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Simulating shrubs and their energy and carbon dioxide fluxes in Canada's Low Arctic with the Canadian Land Surface Scheme Including Biogeochemical Cycles (CLASSIC)

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S1 Supplementary Materials

The parameters in (Table 2) that were adjusted for shrub and sedge PFTs are used in the following equations. The leaf life span (τ_L; yr) is used to calculate the specific leaf area (SLA; $\mathrm{m}^2(\mathrm{kg\ C})^{-1}$) as

$$\mathrm{SLA} = \gamma_L \tau_L^{-0.5} \tag{S1}$$

with the constant $\gamma_L = 25\ \mathrm{m}^2(\mathrm{kg\ C})^{-1}\mathrm{yr}^{0.5}$. SLA then determines the LAI as

$$\mathrm{LAI} = C_L \mathrm{SLA}. \tag{S2}$$

CLASSIC includes an age-related mortality (m_{intr}; day^{-1}) dependent on the maximum age of a PFT ($A_{\max}$; yr) with the mortality rate

$$m_{intr} = 1 - \exp(-4.605/A_{max}), \tag{S3}$$

so that only 1% of the vegetation exceeds that PFTs A_{max}, accounting for disturbances like wind throw, insect attacks, hail and others that are not explicitly taken into account in the model (Melton and Arora, 2016).

The root distribution and depth are dynamically simulated in CLASSIC (Arora and Boer, 2003) and have an exponential form, where the cumulative root fraction at depth z (m) is determined as

$$f_R(z) = 1 - \exp(-\iota z). \tag{S4}$$

The depth containing 99% of the root mass (d_R; m) is given by

$$d_R = \frac{-ln(1-f_R)}{\iota} = \frac{-ln(1-0.99)}{\iota} = \frac{4.605}{\iota}, \tag{S5}$$

where the exponential root distribution is described by the parameter ι (dimensionless)

$$\iota = \bar{\iota}\left(\frac{\overline{C_R}}{C_R}\right)^{0.8}. \tag{S6}$$

The PFT-dependent parameter $\bar{\iota}$ (dimensionless) is given in Table 2 and $\overline{C_R}$ (kg C m^{-2}) is the average root biomass. If the calculated rooting depth d_R exceeds the soil depth or active layer depth, it is set to the soil depth or mean annual maximum active layer depth and ι is recalculated using Equation S5. The root distribution profile is calculated using the new ι and then determines the percentage of roots in each soil layer following Equation S4.

In CLASSIC, the two components of ecosystem respiration (R_e; mol CO_2 m^{-2} s^{-1}), autotrophic respiration (R_a; mol CO_2 m^{-2} s^{-1}) from the live vegetation components and heterotrophic respiration (R_h; mol CO_2 m^{-2} s^{-1}) from the litter and soil C pools, are determined separately. Calculation of the different respiration components is described in detail by Melton and Arora (2016). Briefly, R_a is calculated as the sum of maintenance (R_m; mol CO_2 m^{-2} s^{-1}) and growth respiration (R_g; mol CO_2 m^{-2} s^{-1}). For the leaves, R_m is calculated on a half-hourly time step, same as photosynthesis, while the stem (R_{mS}) and root (R_{mR}) components are calculated on a daily time step (Melton and Arora, 2016). Leaf R_m (R_{mL}) is a function of the maximum rate of carboxylation by the Rubisco enzyme (V_{cmax}) adjusted for temperature and soil moisture limitations (V_m), $Q_{10d,n}$, the temperature sensitivity during the day(d) and night(n), and the photosynthetically active radiation (PAR) absorbed throughout the canopy, which scales up R_{mL} to the canopy level,

$$R_{mL} = \varsigma_L V_m f_{25}(Q_{10d,n}) f_{PAR}, \tag{S7}$$

with the leaf maintenance respiration coefficient ς_L (kg C (kg C)$^{-1}$ yr^{-1}). The root and stem components of R_m depend on the stem and root base respiration rates at 15°C (ς_S and ς_R; kg C (kg C)$^{-1}$ yr^{-1}), the stem or root C mass (C_i; kg C m^{-2}) and the live fraction of the stem or roots ($l_{v,i}$) and are calculated as

$$R_{m,i} = 2.64 \times 10^{-6} \varsigma_i l_{v,i} C_i f_{15}(Q_{10}),\ i = S, R, \tag{S8}$$

where 2.64×10^{-6} converts from kg C m^{-2} yr^{-1} to mol CO_2 m^{-2} s^{-1}. Q_{10} is constrained between 1.5 and 4.0 and is determined by the temperature-dependent function

$$Q_{10} = 3.22 - 0.046\left(\frac{15.0 + T_{\{S,R\}}}{1.9}\right), \tag{S9}$$

where $T_{\{S,R\}}$ is the stem or root temperature (°C). Air temperature is used as T_S and the root temperature T_R is determined from soil temperatures and the fraction of roots in each layer (Melton and Arora, 2016). After accounting for R_m, R_g is determined as a fraction (15 % for all PFTs) of gross canopy photosynthesis. Soil (C_H; kg C m^{-2}) and litter C (C_D; kg C m^{-2}), soil temperature and moisture as well as PFT-dependent base respiration rates at 15°C (ς_i; kg C (kg C)$^{-1}$ yr^{-1}; Table 2) determine R_h as

$$R_{h,i} = 2.64 \times 10^{-6} \varsigma_i C_i f_{15}(Q_{10}) f(\Psi)_i, \; i = D, H, \tag{S10}$$

where Ψ (MPa) is the soil matric potential with f(Ψ) limiting R_h when soil moisture is low or high. The temperature-dependent Q_{10} used to determine R_h is calculated as

$$Q_{10} = 1.44 + 0.56 \tanh[0.075(46.0 - T_i)], \; i = D, H, \tag{S11}$$

using the litter or soil C pool temperature (°C), respectively. The mean soil temperature of the rooting zone taking into account the root fractions in the different layers is taken to be the soil C pool temperature, while the litter temperature is determined as $T_D = 0.7\,T_1 + 0.3\,T_R$, as leaves, stems and roots all contribute to the litter C pool, where T_1 is the temperature of the top soil layer. Turnover of stem (D_S; kg C m^{-2} day^{-1}) and root (D_R; kg C m^{-2} day^{-1}) biomass depend on their respective PFT-dependent turnover timescales (τ_S and τ_R; yr; Table 2). The amounts of C added to the litter pool are calculated as

$$D_i = C_i[1 - exp(-\frac{1}{365\tau_i})], \; i = S, R. \tag{S12}$$

The fraction of $R_{h,D}$, determined by the PFT-dependent humification factor χ (Table 2), transferred from the litter to the soil C pool is

$$C_{D \rightarrow H} = \chi R_{h,D}. \tag{S13}$$

Similar to the root distribution, C is assumed to follow an exponential distribution within the soil column, but is not explicitly tracked per layer (Melton and Arora, 2016).

Table S1. Soil layer thicknesses, total soil depth and depth of the permeable soil layer used in the simulations.

Layer	Soil thickness [m]
1	0.1
2	0.1
3	0.1
4	0.1
5	0.1
6	0.1
7	0.1
8	0.1
9	0.1
10	0.1
11	0.2
12	0.2
13	0.2
14	0.3
15	0.3
16	0.3
17	0.5
18	0.5
19	0.5
20	1.0
21	5.0
22	10.0
Total soil depth	20.0
Permeable depth	5.0

S1.1 Atmospheric forcing data

The following figures and Table S2 show the atmospheric forcing variables used in the simulations for 2004-2017 as well as the mean values and standard deviation for the full time period and for 2004-2009 and 2010-2017.

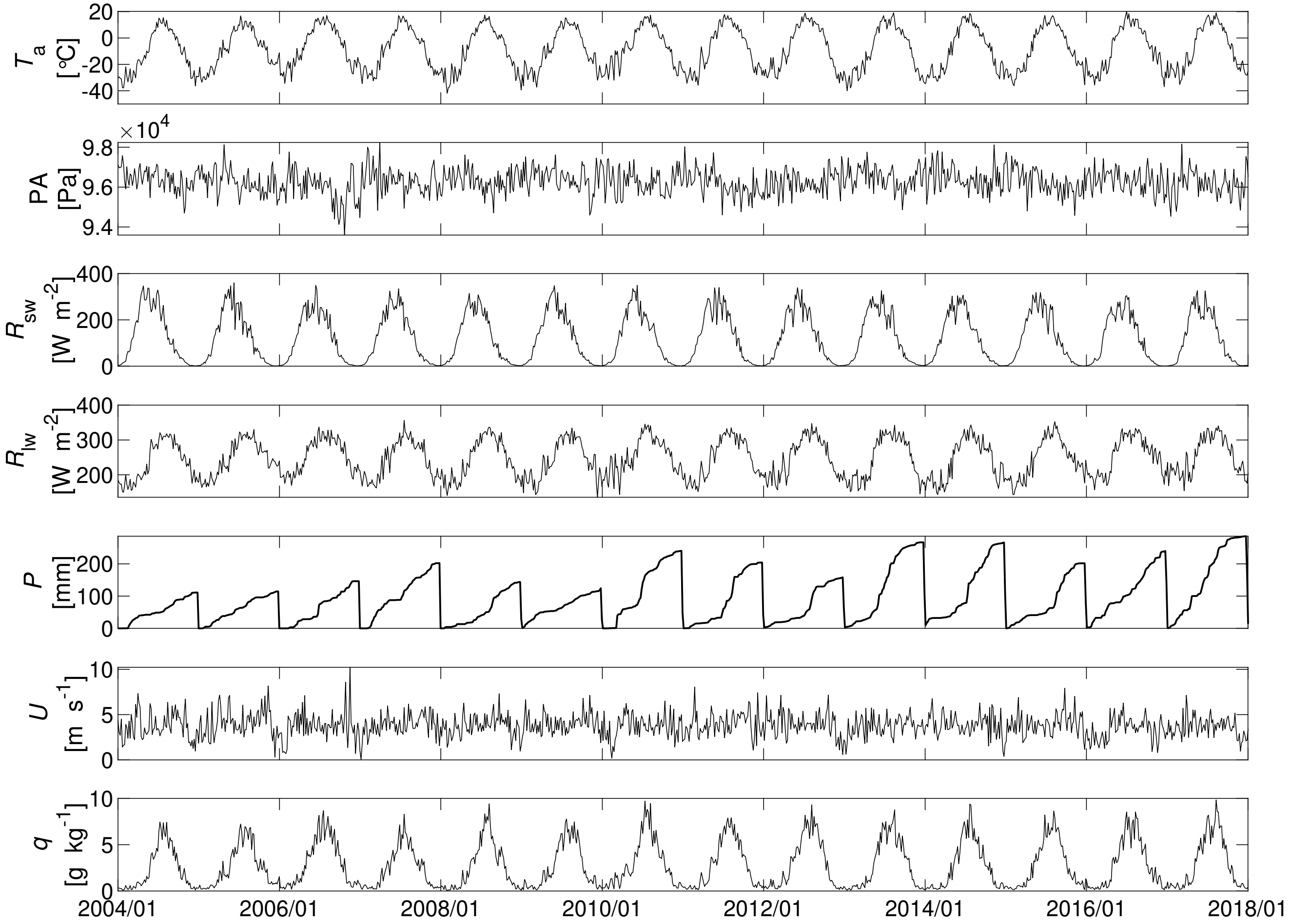

Figure S1. 5-day average atmospheric forcing variables air temperature (T_a), air pressure (PA), incoming shortwave radiation (R_{sw}), incoming longwave radiation (R_{lw}), cumulative precipitation (P), wind speed (U) and specific humidity (q) for 2004-2017.

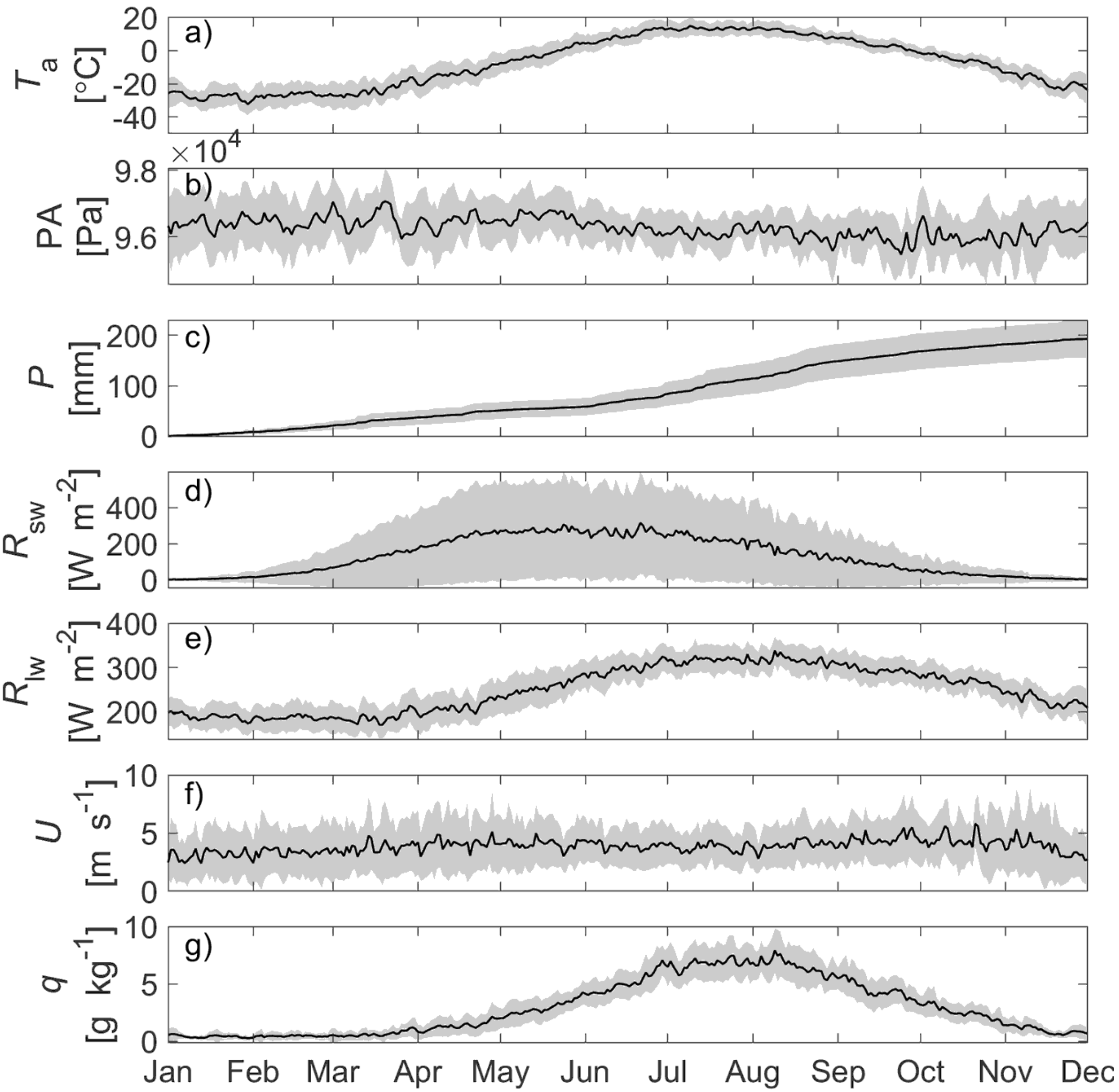

Figure S2. Mean daily air temperature (T_a), air pressure (PA), precipitation (P), incoming shortwave radiation (R_{sw}), incoming longwave radiation (R_{lw}), wind speed (U) and specific humidity (q) averaged over 2004-2017. Shaded areas show the standard deviation for 2004-2017.

Table S2. Mean ± SD annual and growing season (GS; May 1 - October 1) air temperature (T_a), total precipitation (P), daily air pressure (PA), incoming shortwave (R_{sw}) and longwave radiation (R_{lw}), wind speed (U) and specific humidity (q) averaged over 2004-2009, 2010-2017 and the whole time period 2004-2017, respectively. Values which are significantly different between the two periods (2004-2009 vs. 2010-2017) are noted by * (p < 0.05 using a two-tailed t-test).

Variable	2004-2009		2010-2017		2004-2017	
	Annual	GS	Annual	GS	Annual	GS
$T_a[°C]$	-9.4 ± 5.3	5.7 ± 3.9	-8.5 ± 5.3	7.8 ± 3.9	-8.8 ± 5.4	7.0 ± 4.1
$P[mm]$	141 ± 24*	68 ± 17*	237 ± 44*	151 ± 38*	198 ± 37	117 ± 32
$R_{sw}[Wm^{-2}]$	122 ± 32	203 ± 57	120 ± 33	201 ± 61	121 ± 33	202 ± 59
$R_{lw}[Wm^{-2}]$	243 ± 26	291 ± 25	248 ± 29	299 ± 27	246 ± 28	296 ± 26
$PA[hPa]$	962.8 ± 7.4	962.4 ± 6.1	962.6 ± 7.4	961.8 ± 6.3	962.7 ± 7.6	962.1 ± 6.3
$U[ms^{-1}]$	3.9 ± 1.8	4.0 ± 1.5	3.8 ± 1.7	4.0 ± 1.4	3.8 ± 1.8	4.0 ± 1.5
$q[gkg^{-1}]$	2.6 ± 0.8*	4.8 ± 1.2	2.8 ± 0.8*	5.4 ± 1.3	2.7 ± 0.8	5.1 ± 1.3

S1.2 Model results

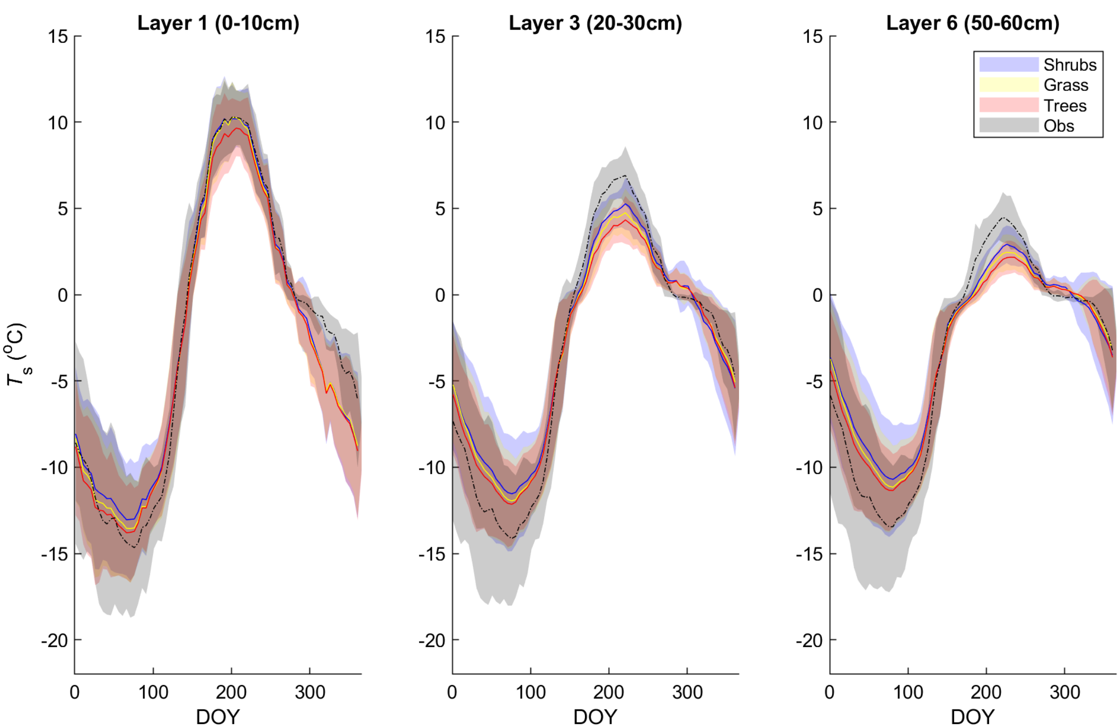

Figure S3. Mean 5-day average soil temperature for layer 1 (0-10 cm depth), 3 (20-30 cm depth) and 6 (50-60 cm depth) of the shrub, grass and tree simulations and measured at 5, 25 and 60 cm depth, respectively, averaged over 2004-2017. Shaded areas show the standard deviation for 2004-2017.

Table S3. Statistics of daily modelled vs. measured values for the shrub, grass and tree simulation.

Variable	Shrubs				Grass				Trees			
	Slope	**Intercept**	**R^2**	**RMSE**	**Slope**	**Intercept**	**R^2**	**RMSE**	**Slope**	**Intercept**	**R^2**	**RMSE**
LE ($W\ m^{-2}$)	0.61	5.91	0.39	22.99	0.64	7.28	0.36	24.19	0.67	5.76	0.50	19.83
H ($W\ m^{-2}$)	0.97	14.76	0.73	21.62	0.99	10.92	0.68	22.03	0.94	27.08	0.56	34.42
NEP ($g\ C\ m^{-2}$)	0.77	0.29	0.51	0.55	0.29	0.32	0.04	1.03	0.92	0.43	0.45	0.76
GPP ($g\ C\ m^{-2}$)	0.84	0.62	0.72	0.78	0.75	0.65	0.39	1.23	1.16	0.74	0.80	1.21
R_e ($g\ C\ m^{-2}$)	0.68	0.54	0.73	0.43	0.68	0.46	0.71	0.42	0.88	0.69	0.80	0.64
T_s Layer 1 (°C)	0.92	-0.18	0.93	2.34	0.93	-0.42	0.93	2.40	0.92	-0.72	0.93	2.44
T_s Layer 3 (°C)	0.77	-0.23	0.93	2.28	0.76	-0.52	0.92	2.38	0.76	-0.76	0.92	2.40
T_s Layer 6 (°C)	0.73	-0.25	0.92	2.26	0.73	-0.49	0.90	2.29	0.74	-0.70	0.91	2.24
Rel. VWC Layer 1 (%)	1.09	-0.01	0.77	0.12	0.96	-0.01	0.76	0.11	1.03	-0.02	0.72	0.13
Snow depth (m)	0.69	0.08	0.53	0.10	0.69	0.07	0.53	0.10	0.68	0.07	0.55	0.09
R_n ($W\ m^{-2}$)	1.02	3.14	0.93	16.71	1.01	2.67	0.93	15.98	1.00	17.95	0.82	32.18
Net R_{sw} ($W\ m^{-2}$)	0.99	16.82	0.94	27.48	0.97	15.74	0.94	24.96	0.92	36.12	0.87	42.67
Net R_{lw} ($W\ m^{-2}$)	0.99	-7.28	0.93	11.43	0.96	-6.97	0.92	10.28	0.92	-7.85	0.92	9.99

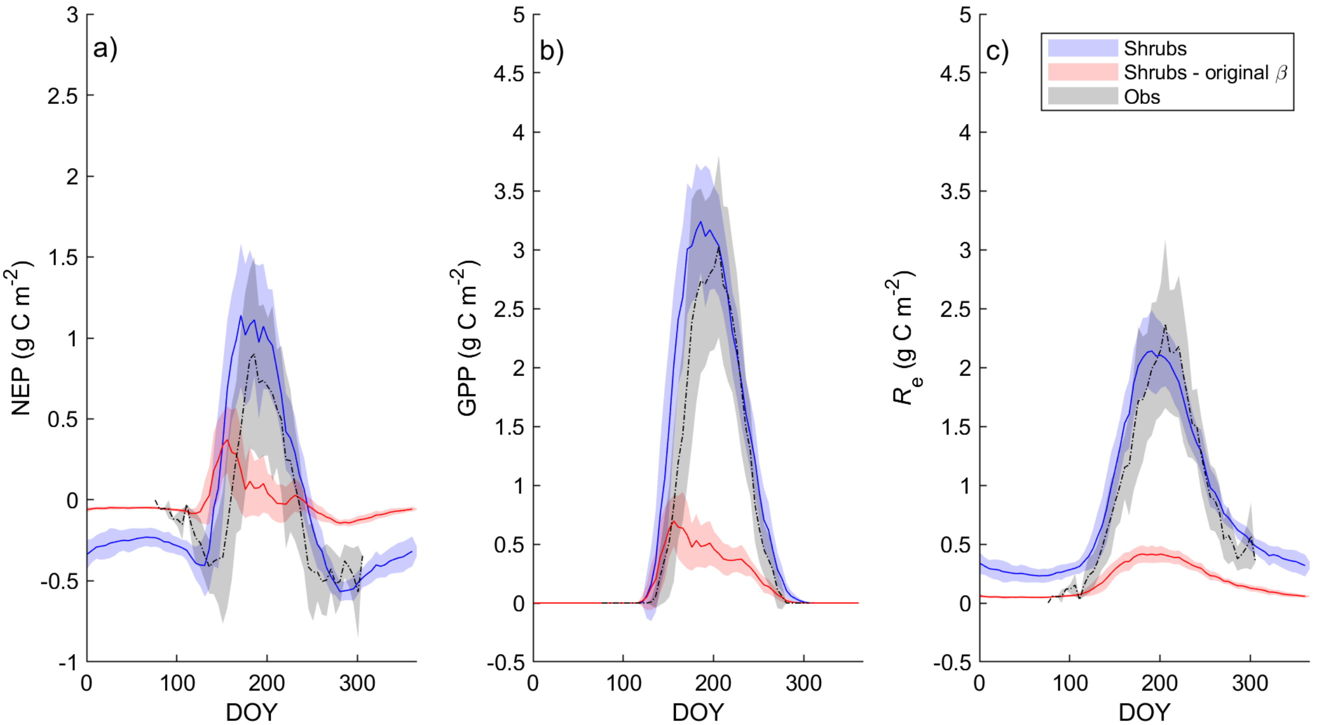

Figure S4. Mean 5-day average a) net ecosystem productivity (NEP), b) gross primary productivity (GPP) and c) ecosystem respiration (R_e) averaged over 2004-2017 for the shrub simulations using the new (Merlin et al., 2011) and original β (Lee and Pielke, 1992) formulation. Shaded areas show the standard deviation for 2004-2017.

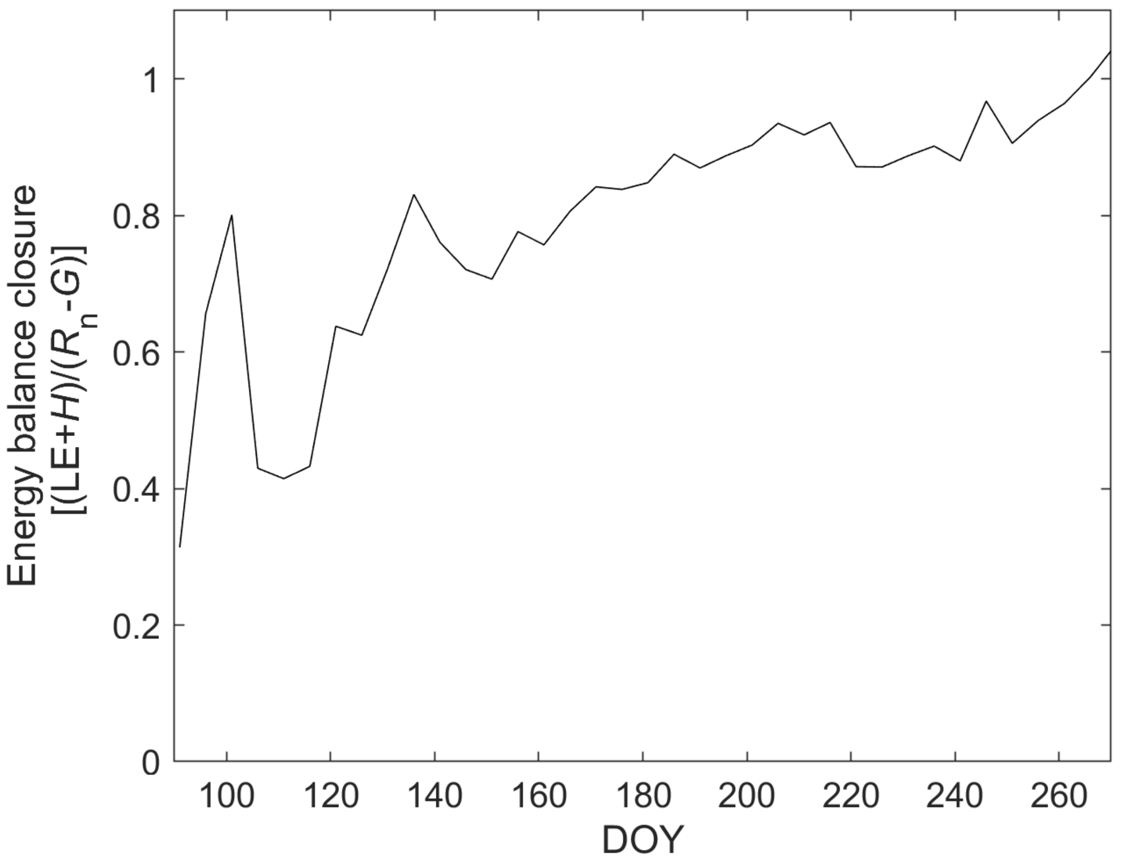

Figure S5. Mean 5-day average energy balance closure at DL1 over 2004-2017 calculated from the EC tower data.

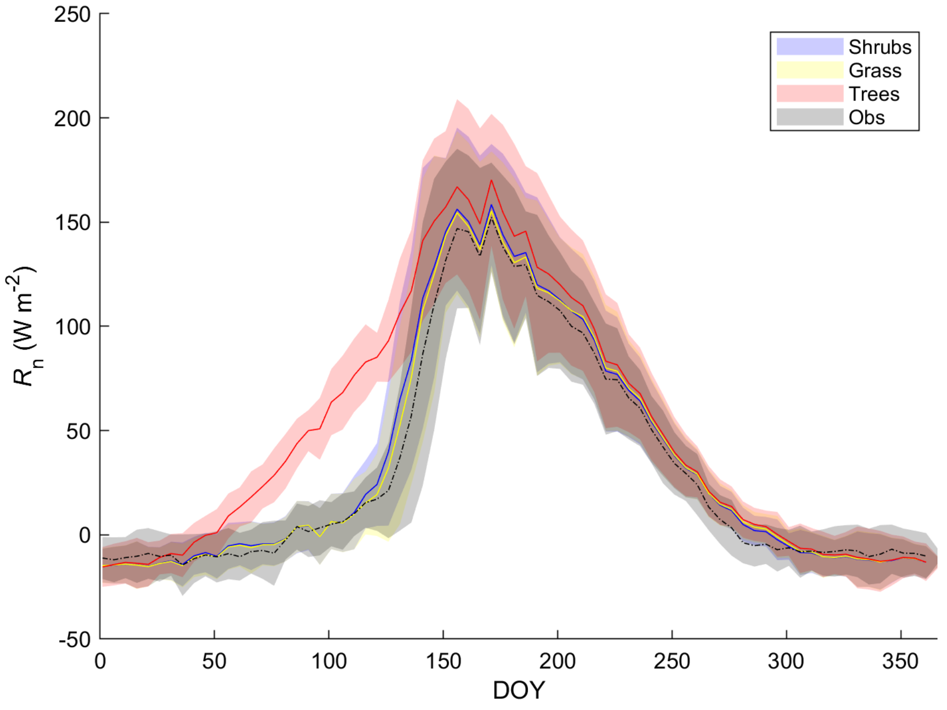

Figure S6. Mean 5-day average net radiation (R_n) for the shrub, grass and tree simulations as well as measured R_n averaged over 2004-2017. Shaded areas show the standard deviation for 2004-2017.

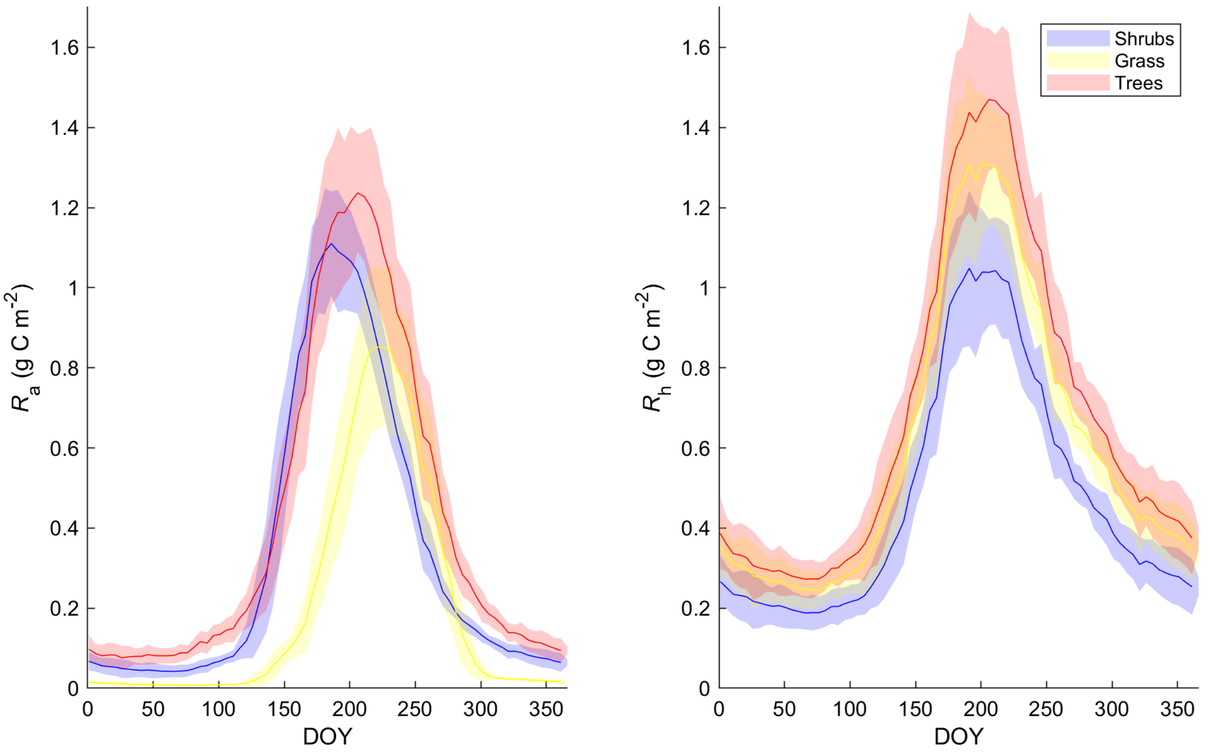

Figure S7. Mean 5-day average autotrophic (R_a) and heterotrophic respiration (R_h) for the shrub, grass and tree simulations averaged over 2004-2017. Shaded areas show the standard deviation for 2004-2017.

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