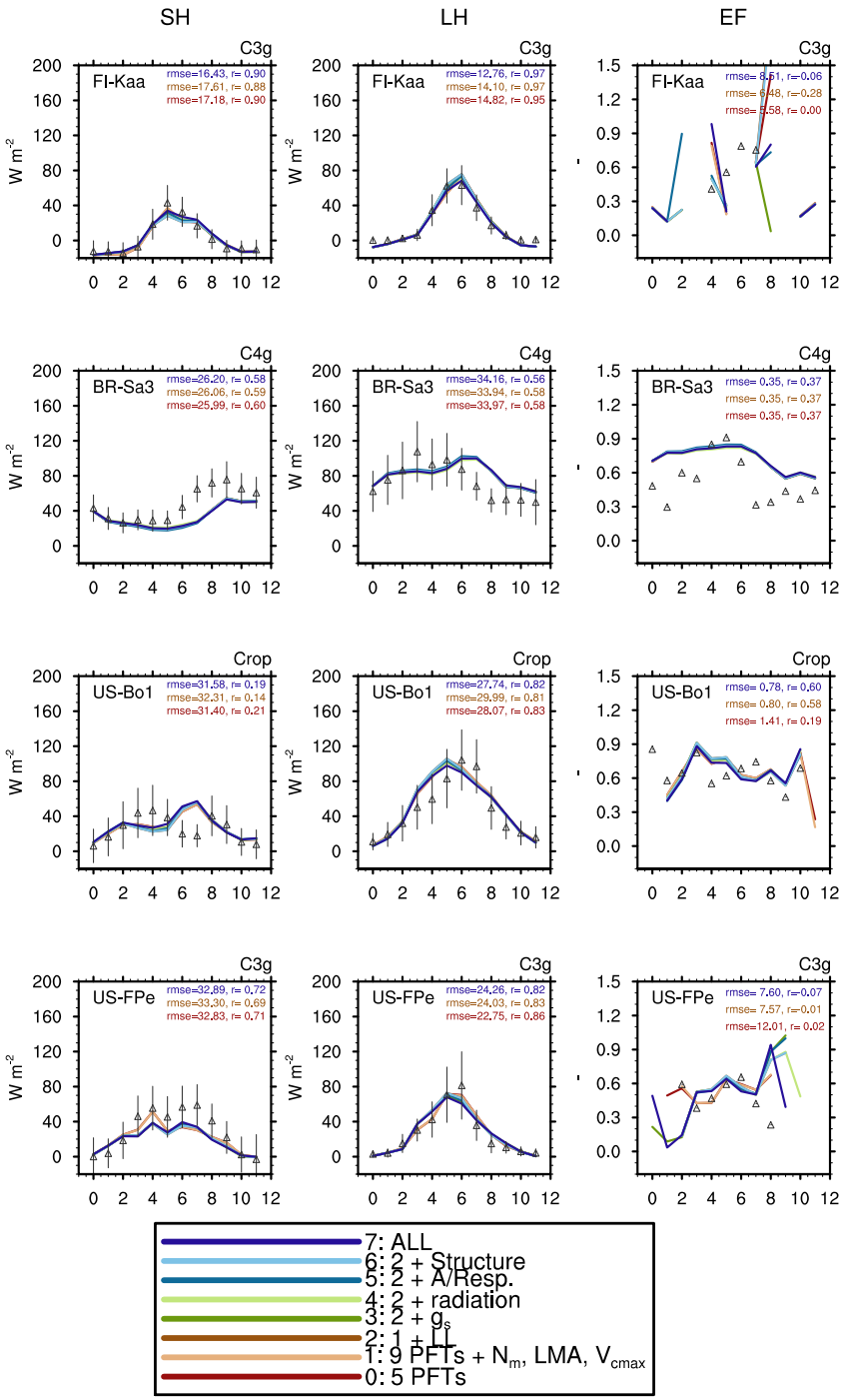


Figure S4c. As in Fig. S4a but for the grass sites.

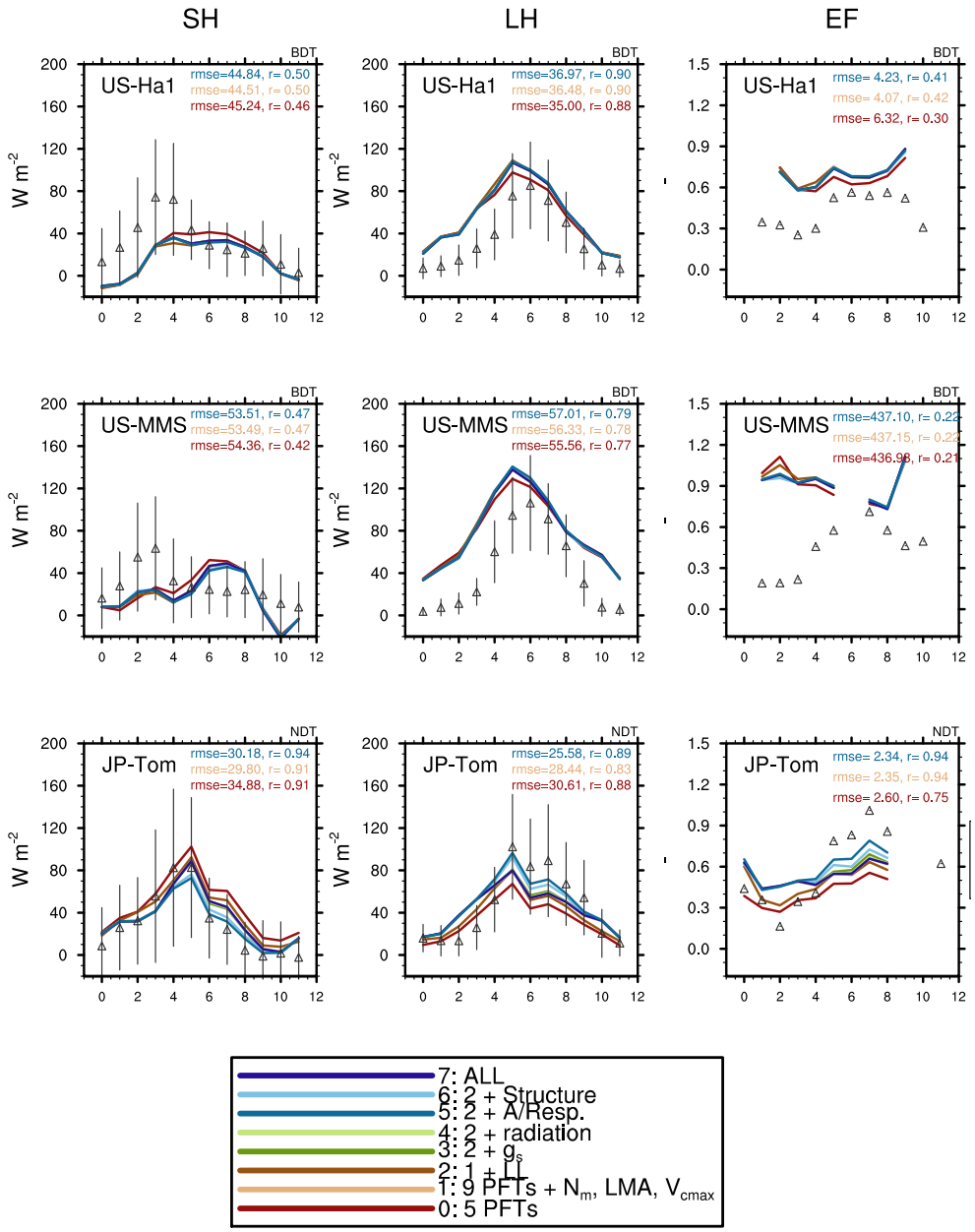


Figure S4d. As in Fig. S4a but for the deciduous tree sites.

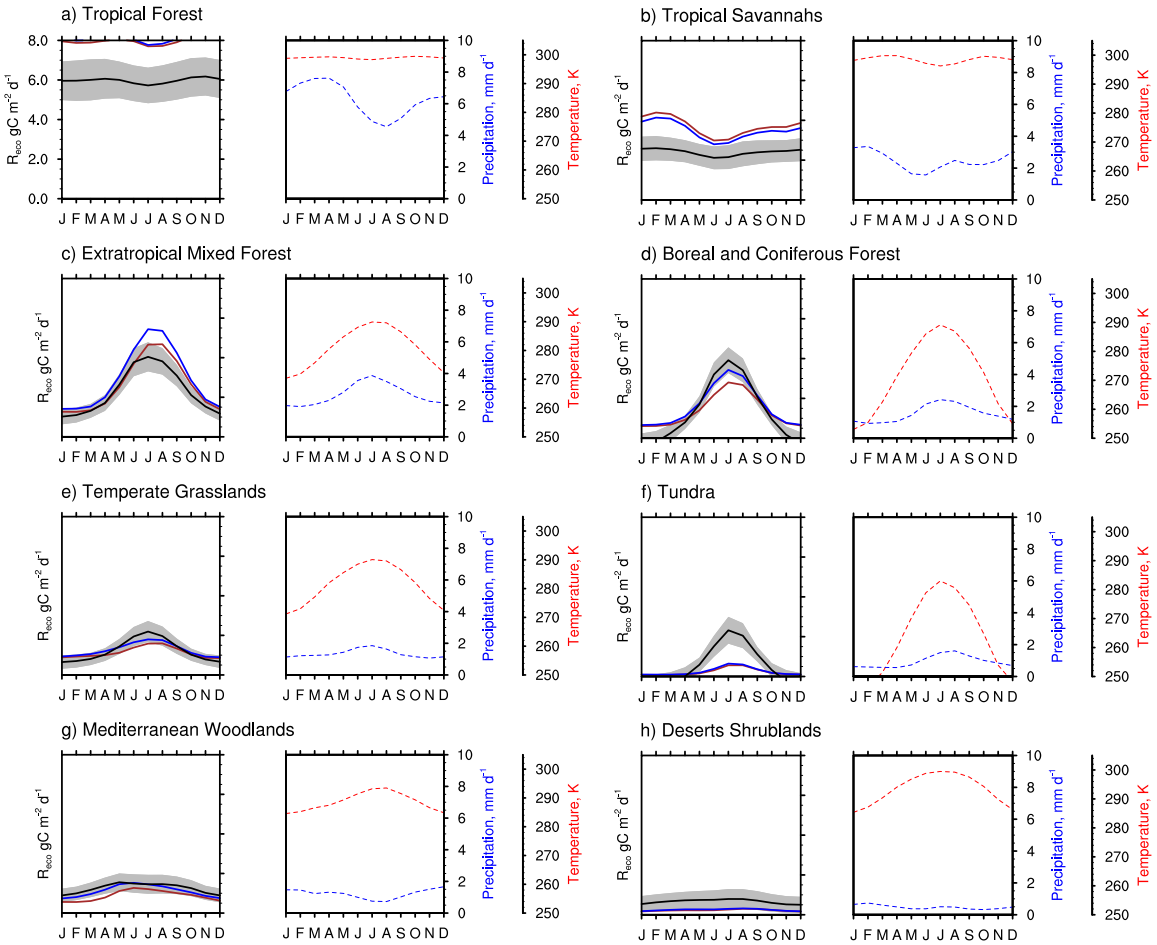


Figure S5. Seasonal cylces of Reco from the biomes shown in Fig. 3, comparing JULES5, JULES9, and the Jung et al. (2011) MTE. Also shown are the temperature and precipitation from the CRU-NCEP dataset used to force the JULES simulations.