Modeling of CO_2 Efflux from Forest and Grassland Soils Depending on Weather Conditions

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Supplementary Materials:

The site location and the terrain profile

The terrain profile (Figure S1) can be taken for reference of the height change only as the google-reported elevation difference is about 7.5 and clearly violates to the direct elevation difference measured on-site (4-m difference from the forest site to the grassland). The river Sushka is located about 330 m west-southwest and about 20 m down slope from the sites.

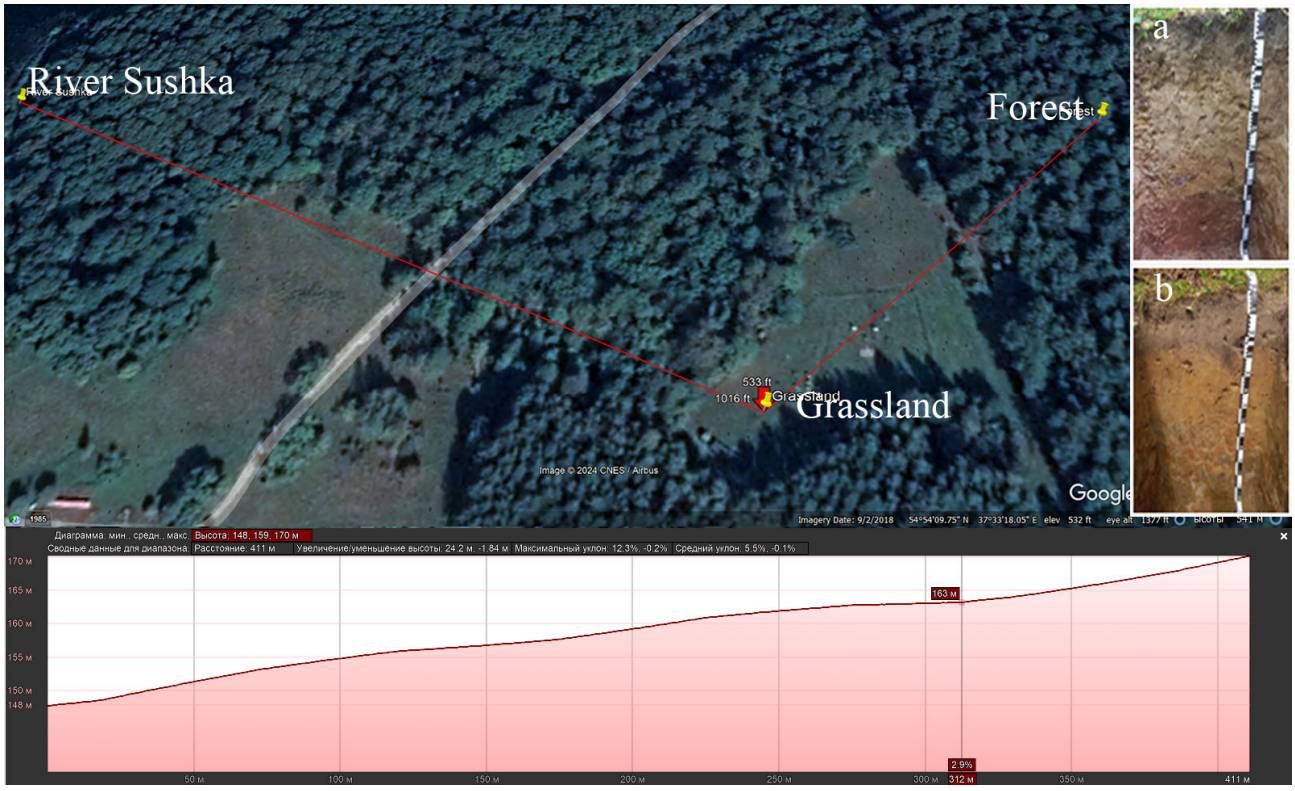


Figure S1. Grassland and forest site locations related to the nearby river Sushka and the local Google-Earth derived terrain orography (bottom) illustrating the relative site elevations and the terrain slope toward the river ("Prioksko-Terrasny Reserve", 54°54′ N, 37°33′ E, Google Earth. February 2018. 7 March 2024); a – the forest site soil profile, b – the grassland site soil profile. The grassland site is located near the Complex Background Monitoring Station (red).

The illustration of the R_0 identification procedure

The R_0 identification procedure based on the intercept minimization technique Kivalov et al. (2023a, b) [**Error! Reference source not found.**,**Error! Reference source not found.**,**Error! Reference source not found.**] of the linear comparison between the measured and modeled data

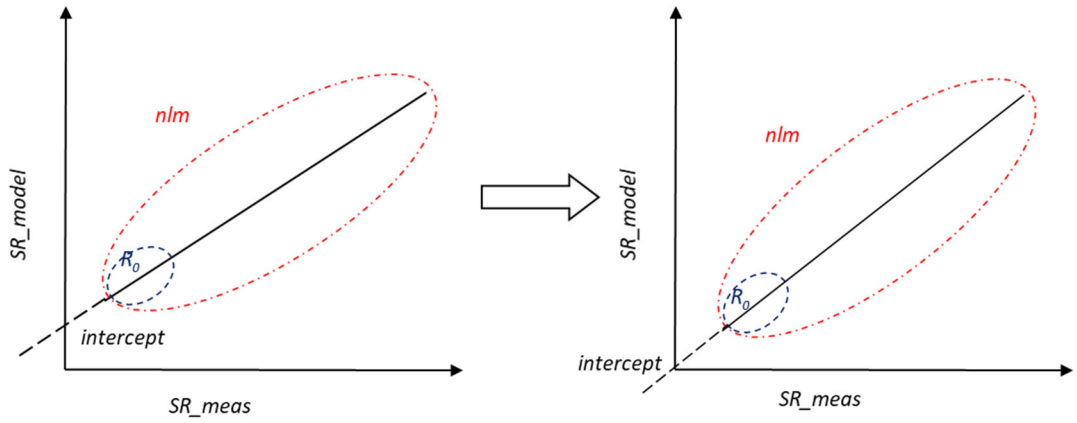


Figure S2. The R_0 identification procedure: Red – the cloud of all nlm-involved points, blue -the cloud of only R_0-involved points

Table S1. Correlation coefficients between the CO_2 efflux (SR) and temperature and moisture sources for the 0 < Tsoil < 1 °C soil temperatures: Tsoil – local soil temperature; Tair – Danki' Monitoring station temperature; Tlit_m – modeled litter (for forest) or sod (for grassland) horizon temperature; Tsoil_m – modelled soil temperature; Prec - monitoring station precipitation; Mlit_m – modeled litter or sod horizon moisture; Msoil_m – modeled soil moisture; *p*-value – significance of Pearson correlation coefficient

Correlations	Forest	*p*-value	Grassland	*p*-value
Cor(SR,Tsoil)	0.22	°	0.14	°
Cor(SR,Tair)	0.17	°	0.14	°
Cor(SR,Tlit_m)	-0.05	·	**0.53**	**
Cor(SR,Tsoil_m)	-0.03	·	0.34	°
Cor(SR,Prec)	**0.42**	*	0.03	·
Cor(SR, Mlit_m)	0.16	°	-0.18	°
Cor(SR,Msoil_m)	0.17	°	-0.25	°

p-value: 0 < *** < 0.0005 < ** < 0.005 < * < 0.05 < ° < 0.5 < · < 0

Table S2. Comparison among the all-at-once (TPPC, TPPrh) and condition-specific (TPPC_nwd, TPPrh_nwd) models by R^2 and slope of the linear model, |MBE|, and RMSE; Types of parameterizations: air – Tair-Prec, litter or sod horizon modeled – Tlit_m-Mlit_m, soil measured – Tsoil-Prec, and soil modeled – Tsoil_m-Msoil_m

Model	**Type**	**Forest**				**Grassland**			
		R^2	slope	|MBE|	RMSE	R^2	slope	|MBE|	RMSE
TPPC	air (Tair-Prec)	0.7	**0.876**	0.186	0.59	0.683	0.834	0.311	0.891
TPPC_nwd		**0.735**	**0.896**	**0.154**	**0.547**	0.699	0.849	0.29	0.866
TPPrh		0.664	0.825	0.182	0.612	**0.704**	**0.859**	0.233	0.842

TPPrh_nwd		**0.724**	0.861	0.177	0.555	**0.729**	**0.86**	**0.206**	**0.795**
TPPC	litM (Tlit_m-Mlit_m)	0.682	**0.862**	0.209	0.614	0.539	0.739	0.497	1.146
TPPC_nwd		**0.709**	**0.882**	0.194	0.585	**0.669**	**0.829**	0.336	0.922
TPPrh		0.67	0.803	0.125	0.584	0.653	0.805	0.229	0.9
TPPrh_nwd		**0.725**	0.806	**0.073**	**0.515**	**0.717**	0.796	**0.105**	**0.771**
TPPC	soil (Tsoil-Prec)	0.697	0.869	0.197	0.595	0.617	0.793	0.393	1.008
TPPC_nwd		**0.722**	**0.884**	0.174	0.565	0.59	0.781	0.416	1.057
TPPrh		0.708	0.843	**0.133**	0.555	**0.696**	**0.806**	**0.178**	**0.818**
TPPrh_nwd		**0.732**	0.854	0.157	**0.538**	**0.647**	**0.802**	**0.26**	**0.921**
TPPC	soilM (Tsoil_m-Msoil_m)	0.623	0.835	0.249	0.687	0.23	0.439	1.083	1.754
TPPC_nwd		0.634	**0.857**	0.254	0.687	0.494	0.724	0.603	1.261
TPPrh		**0.679**	0.819	0.075	**0.57**	0.56	0.797	0.331	1.088
TPPrh_nwd		0.656	0.854	**0.17**	0.632	**0.63**	**0.799**	**0.191**	**0.93**

Table S3. Comparison between the TPPC- and TPPrh-type models parameterized by the measured data: (a) – air and (s) – soil, and the modeled data: (ml) – litter or sod horizon and (ms) – soil depending on weather conditions – normal, dry, and wet years

Model	**Weather**	**Forest**				**Grassland**			
		R^2	slope	|MBE|	RMSE	R^2	slope	|MBE|	RMSE
TPPCa	dry	**0.673**	**0.882**	0.152	0.461	0.678	**0.838**	0.255	0.7
TPPCml		0.581	**0.833**	0.219	0.55	0.618	0.804	0.314	0.785
TPPCms		0.459	0.767	0.31	0.676	0.319	0.566	0.705	1.236
TPPCs		**0.694**	**0.886**	**0.147**	**0.442**	0.583	0.787	0.339	0.832
TPPrha		0.634	0.812	0.187	0.485	**0.716**	**0.859**	**0.19**	**0.636**
TPPrhml		0.655	0.698	**0.016**	**0.41**	**0.708**	0.744	**0.038**	**0.589**
TPPrhms		0.448	0.747	0.317	0.68	0.602	0.797	0.224	0.771
TPPrhs		0.632	0.742	0.25	0.499	0.492	0.683	0.366	0.905
TPPCa	normal	0.735	**0.893**	0.172	0.625	**0.654**	**0.818**	0.371	1.041
TPPCml		0.71	**0.873**	0.209	0.662	0.623	0.795	0.419	1.102
TPPCms		0.664	0.854	0.241	0.727	0.453	0.673	0.676	1.434
TPPCs		**0.754**	**0.894**	**0.172**	**0.598**	0.506	0.716	0.585	1.33
TPPrha		0.734	0.873	0.199	0.627	**0.693**	**0.839**	**0.244**	**0.941**
TPPrhml		0.716	0.845	0.166	0.63	0.673	0.797	**0.205**	**0.947**
TPPrhms		0.709	0.839	0.074	0.621	0.559	0.741	0.204	1.125
TPPrhs		**0.765**	**0.856**	**0.088**	**0.551**	0.639	0.794	0.246	1.017
TPPCa	wet	0.766	**0.902**	0.118	0.533	0.787	**0.909**	0.194	0.772
TPPCml		**0.808**	**0.921**	0.122	**0.482**	**0.793**	**0.902**	0.211	0.76
TPPCms		0.708	0.891	0.172	0.62	0.738	0.887	0.246	0.874
TPPCs		0.652	0.857	0.23	0.697	0.772	0.894	0.228	0.804
TPPrha		0.757	0.851	0.11	0.528	0.787	0.888	0.163	0.755
TPPrhml		**0.817**	0.831	**0.003**	**0.439**	**0.805**	0.838	**0.039**	**0.688**
TPPrhms		0.741	0.872	**0.074**	0.549	0.77	0.874	**0.095**	0.772
TPPrhs		0.72	0.873	0.112	0.583	0.79	0.859	0.076	0.726

Table S4. The cold period (Tsoil ≤ 2°C) statistics for the combined condition-specific models depended on the Types of parameterizations: air – Tair-Prec, litM – Tlit_m-Mlit_m, soil – Tsoil-Prec, and soilM – Tsoil_m−Msoil_m

Model	Type	Forest			Grassland		
		R^2	|MBE|	RMSE	R^2	|MBE|	RMSE
TPPC_nwd	soil	0.132	0.222	0.393	0.018	0.393	0.624
TPPC_nwd	air	0.110	0.245	0.431	0.034	0.389	0.631
TPPrh_nwd	soil	0.041	0.245	0.420	0.000	0.378	0.630
TPPrh_nwd	air	0.069	0.293	0.483	0.033	0.450	0.707
TPPC_nwd	soilM	0.036	0.307	0.462	0.016	0.517	0.715
TPPC_nwd	litM	0.065	0.226	0.411	0.034	0.347	0.591
TPPrh_nwd	soilM	0.031	0.305	0.472	0.029	0.441	0.685
TPPrh_nwd	litM	0.045	0.114	0.391	0.024	0.206	0.565

Table S5. Parameters of the linear regressions between the measured and modeled values for the TPPC, and T models on the Entic Podzol (mixed forest ecosystem) and the Romul_Hum and T models on the Haplic Luvisol (deciduous forest ecosystem) depending on the weather-specific conditions

Forest site	years		R^2	Slope
Entic Podzol TPPC (CO_2 efflux) current study	wet		0.76-0.80	0.88-0.92
	dry		0.58-0.69	0.83-0.88
	normal		0.71-0.76	0.85-0.89
	all-years		0.70	0.87
Haplic Luvisol Romul_Hum (Rh) [**Error! Reference source not found.**]	wet		0.772	0.60
	dry		0.339	1.90
	all-years		0.524	0.914
Entic Podzol T model (CO_2 efflux) [**Error! Reference source not found.**]	wet		0.61	-
	dry		0.45	-
	normal		0.59	-
Haplic Luvisol T model (CO_2 efflux) [**Error! Reference source not found.**]	wet		0.54	-
	dry		0.47	-
	normal		0.56	-

Table S6. Parameters of the linear regression between the measured and modeled values for the TPPC, and T models on the Entic Podzol (grassland ecosystem) and the T model on the Haplic Luvisol (grassland ecosystem) depending on the weather-specific conditions

Grassland site	years	R^2	Slope
Entic Podzol TPPC	wet	0.77-0.8	0.88-0.9
	dry	0.58-0.70	0.79-0.84

(CO_2 efflux) current study	normal	0.6-0.62	0.78-0.84
	all-years	0.70	0.74-0.8
Entic Podzol T model (CO_2 efflux) [**Error! Reference source not found.**]	wet	0.63	-
	dry	0.54	-
	normal	0.56	-
Haplic Luvisol T model (CO_2 efflux) [**Error! Reference source not found.**]	wet	0.58	-
	dry	0.56	-
	normal	0.59	-

References

14 Jílková, V. Soil respiration in temperate forests is increased by a shift from coniferous to deciduous trees but not by an increase in temperature. *Appl. Soil Ecol.* **2020**, *154*, 103635.

15 Raich, J.W.; Tufekciogul, A. Vegetation and soil respiration: Correlations and controls. *Biogeochemistry* **2000**, *48*, 71–90.

20 Raich, J.W.; Potter, C.S. Global patterns of carbon dioxide emission from soils. *Glob. Biogeochem. Cycles* **1995**, *9*, 23–36.

38 Macdonald, C.A.; Anderson, I.C.; Khachane, A.; Singh, B.P.; Barton, C.V.M.; Duursma, R.A.; Ellsworth, D.S.; Singh, B.K. Plant productivity is a key driver of soil respiration response to climate change in a nutrient-limited soil. *Basic Appl. Ecol.* **2021**, *50*, 155–168.

39 Lal, R. Forest soils and carbon sequestration. *For. Ecol. Manag.* **2005**, *220*, 242–258.

47 Reichstein, M.; Beer, C. Soil respiration across scales: The importance of a model-data integration framework for data interpretation. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 344–354.