Supplementary Material

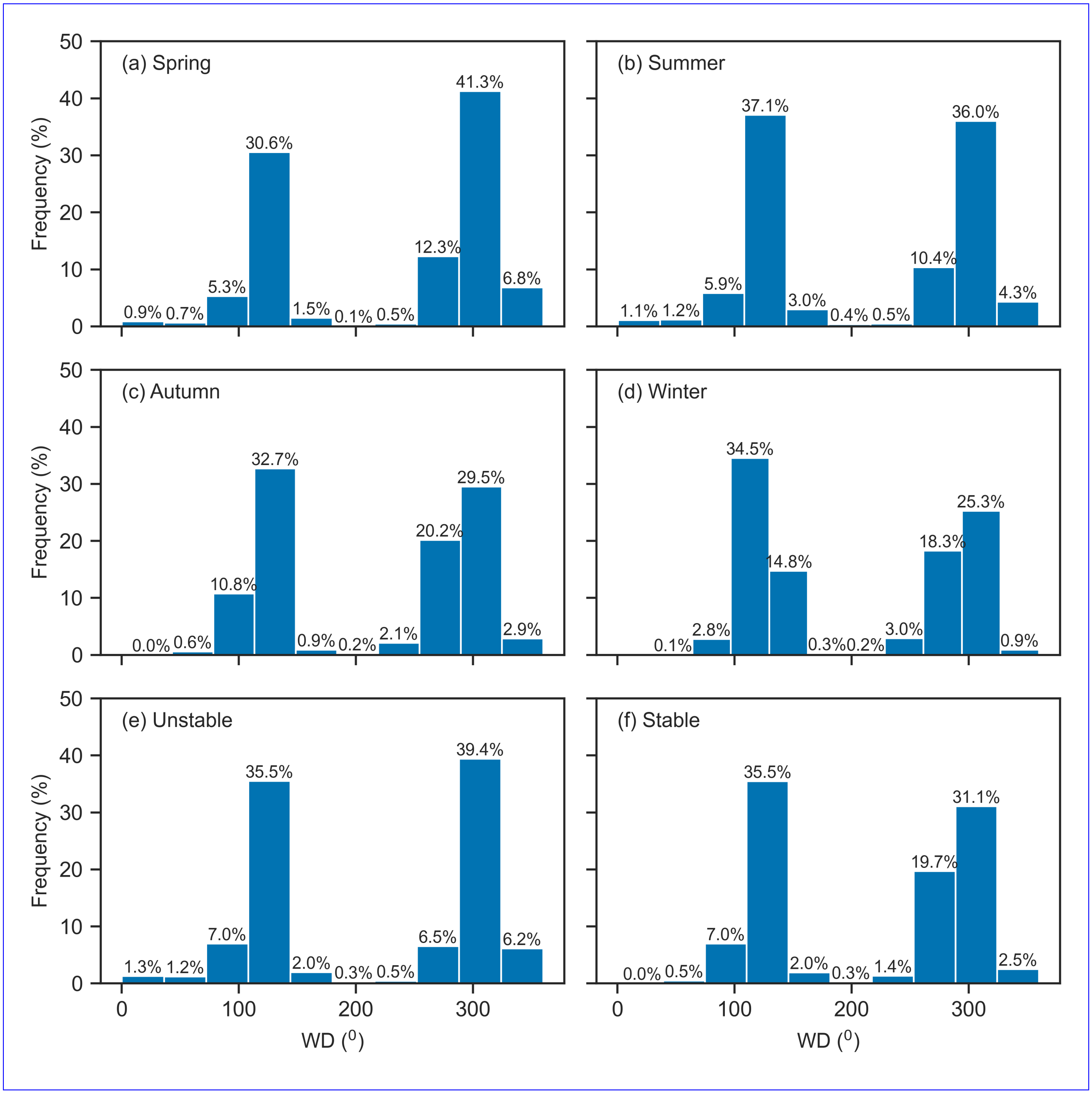

Figure S1: Wind direction distributions: a) spring, b) summer, c) autumn, d) winter, e) unstable conditions and f) stable conditions. Unstable conditions were defined as h/Lmo<0 and stable conditions as h/Lmo>0, where Lmo is the Monin-Obukhov length and h is the measurement height.

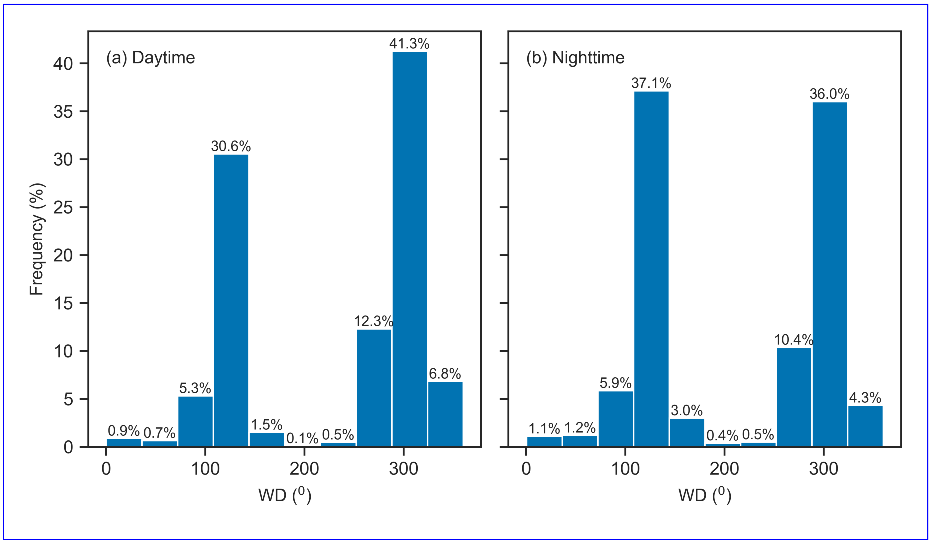

Figure S2: Wind direction distributions: a) daytime and b) nighttime including data from March to November.

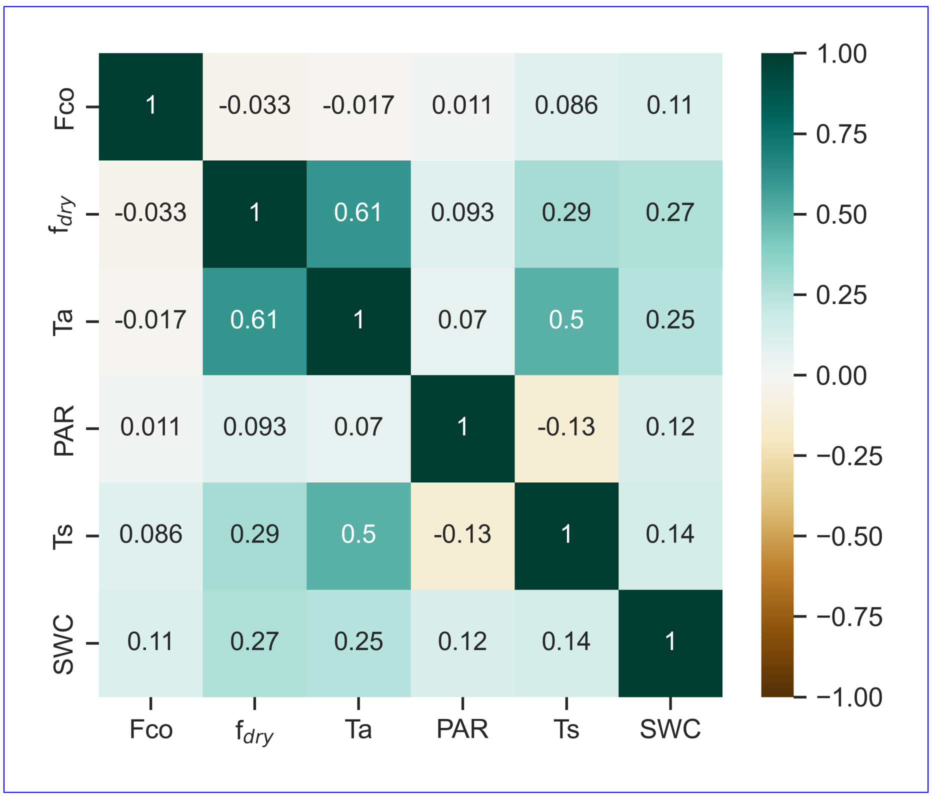

Figure S3: The correlation matrix of Spearman's rank correlation coefficients for wintertime CO flux (Fco) and flux drivers: soil temperature at a depth of 10 cm (Ts), soil water content at a depth of 10 cm (SWC), photosynthetically active radiation (PAR), air temperature (Ta), and fraction of dry surface area (f_{dry}) calculated for half-hourly values.

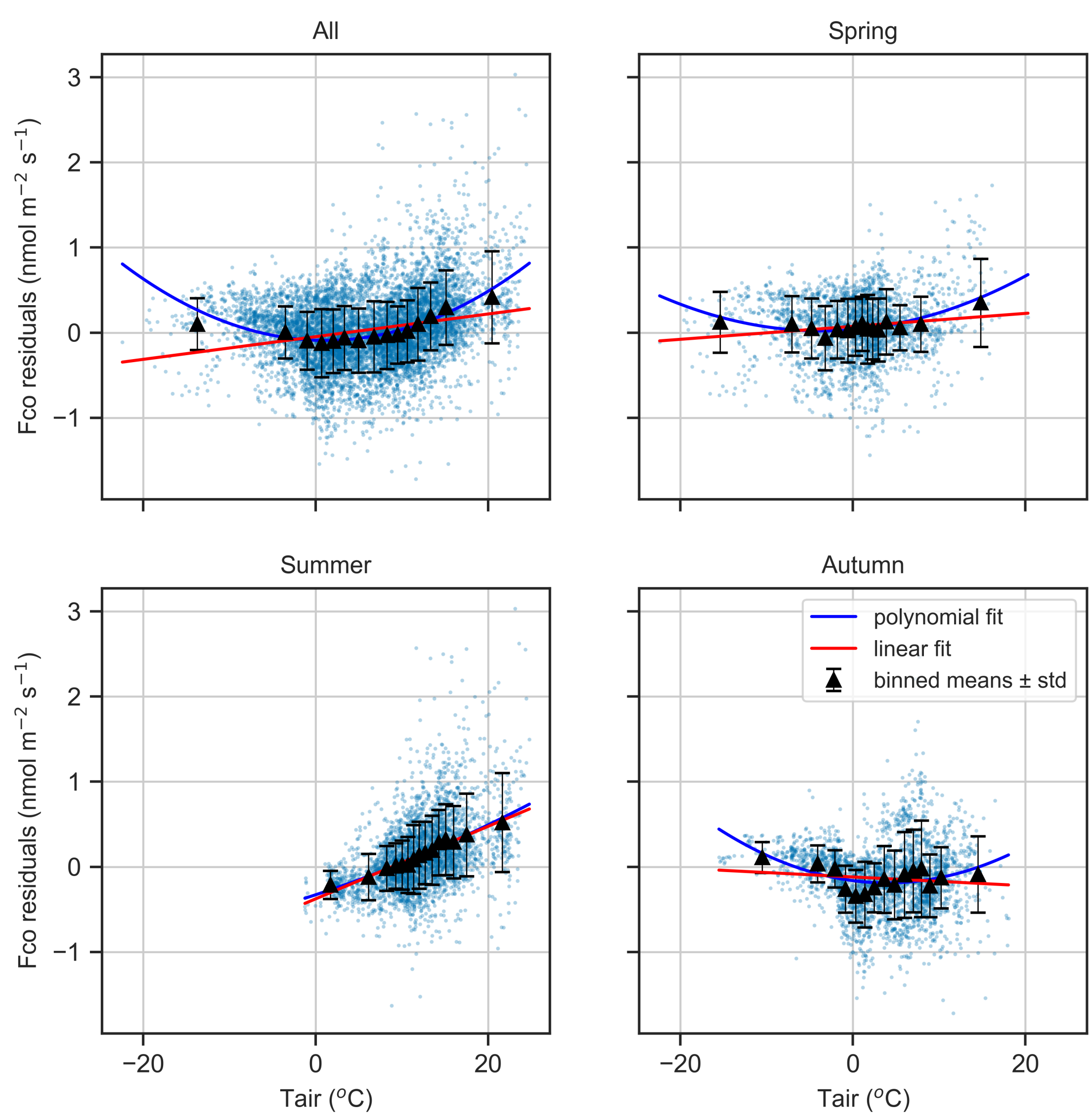

Figure S4: CO flux residuals from a linear model (Fco = a*PAR + c) plotted against air temperature. Residuals are shown as 30-minute flux data (blue dots), aggregated into binned means ± standard deviation (black triangle). Both least-squares linear (red) and second-degree polynomial (blue) fits are applied to the data.

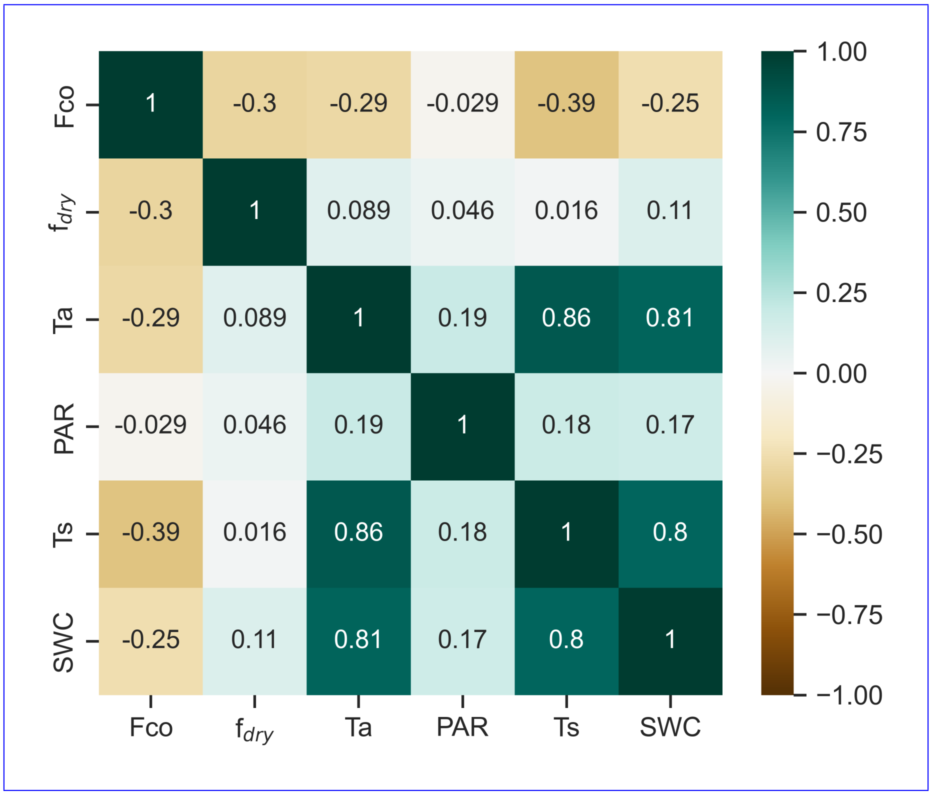

Figure S5: The correlation matrix of Spearman's rank correlation coefficients for nighttime CO flux (Fco) and flux drivers: soil temperature at a depth of 10 cm (Ts), soil water content at a depth of 10 cm (SWC), photosynthetically active radiation (PAR), air temperature (Ta), and fraction of dry surface area (f_{dry}) calculated for half-hourly values. Nighttime was defined as PAR <1 μmol m^{-2} s^{-1}.

Table S1: The data coverage in different seasons.

Season	Daytime coverage (%)	Nighttime coverage (%)	Total coverage (%)
Winter	19.7	16.1	21.5
Spring	33.8	9.4	31.0
Summer	42.4	25.0	42.1
Autumn	35.8	14.0	31.9
Total data	35.7	14.0	31.7

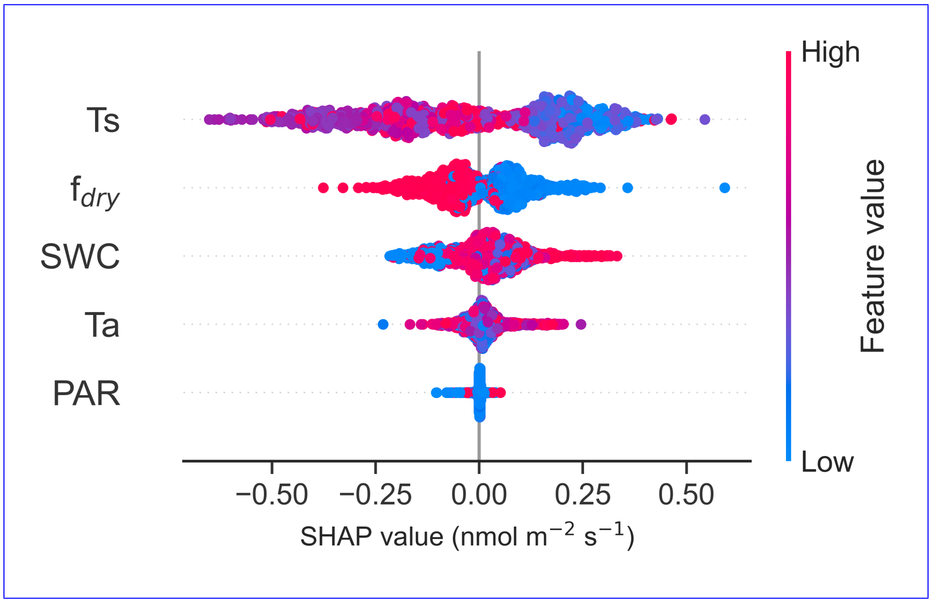

Figure S6: SHAP values of the nighttime RF model for CO flux drivers: photosynthetically active radiation (PAR), air temperature (Ta), soil temperature at a depth of 10 cm (Ts), soil water content at a depth of 10 cm (SWC) and fraction of dry surface area (f_{dry}). The SHAP values indicate the impact each feature has on the model output, with a negative value indicating a reduced flux and a positive value an increased flux. The blue color represents low feature values and red color high feature values. The zero line is the baseline (the average prediction). The SHAP values are calculated data from March to November and nighttime was defined as PAR < 1 µmol m^{-2}s^{-1}.

Table S2: Comparison of model performance using only photosynthetically active radiation (PAR) as an explanatory variable versus including air temperature (Ta).

Season	RMSE (only PAR)	RMSE (PAR and Ta)	R^2 (only PAR)	R^2 (PAR and Ta)
All	~~0.389~~ 0.413	~~0.364~~ 0.380	~~0.639~~ 0.669	~~0.684~~ 0.720
All dry	~~0.404~~ 0.423	~~0.374~~ 0.388	~~0.650~~ 0.676	~~0.700~~ 0.728
All wet	~~0.339~~ 0.372	~~0.329~~ 0.352	~~0.640~~ 0.668	~~0.659~~ 0.702
Spring (all)	~~0.355~~ 0.403	~~0.335~~ 0.406	~~0.678~~ 0.742	~~0.713~~ 0.739
Spring (dry)	~~0.375~~ 0.414	~~0.335~~ 0.390	~~0.646~~ 0.768	~~0.717~~ 0.793
Spring (wet)	~~0.336~~ 0.361	~~0.316~~ 0.350	~~0.691~~ 0.719	~~0.727~~ 0.737
Summer (all)	~~0.383~~ 0.403	~~0.396~~ 0.406	~~0.720~~ 0.742	~~0.701~~ 0.739
Summer (dry)	~~0.399~~ 0.414	~~0.385~~ 0.390	~~0.747~~ 0.768	~~0.765~~ 0.794
Summer (wet)	~~0.337~~ 0.362	~~0.331~~ 0.350	~~0.693~~ 0.719	~~0.704~~ 0.737
Autumn (all)	~~0.381~~ 0.397	~~0.377~~ 0.400	~~0.169~~ 0.260	~~0.183~~ 0.250
Autumn (dry)	~~0.384~~ 0.401	~~0.380~~ 0.399	~~0.230~~ 0.297	~~0.246~~ 0.304
Autumn (wet)	~~0.301~~ 0.316	~~0.308~~ 0.331	~~0.196~~ 0.315	~~0.158~~ 0.245

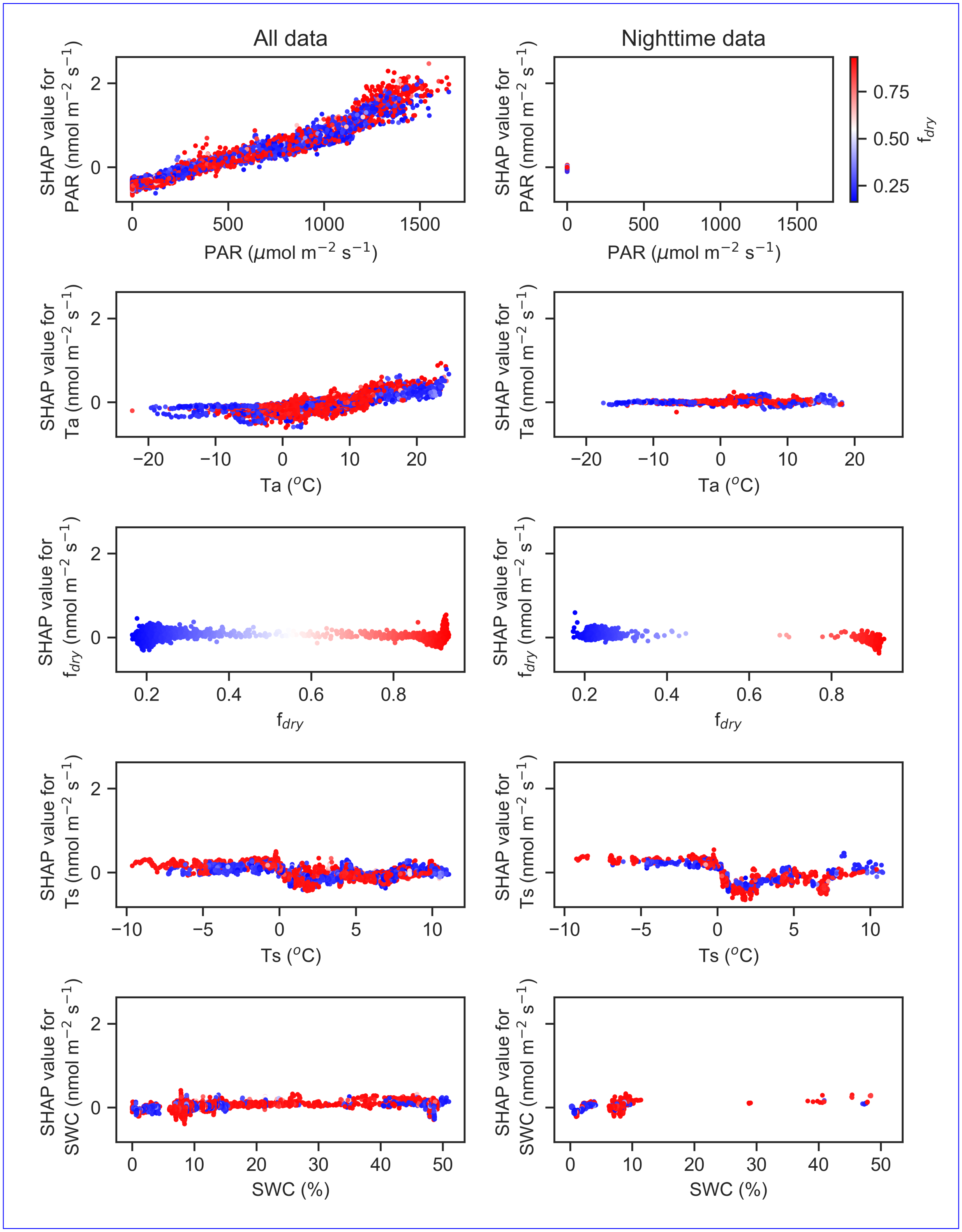

Figure S7: Partial dependence plots of SHAP values against features of RF model: photosynthetically active radiation (PAR), air temperature (Ta), soil temperature at a depth of 10 cm (Ts), soil water content at a depth of 10 cm (SWC), and fraction of dry surface area (f_{dry}). The colors represent interactions with surface cover type (f_{dry}), with red color indicating high f_{dry} and blue color indicating low f_{dry}. The left plots show relationships using all data, while the right plots are based on nighttime data.

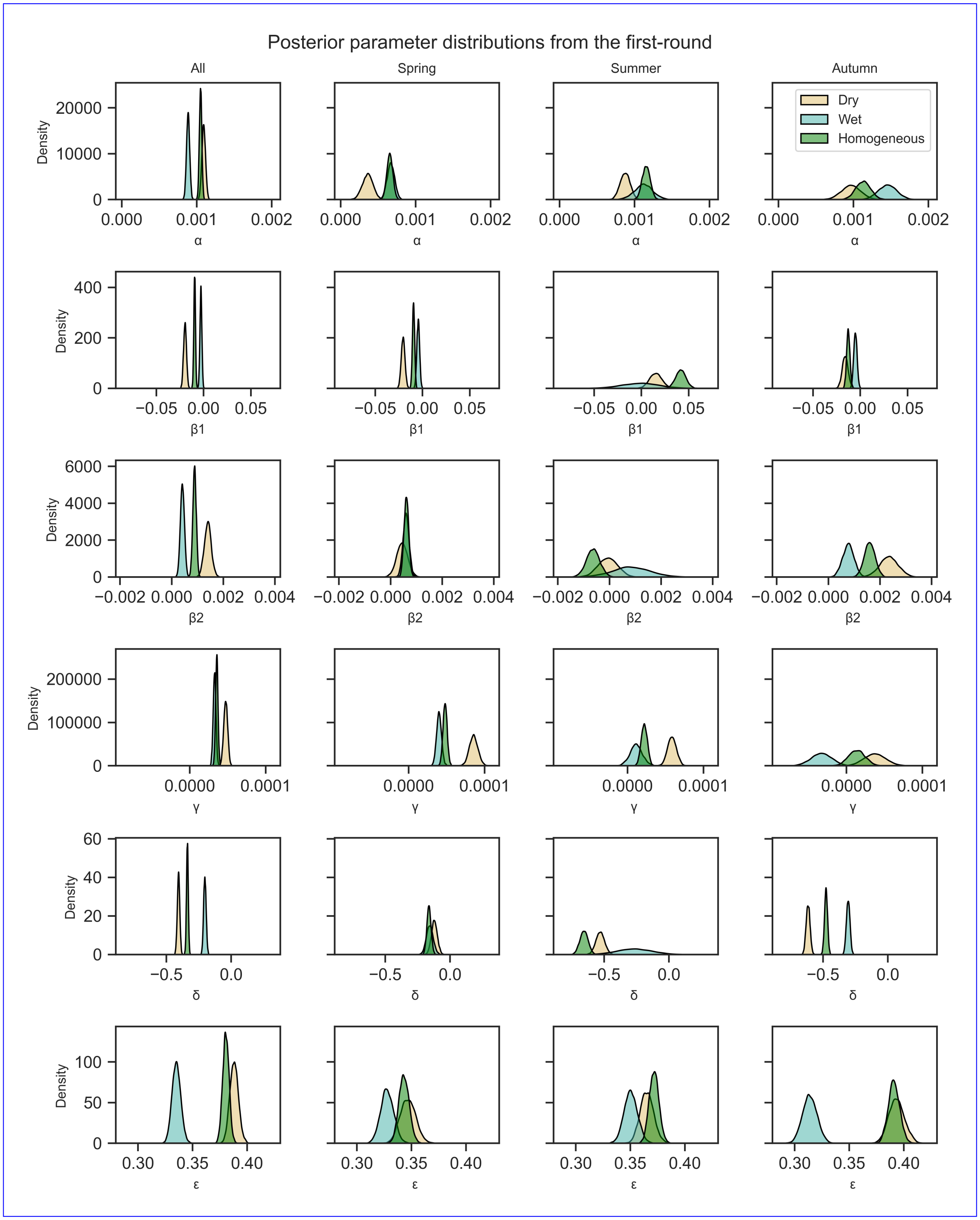

Figure S8: Posterior parameter distributions of the model parameters α and $\beta1$, $\beta2$,γ , δ, and residuals (ϵ) after the first model run. The parameters are estimated separately for wet (turquoise) and dry (yellow). Homogeneous parameters represent the parameters without considering surface structure (green).

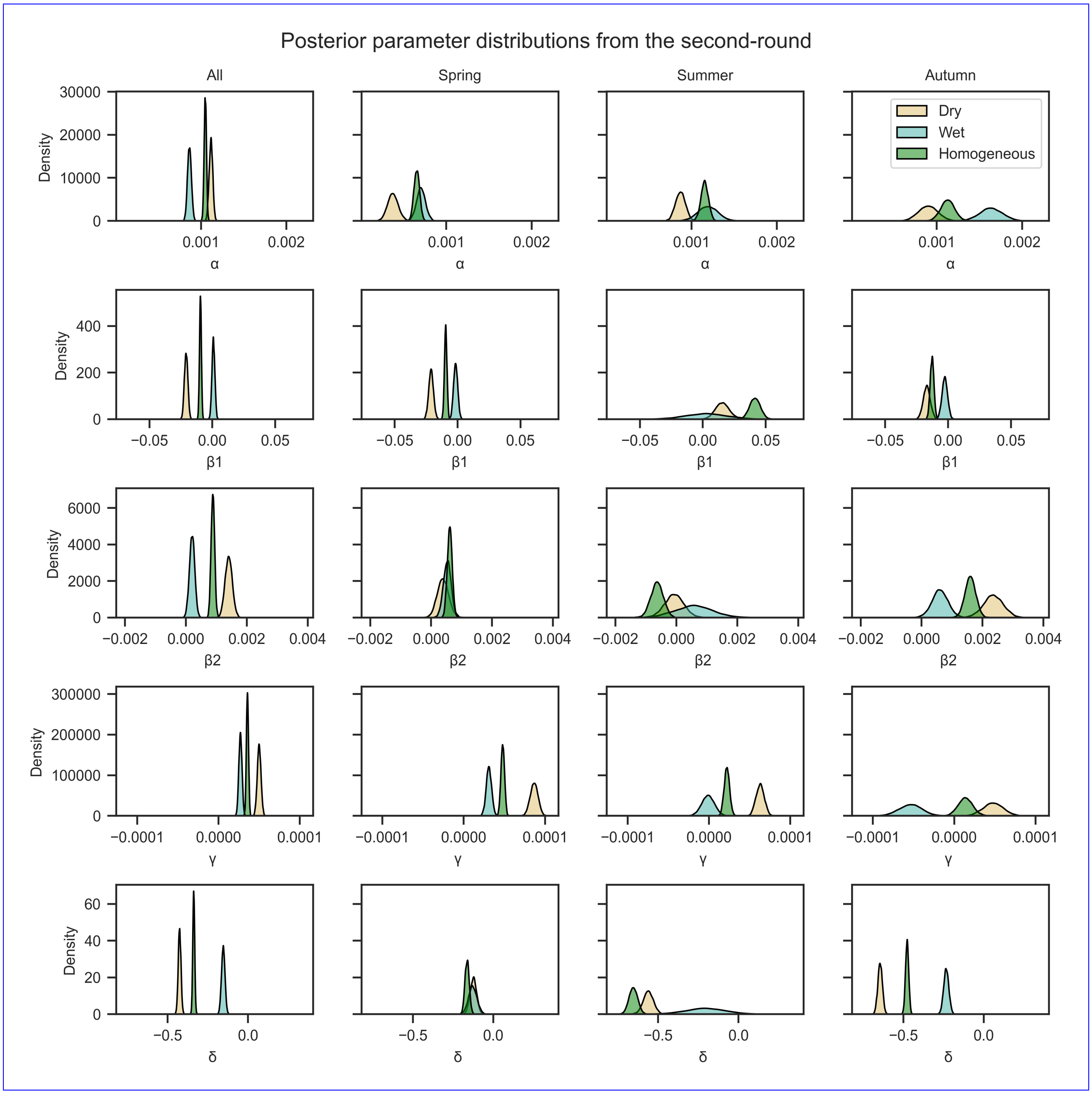

Figure S9: Posterior parameter distributions of the model parameters α and $\beta1$, $\beta2$,γ , and δ after the second model run. The parameters for wet (turquoise) and dry (yellow) are estimated considering the mixed contributions from both wet and dry surfaces. Homogeneous parameters represent the parameters without considering surface structure (green).

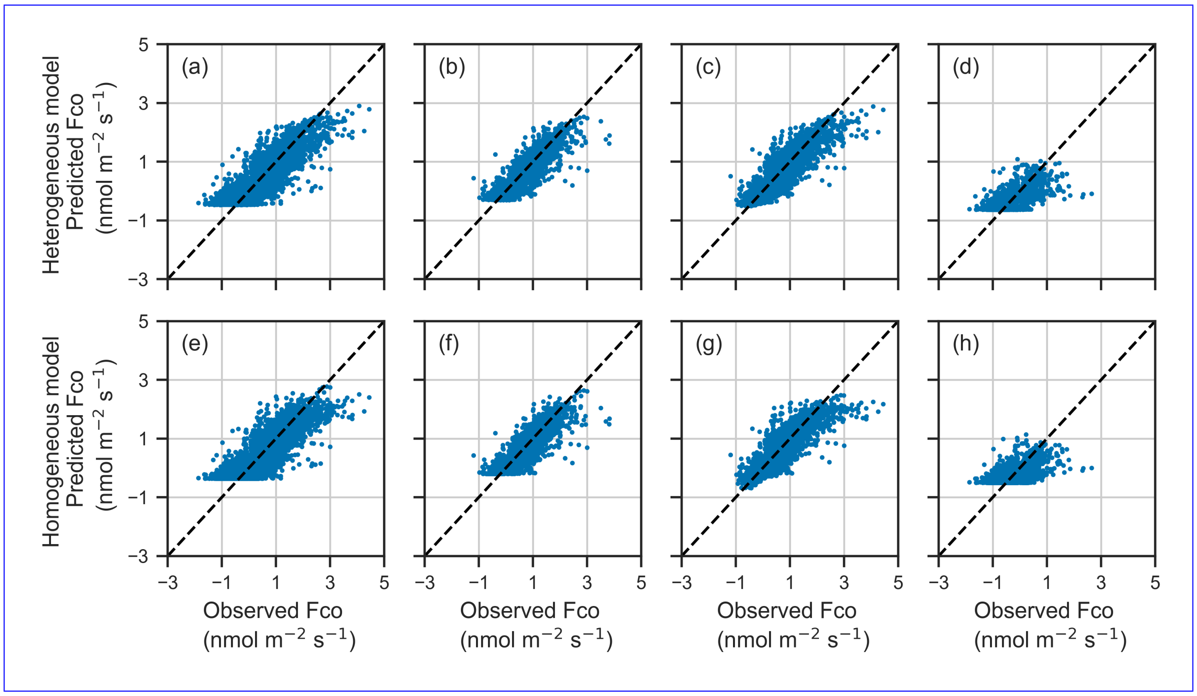

Figure S10: Predicted versus observed CO fluxes for: a) and e) all data, b) and f) spring, c) and g) summer, and d) and h) autumn. The top row shows fluxes from the heterogeneous model, while the bottom row shows fluxes from the homogeneous model. The black line represents the 1:1 relationship between observed and predicted values, and the blue dots represent 30-minute flux measurements.

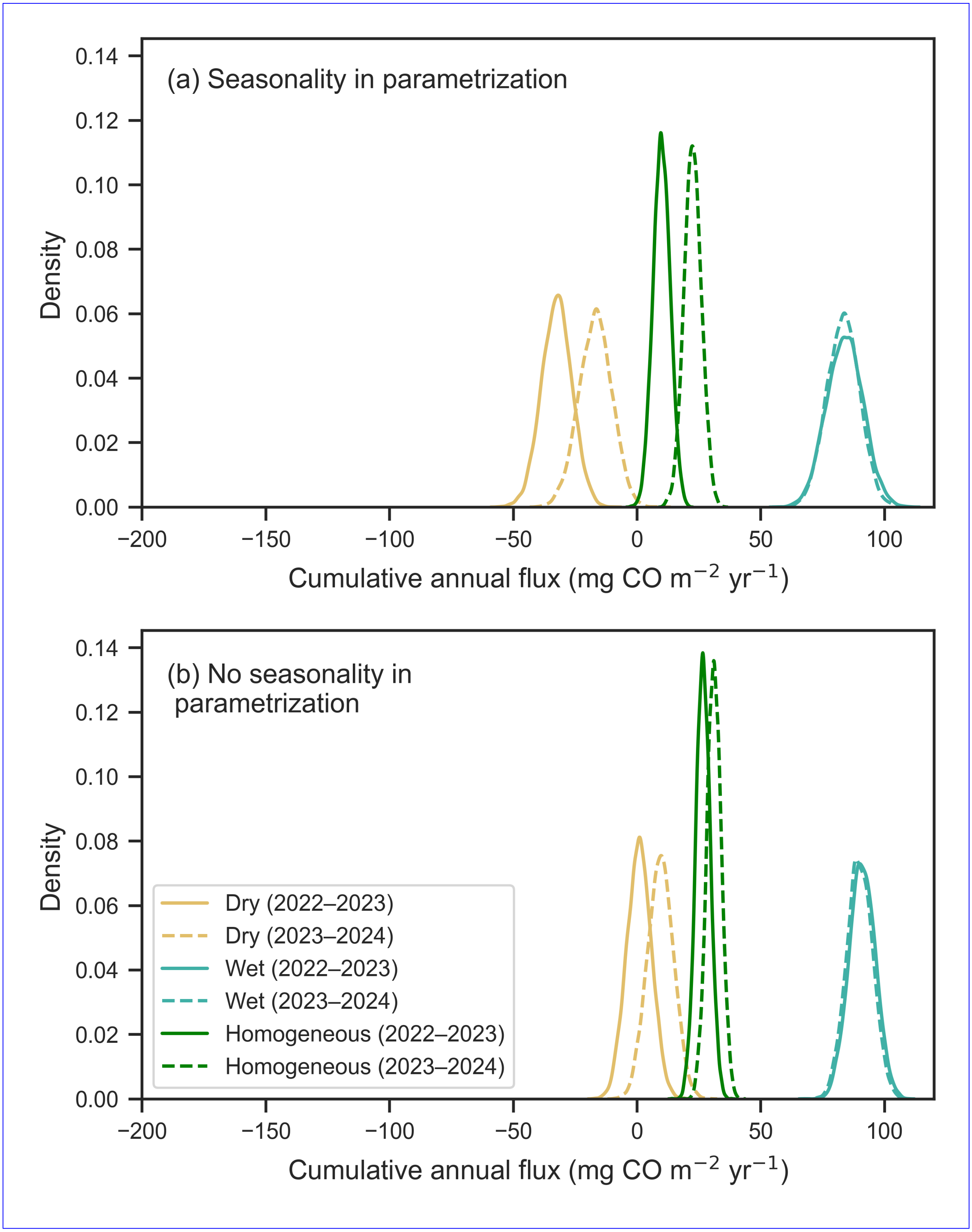

Figure S11: Probability distribution of cumulative annual fluxes in wet (turquoise), dry (yellow) surfaces, and in homogeneous surface (green) (a) using seasonal parametrization and (b) using no seasonality in parametrization.

Table S3: Priors distributions used in Bayesian inference approach.

Uniform distributions in first model run		
Parameter	Lower limit	Upper limit
α, α_{dry}, α_{wet}	0	1
$\beta1$, $\beta1_{\text{dry}}$, $\beta1_{\text{wet}}$	-1	1
$\beta2$, $\beta2_{\text{dry}}$, $\beta2_{\text{wet}}$	-1	1
γ, γ_{dry}, γ_{wet}	-1	1
δ, δ_{dry}, δ_{wet}	-1	1
ϵ	0	1
Normal distributions in second model run (All data)		
Parameter	Mean	Standard deviation
α, α_{dry}, α_{wet}	~~0.000935, 0.000984, 0.000774~~ 0.00109, 0.000883, 0.00105	~~1.570~~2.418e-5, ~~2.373~~2.091e-5, ~~1.986e~~
$\beta1$, $\beta1_{\text{dry}}$, $\beta1_{\text{wet}}$	~~-0.0101, -0.0196, -0.00368~~ -0.0197, -0.00290, -0.00953	~~0.000815, 0.00151, 0.000872~~ 0.00152, 0.0
$\beta2$, $\beta2_{\text{dry}}$, $\beta2_{\text{wet}}$	~~0.000726, 0.00129, 0.000269~~ 0.00140, 0.00041, 0.00088	~~6.563~~13.547e-5, ~~0.000135, 7.116~~7.781
γ, γ_{dry}, γ_{wet}	~~3.263~~4.717e-5, ~~4.352~~3.256e-5, ~~2.913~~3.547e-5	~~1.507~~2.607e-6, ~~2.579~~1.830e-6, ~~1.71~~
δ, δ_{dry}, δ_{wet}	~~-0.311, -0.386, -0.187~~ -0.406, -0.203, -0.338	~~0.00645, 0.00910, 0.00730~~ 0.00944, 0.0
ϵ	~~0.364, 0.375, 0.315~~ 0.388, 0.335, 0.380	~~0.00269, 0.00378, 0.00363~~ 0.00392, 0.0
Normal distributions in second model run (Spring)		
α, α_{dry}, α_{wet}	~~0.000604, 0.000293, 0.000623~~ 0.000358, 0.000668, 0.000653	~~3.900~~7.166e-5, ~~7.249~~4.992e-5, ~~4.94~~
$\beta1$, $\beta1_{\text{dry}}$, $\beta1_{\text{wet}}$	~~-0.00957, -0.0206, -0.00478~~ -0.0205, -0.00456, -0.00953	~~0.00112, 0.00193, 0.00139~~ 0.00196, 0.0
$\beta2$, $\beta2_{\text{dry}}$, $\beta2_{\text{wet}}$	~~0.000468, 0.000508, 0.000400~~ 0.000445, 0.000597, 0.000610	~~9.0156e-5, 0.000219, 0.000113~~ 0.000214, 0.
γ, γ_{dry}, γ_{wet}	~~4.155~~8.545e-5, ~~7.905~~3.987e-5, ~~3.335~~4.787e-5	~~2.691~~5.747e-6, ~~5.871~~3.252e-6, ~~3.20~~
δ, δ_{dry}, δ_{wet}	~~-0.121, -0.138, -0.151~~ -0.122, -0.157, -0.163	~~0.015, 0.0222, 0.0256~~ 0.0227, 0.026
ϵ	~~0.331, 0.334, 0.314~~ 0.347, 0.328, 0.343	~~0.00442, 0.00689, 0.00568~~ 0.00708, 0.0
Normal distributions in second model run (Summer)		
Parameter	Mean	Standard deviation
α, α_{dry}, α_{wet}	~~0.00107, 0.000806, 0.00105~~ 0.000872, 0.00115, 0.00115	~~5.252~~6.670e-5, ~~6.737~~12.159e-5, ~~0.0001~~
$\beta1$, $\beta1_{\text{dry}}$, $\beta1_{\text{wet}}$	~~0.0455, 0.0188, 0.00467~~ 0.0151, -0.0126, 0.0416	~~0.00519, 0.00662, 0.0186~~ 0.00656, 0.0
$\beta2$, $\beta2_{\text{dry}}$, $\beta2_{\text{wet}}$	~~-0.000946, -0.000235, 0.000479~~ -6.402e-5, 0.00085, -0.00064	~~0.000253, 0.000378, 0.000696~~ 0.000377, 0.
γ, γ_{dry}, γ_{wet}	~~1.732~~5.842e-5, ~~5.178~~1.112e-5, ~~5.791e-6~~ 2.187e-5	~~4.020~~8.875e-6, ~~5.984~~8.202e-6, ~~7.71~~
δ, δ_{dry}, δ_{wet}	~~-0.666, -0.544, -0.296~~ -0.530, -0.265, -0.655	~~0.0342, 0.129, 0.0304~~ 0.0337, 0.13
ϵ	~~0.360, 0.359, 0.331~~ 0.365, 0.350, 0.372	~~0.00425, 0.00595, 0.00591~~ 0.00618, 0.0
Normal distributions in second model run (Autumn)		
Parameter	Mean	Standard deviation
α, α_{dry}, α_{wet}	~~0.000733, 0.000615, 0.000868~~ 0.000966, 0.00145, 0.00113	~~0.000121, 6.580e-5, 9.0107~~0.000127, 0.0
$\beta1$, $\beta1_{\text{dry}}$, $\beta1_{\text{wet}}$	~~-0.0127 ,-0.0127, -0.00644~~ -0.0161 ,-0.00523, -0.0128	~~0.00142, 0.00303, 0.00144~~ 0.00308, 0.0
$\beta2$, $\beta2_{\text{dry}}$, $\beta2_{\text{wet}}$	~~0.00116, 0.00163, 0.000330~~ 0.00234, 0.00077, 0.000160	~~0.000184, 0.000353, 0.000181~~ 0.000359, 0.
γ, γ_{dry}, γ_{wet}	~~2.888~~3.742e-5, ~~5.191~~-3.301e-5, ~~5.248e-6~~ 1.354e-5	~~1.005~~1.422e-5, ~~1.369~~1.353e-5, ~~4.707e~~
δ, δ_{dry}, δ_{wet}	~~-0.405, -0.554, -0.235~~ -0.616, -0.306, -0.477	~~0.0102, 0.0146, 0.0112~~ 0.0150, 0.01
ϵ	~~0.374, 0.378, 0.299~~ 0.393, 0.314, 0.391	~~0.00492, 0.00676, 0.00579~~ 0.00718, 0.0

Table S4: The model performance of the CO flux using posterior parameters from the second model run. Full indicates surface-type-specific model and simple is the linear model without considering surface structure.

Model	RMSE	R^2
Full (All)	~~0.352~~0.368	~~0.705~~0.737
Simple (All)	~~0.364~~0.380	~~0.684~~0.719
Full (Spring)	~~0.322~~0.336	~~0.734~~0.766
Simple (Spring)	~~0.330~~0.343	~~0.721~~0.756
Full (Summer)	~~0.347~~0.359	~~0.770~~0.795
Simple (Summer)	~~0.360~~0.371	~~0.754~~0.781
Full (Autumn)	~~0.345~~0.362	~~0.318~~0.385
Simple (Autumn)	~~0.373~~0.391	~~0.200~~0.285

Table S5: Annual cumulative CO fluxes for wet, dry and homogeneous surfaces, presented as mean, standard deviation (std), 25th percentile (Q25), and 75th percentile (Q75) confidence intervals.

Year	Stat	Dry	Wet	Homogeneous
2022–2023	Q25	~~-47.5~~-36.6	~~66.0~~78.8	~~-2.3~~7.6
(seasonal model)	Mean ± std	~~-43.3~~ -32.5 ± 6.1	~~70.8~~ 84.0 ± ~~7.1~~7.3	~~-0.03~~9.9 ± 3.4
	Q75	~~-39.2~~-28.4	~~75.6~~88.9	~~2.3~~12.3
2023–2024	Q25	~~-36.7~~-21.3	~~67.0~~78.8	~~9.2~~20.1
(seasonal model)	Mean ± std	~~-32.2~~ -16.9 ± ~~6.4~~6.6	~~71.3~~ 83.3 ± ~~6.4~~6.6	~~11.4~~22.5 ± ~~3.4~~3.5
	Q75	~~-27.8~~-12.4	~~75.5~~87.8	~~13.6~~24.9
2022–2023	Q25	~~-18.4~~-2.6	~~68.9~~87.4	~~9.1~~24.7
(no seasonal parameterization)	Mean ± std	~~-15.1~~ 0.8 ± ~~4.8~~5.0	~~72.3~~ 91.0 ± ~~4.8~~5.3	~~10.9~~26.7± ~~2.7~~2.9
	Q75	~~-11.9~~4.2	~~75.6~~94.6	~~12.8~~28.6
height2023–2024	Q25	~~-10.3~~5.9	~~67.5~~86.5	~~12.9~~29.1
(no seasonal parameterization)	Mean ± std	~~-6.9~~ 9.4 ± ~~3.5~~5.3	~~70.8~~ 90.0 ± ~~4.8~~5.2	~~14.8~~31.1± ~~2.7~~2.9
	Q75	~~-3.5~~13.0	~~74.1~~93.6	~~16.6~~33.1