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Annual net CO_2 fluxes from drained organic soils used for agriculture in the hemiboreal region of Europe

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Table S1. Summary of study sites with drained nutrient-rich organic soil, description of specific measurement period of ecosystem respiration (R_{eco}) and soil heterotrophic respiration (R_{het}) and plant biomass sampling.

Land use	Country	Study sites, coordinates (WGS84 system); X – longitude, Y – latitude	Measurements of R_{eco}			Measurements of R_{het}			Plant biomass sampling (date)	
			No. of plots/ No. of chambers per plot	Measurement period	Frequency of measurement	No. of plots/ No. of chambers per plot	Measure-ment period	Frequency of measure-ment	Above-ground	Below-ground
Cropland	Latvia	CL_LV_1; X: 27.01609, Y: 56.71777	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		CL_LV_2; X: 27.01533, Y: 56.71890	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		CL_LV_3; X: 22.58267, Y: 57.13077	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		CL_LV_4; X: 23.94817, Y: 56.85442	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		CL_LV_5; X: 22.83829, Y: 56.56447	3/1-2	Jan 2021 - Dec 2022	Once a month	3/3	Apr 2021 - Nov 2022	Once a month	04.08.2021	04.08.2021
		CL_LV_6; X: 22.84456, Y: 56.5582	3/1-2	Jan 2021 - Dec 2022	Once a month	3/3	Apr 2021 - Nov 2022	Once a month	11.08.2021	11.08.2021
	Estonia	CL_EE_1; X: 26.730312, Y: 58.035321	3/2	Jan 2021 - Dec 2022	Twice a month	3/3	Apr 2021 - Nov 2022	Twice a month	02.08.2021	28.04.2021, 30.08.2021, 27.-30.07.2022
	Lithuania	CL_LT_1; X: 24.077234, Y: 54.790503	3/1-2	Jul 2021 – Jun 2023	Once a month	3/3	Apr 2021 – Sep 2023	Once a month	15.08.2021, 02.08.2022, 21.08.2023	15.08.2021, 02.08.2022, 21.08.2023
Grassland	Latvia	GL_LV_1; X: 23.58187, Y: 56.91087	1/5	Dec 2016 -Jun 2020	Once a month	-	-	-	-	-
		GL_LV_2; X: 26.73018, Y: 56.59072	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		GL_LV_3; X: 26.80302, Y: 56.40100	1/5	Dec 2016 -Nov 2018	Once a month	-	-	-	-	-
		GL_LV_4; X: 21.11741, Y: 56.2281	3/1-2	Jan 2021 -Dec 2022	Once a month	3/3	Apr 2021 - Nov 2022	Once a month	12.07.2021	12.07.2021
		GL_LV_5; X: 22.84282, Y: 56.55928	3/1-2	Jan 2021 -Dec 2022	Once a month	3/3	Apr 2021 - Nov 2022	Once a month	04.08.2021	04.08.2021
		GL_LV_6; X: 21.18817, Y: 56.21148	3/3	Jul 2021 - Apr 2023	Once a month	3/3	Jul 2021 - Jun 2023	Once a month	09.08.2021	09.08.2021
		GL_LV_7; X: 22.84415, Y: 56.55887	3/3	Jul 2021 - Apr 2023	Once a month	3/3	Jul 2021 - Jun 2023	Once a month	04.08.2021	04.08.2021
		GL_LV_8; X: 24.75663; Y: 56.77254	3/3	Jul 2021 - May 2023	Once a month	3/3	Jul 2021 - Jun 2023	Once a month	09.08.2021	09.08.2021
	Estonia	GL_EE_1; X: 26.671883, Y: 58.430894	3/2	Jan 2021 -Dec 2022	Twice a month	3/3	Apr 2021 - Nov 2022	Twice a month	26.07.2021, 12.09.2021	22.04.2021, 24.08.2021, 27.-30.07.2022
		GL_EE_2; X: 26.732756, Y: 58.03563	3/2	Jan 2021 -Dec 2022	Twice a month	3/3	Apr 2021 - Nov 2022	Twice a month	14.06.2021, 14.09.2021	23.08.2021, 06.05.2022, 27.-30.07.2022
		GL_EE_3; X: 26.6734173, Y: 58.4293805	3/2	Jan 2021 -Dec 2022	Twice a month	3/3	Apr 2021 - Nov 2022	Twice a month	-	22.04.2021, 24.08.2021, 27.-30.07.2022
	Lithuania	GL_LT_1; X: 24.085606, Y: 54.808451	3/1-2	Jul 2021 – Jun 2023	Once a month	3/3	Apr 2021 – Oct 2023	Once a month	17.08.2022, 15.08.2023	01.07.2023.

Table S2. Description of the vegetation species composition in the grassland sites.

Land use	Country	Study sites	Vegetation species composition
Grassland	Latvia	GL_LV_1	Listed by dominance, areal coverage: Canadian Goldenrod (*Solidago canadensis*), Rough-stalked Feather-moss (*Brachythecium rutabulum*), Cock's-foot (*Dactylis glomerate*), Alpine thyme-moss (*Plagiomnium medium*), meadow Fescue (*Festuca pratensis*), Yarrow (*Achillea millefolium*), tufted Vetch (*Vicia cracca*), Yorkshire-fog (*Holcus lanatus*), meadow Oat-grass (*Avenula pratensis*), heath Wood-rush (*Luzula multiflora*), cow Parsley (*Antrischys sylvestris*), hop Trefoil (*Trifolium campestre*), upright Hedge-bedstraw (*Galium album*), common Reed (*Phragmites australis*), field Horsetail (*Equisetum arvense*), germander Speedwell (*Veronica chamaedrys*), sheep's Sorrel (*Rumex acetosella*), common Dandelion (*Taraxacum officinale*), Woodsy Thyme-moss (*Plagiomnium cuspidatum*), three-nerved Sandwort (*Moehringia trinervia),* meadow Vetchling (*Lathyrus pratensis*)
		GL_LV_2	Not determined
		GL_LV_3	Not determined
		GL_LV_4	Listed by dominance, areal coverage: rough Meadow-grass (*Poa trivialis*), tufted Hair-grass (*Deschampsia cespitosa*), Narrow-leaved Meadow-Grass (*Poa angustifolia*), creeping Buttercup (*Ranunculus repens*), soft-Rush (*Juncus effusus*), Gipsywort (*Lycopus europaeus*), Tormentil (*Potentilla erecta*), Willow (*Salix* sp.), tufted Vetch (*Vicia cracca*), lesser Trefoil (*Trifolium dubium*), hoary Willowherb (*Epilobium parviflorum*), lesser Hemp-nettle (*Galeopsis bifida*), red Bartsia (s.l.) (*Odontites vulgaris*)
		GL_LV_5	Listed by dominance, areal coverage: Tall fescue (Lolium arundinaceum), Ground-ivy (*Glechoma hederacea*), lesser Stitchwort (*Stellaria graminea*), creeping Buttercup (*Ranunculus repens*), perennial Rye-grass (*Lolium perrene*), Mugwort (*Artemisia vulgaris*), curled Thistle (*Carduus crispus*), northern Dock (*Rumex longifolius*), Narrow-leaved Meadow-Grass (*Poa angustifolia*), Silverweed (*Potentilla anserina*), white Clover (*Trifolium repens*), common Dandelion (*Taraxacum officinale*), zigzag Clover (*Trifolium medium*), alsike Clover (*Trifolium hybridum*), common Bent (*Agrostis tenuis*), annual Meadow-grass (*Poa annua*), field Bindweed (*Convolvulus arvensis*), Redshank (*Persicaria maculosa*), common Chickweed (*Stellaria media*), tufted Vetch (*Vicia cracca*), Black-bindweed (*Fallopia convolvulus*), greater Plantain (*Plantago major*), perennial Sow-thistle (*Sonchus arvensis*), field Pansy (*Viola arvensis*), common Hemp-nettle (*Galeopsis tetrahit*), water Avens (*Geum rivale*), Shepherd's-purse (*Capsella bursa-pastoris*)
		GL_LV_6	The dominant plant functional group: graminoid (more detailed information is not available)
		GL_LV_7	The dominant plant functional group: graminoid (more detailed information is not available)
		GL_LV_8	The dominant plant functional group: forbs and graminoid (more detailed information is not available)
	Estonia	GL_EE_1	Listed by dominance, areal coverage: meadowsweet or mead wort (*Filipendula ulmaria*), meadow foxtail (*Alopecurus pratensis*), Canary grass (*Phalaris arundinacea*), geraniums (*Geranium* sp), ground elder (*Aegopodium podagraria*), buttercups (*Ranunculus* sp), water avens (*Geum rivale*)
		GL_EE_2	Listed by dominance, areal coverage: couch grass (*Elymus repens*), meadow foxtail (*Alopecurus pratensis*), tall fescue (*Lolium arundinaceum*), reed grass or smallweed (*Calamagrostis* sp), Cocksfoot (*Dactylis glomerata* L.)
		GL_EE_3	Listed by dominance, areal coverage: gabbage thistle (*Cirsium oleraceum*), meadowsweet or mead wort (*Filipendula ulmaria*), Canary grass (*Phalaris arundinacea*), common comfrey (*Symphytum officinale*), cleavers, clivers, catchweed, robin-run-the-hedge, goosegrass, and sticky willy (*Galium aparine*, *c* sp)
	Lithuania	GL_LT_1	Milk-parsley (*Peucedanum palustre* (L.) Moench), meadowsweet (*Filipendula ulmaria* (L.) Maxim.), common marsh bedstraw (*Galium palustre* L.), common couch (*Elymus repens* (L.) Gould), wild mint (*Mentha arvensis* L.), common nettle (*Urtica dioica* L.), and creeping bent grass (*Agrostis stolonifera* L.)

Table S3. Results of Spearman's rank correlation between mean instantaneous ecosystem respiration (R_{eco}) and different site and soil characteristics in cropland and grassland (ρ value, p value). Statistically significant correlations ($p < 0.050$) are highlighted in bold.

Land use	Cropland			Grassland		
Site characteristics						
Thickness of organic soil layer (mean)	-0.43, 0.092			0.01, 0.939		
Water-table level (mean)	0.08, 0.775			-0.33, 0.075		
Soil characteristics						
Soil layer	**0-20 cm**	**20-40 cm**	**40-80 cm**	**0-20 cm**	**20-40 cm**	**40-80 cm**
TC	-0.48, 0.097	-0.49, 0.089	0.05, 0.892	0.13, 0.492	0.11, 0.553	0.14, 0.501
OC	-0.48, 0.097	-0.49, 0.089	0.05, 0.892	0.11, 0.579	0.11, 0.577	0.10, 0.649
TN	-0.49, 0.089	-0.42, 0.157	0.07, 0.865	0.15, 0.435	0.06, 0.740	0.13, 0.524
C/N	0.10, 0.737	-0.47, 0.110	-0.26, 0.470	-0.15, 0.435	0.10, 0.603	0.23, 0.268
pH	0.43, 0.146	-0.12, 0.696	-0.45, 0.191	-0.06, 0.761	0.05, 0.803	0.04, 0.864
K	**0.78, 0.003**	0.52, 0.074	0.25, 0.492	0.16, 0.384	0.13, 0.508	0.05, 0.795
Ca	**-0.94, <0.001**	**-0.93, <0.001**	-0.31, 0.387	0.07, 0.728	-0.04, 0.829	0.01, 0.958
Mg	**0.59, 0.036**	0.44, 0.135	0.08, 0.838	0.10, 0.587	0.04, 0.831	0.18, 0.396
P	-0.33, 0.272	0.11, 0.723	0.16, 0.657	0.11, 0.567	0.07, 0.714	0.06, 0.781
Bulk density	0.54, 0.061	0.16, 0.604	-0.02, 0.973	-0.15, 0.418	-0.03, 0.866	-0.09, 0.673

Table S4. Results of the PLS regression analyses explaining the variation in mean instantaneous Reco among study sites in cropland depending on the soil physico-chemical variables (VIP values > 0.5 in decreasing order, statistics of regression coefficients).

Soil physico-chemical variable, soil layer	VIP value	Regression coefficients		
		Coefficient	SE	p-value
Ca, 0-20 cm	1.92	-0.109	0.0329	0.006
Ca, 20-40 cm	1.81	-0.103	0.0295	0.005
K, 0-20 cm	1.42	0.0806	0.0221	0.004
K, 20-40 cm	1.21	0.0690	0.0150	0.001
Mg, 0-20 cm	0.91	0.0521	0.0174	0.012
TC, 0-20 cm	0.91	-0.0517	0.0143	0.004
Bulk density, 0-20 cm	0.81	0.0460	0.0114	0.002
Mg, 20-40 cm	0.79	0.0451	0.0254	0.108
TN, 0-20 cm	0.76	-0.0430	0.0161	0.022
TC, 20-40 cm	0.67	-0.0382	0.0169	0.045
OC, 0-20 cm	0.66	-0.0374	0.0190	0.075
P, 20-40 cm	0.66	0.0376	0.0290	0.218
TN, 20-40 cm	0.64	-0.0364	0.0184	0.074
Thickness of organic soil layer	0.62	-0.0355	0.0274	0.221
OC, 20-40 cm	0.57	-0.0324	0.0185	0.110
pH, 0-20 cm	0.56	0.0318	0.0321	0.349
C/N, 20-40 cm	0.54	-0.0306	0.0396	0.439

Table S5. Mean carbon (C) and nitrogen (N) concentration and C/N ratio in above- and belowground plant biomass in the studied croplands and grasslands.

Type of land use, vegetation	Value	C concentration, g kg^{-1}		N concentration, g kg^{-1}		C/N ratio	
		Aboveground	Belowground	Aboveground	Belowground	Aboveground	Belowground
Cropland, arable crops (n=10)	Mean ± S.E.	450 ± 4	404 ± 4	17 ± 2	11 ± 1	29 ± 3	40 ± 4
	Median	449	414	17	9	28	44
	Range	431–473	383–414	11–26	8–18	19–42	22–51
Grassland, perennial grass (n=12)	Mean ± S.E.	449 ± 2	407 ± 16	20 ± 2	16 ± 2	25 ± 2	28 ± 2
	Median	447	402	18	16	26	26
	Range	442–463	347–484	13–30	10–24	15–34	20–36

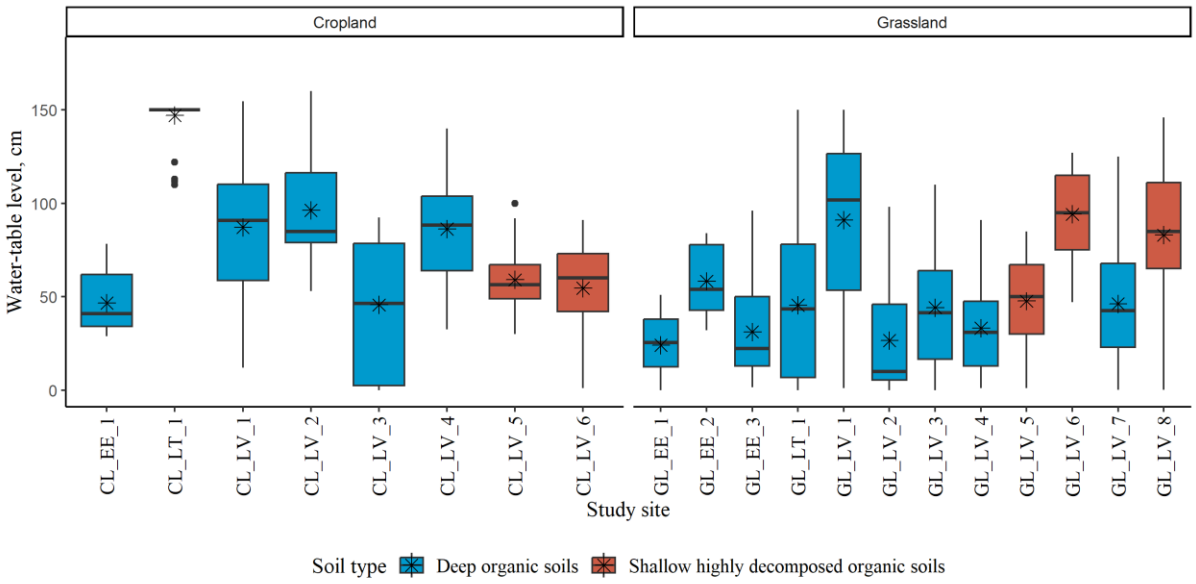

Figure S1: Variation in water-table level in the study sites in cropland (left graph) and grassland (right graph). The boxes indicate the interquartile range (from 25th to 75th percentiles), the bold horizontal line in the boxes shows median value, asterisks show mean values, the whiskers denote the minimum and maximums values, black dots show outliers.

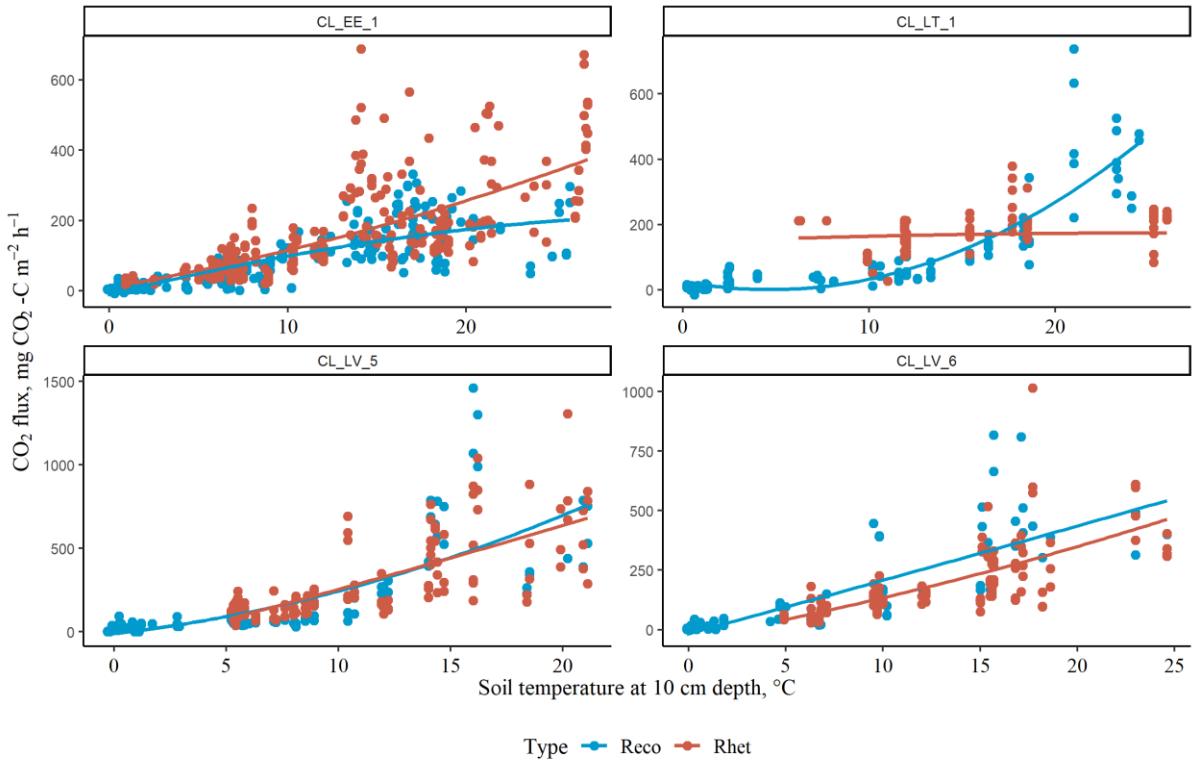

Figure S2: Comparison of instantaneous ecosystem respiration (R_{eco}) and heterotrophic respiration (R_{het}) as a polynomial function of a soil temperature at 10 cm depth in cropland.

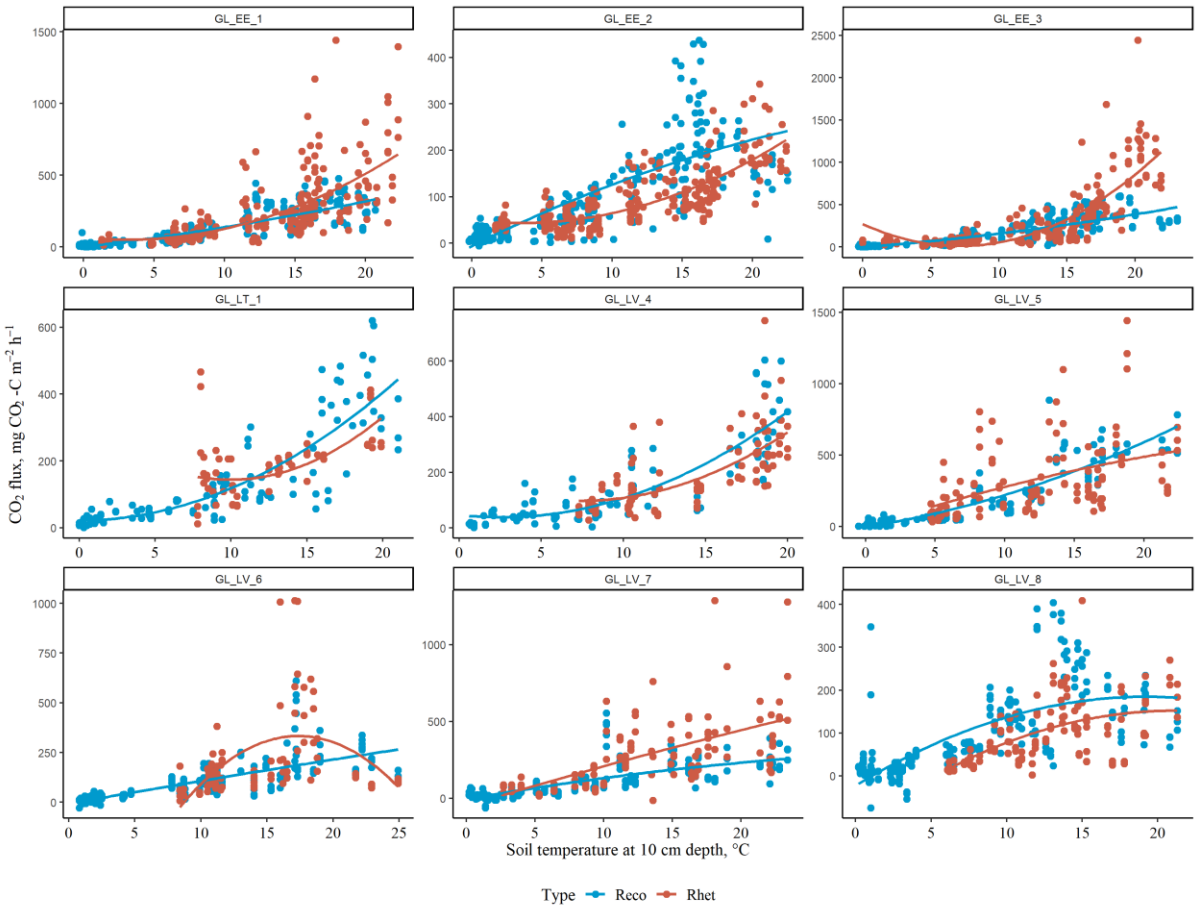

Figure S3: Comparison of instantaneous ecosystem respiration (R_{eco}) and heterotrophic respiration (R_{het}) as a polynomial function of a soil temperature at 10 cm depth in grassland.

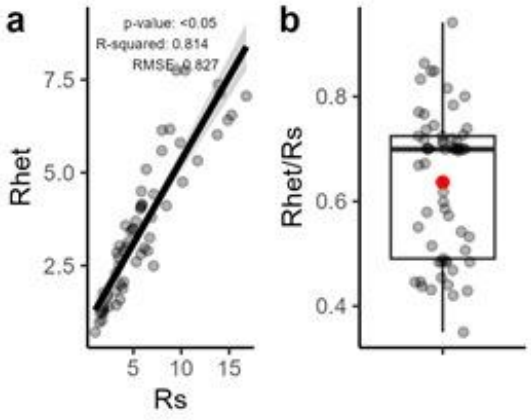

Figure S4: Relationship (a) between soil heterotrophic respiration (R_{het}) and soil surface respiration (R_s) and variation in R_{het}/R_s ratios (b); results of previous studies (n = 61) conducted in temperate and boreal regions (Jian et al., 2021). The interquartile range of the R_{het}/R_s from previous studies is 0.49 to 0.72. However, in all our study sites, we used a consistent approach with a fixed conversion coefficient of 0.64. This decision is based on observations from research (n = 61) that show a linear relationship (R^2 = 0.81) between R_{het} and R_s (t CO_2-C ha^{-1} $year^{-1}$), regardless of the inclusion of agricultural vegetation (n = 22) and soil type (n = 17) in the data set. The confidence interval for this coefficient is 0.04 around the mean of 0.64, which is less than 6 %, thereby ensuring acceptable calculation accuracy.

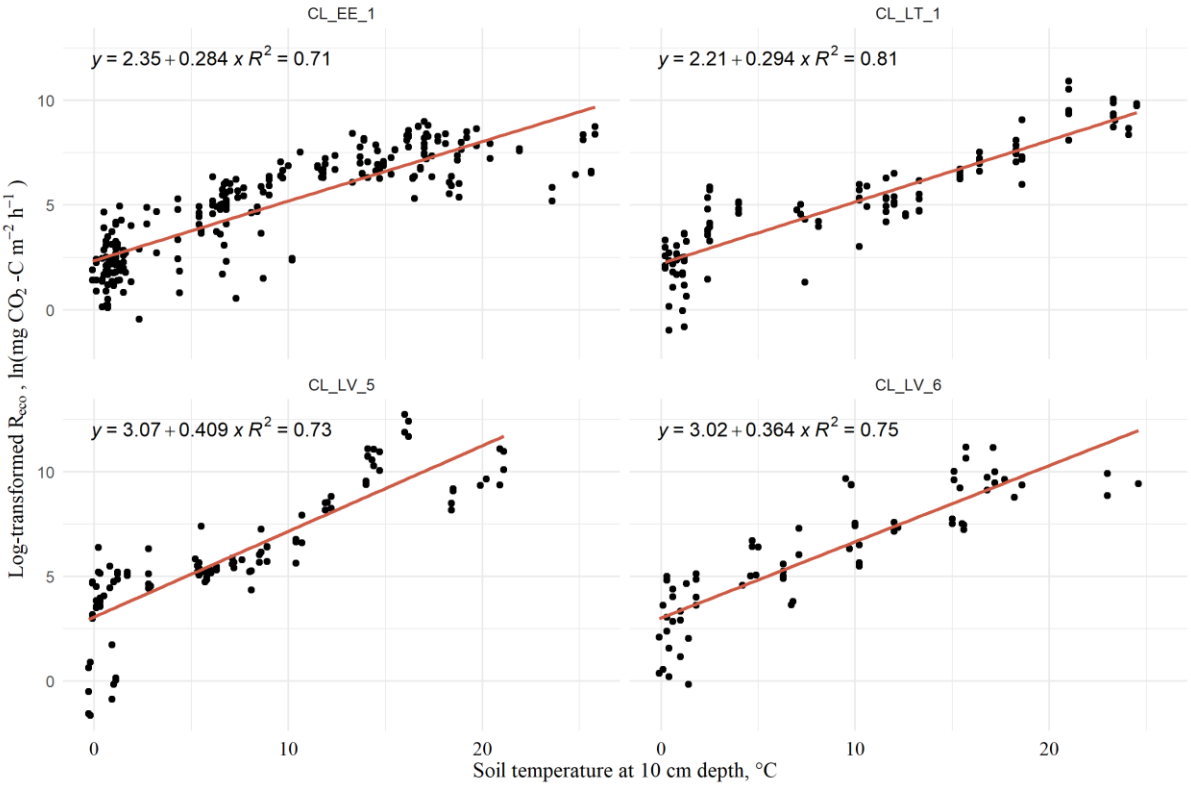

Figure S5: The relationship between log-transformed instantaneous ecosystem respiration (R_{eco}) and soil temperature at 10 cm depth in study sites in cropland.

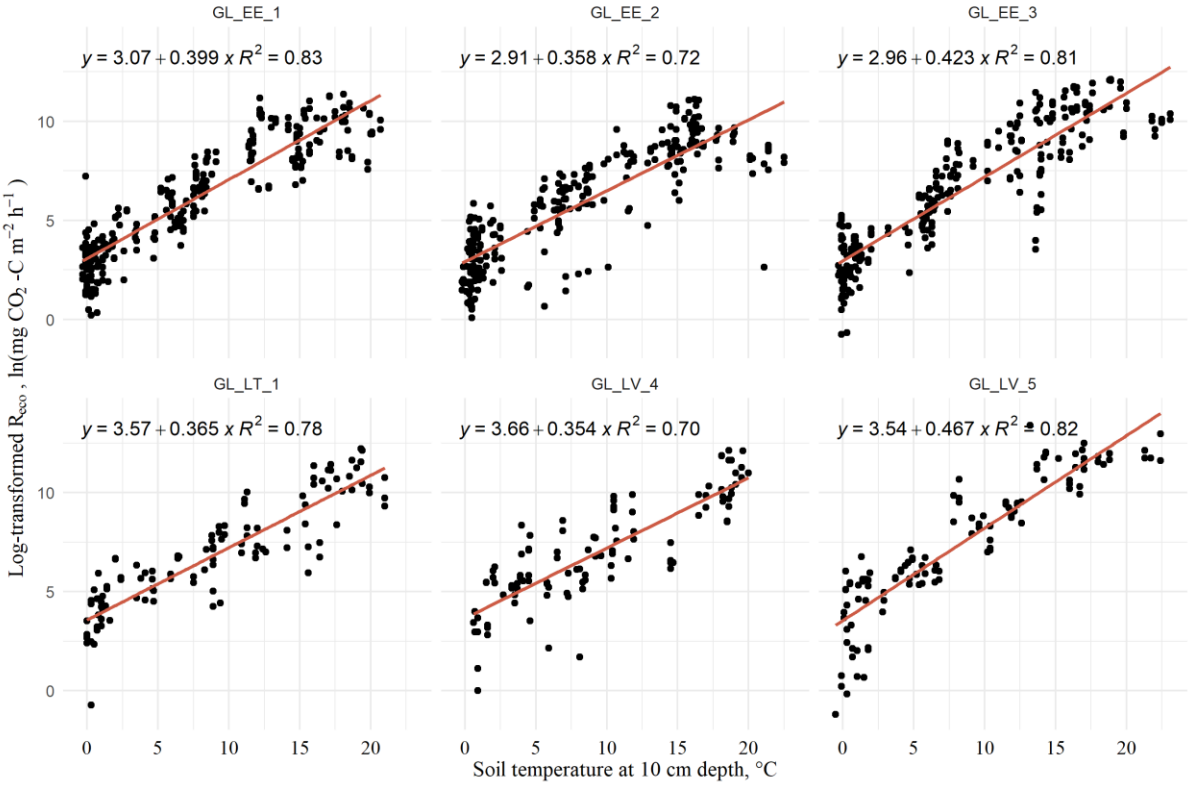

Figure S6: The relationship between log-transformed instantaneous ecosystem respiration (R_{eco}) and soil temperature at 10 cm depth in study sites in grassland.

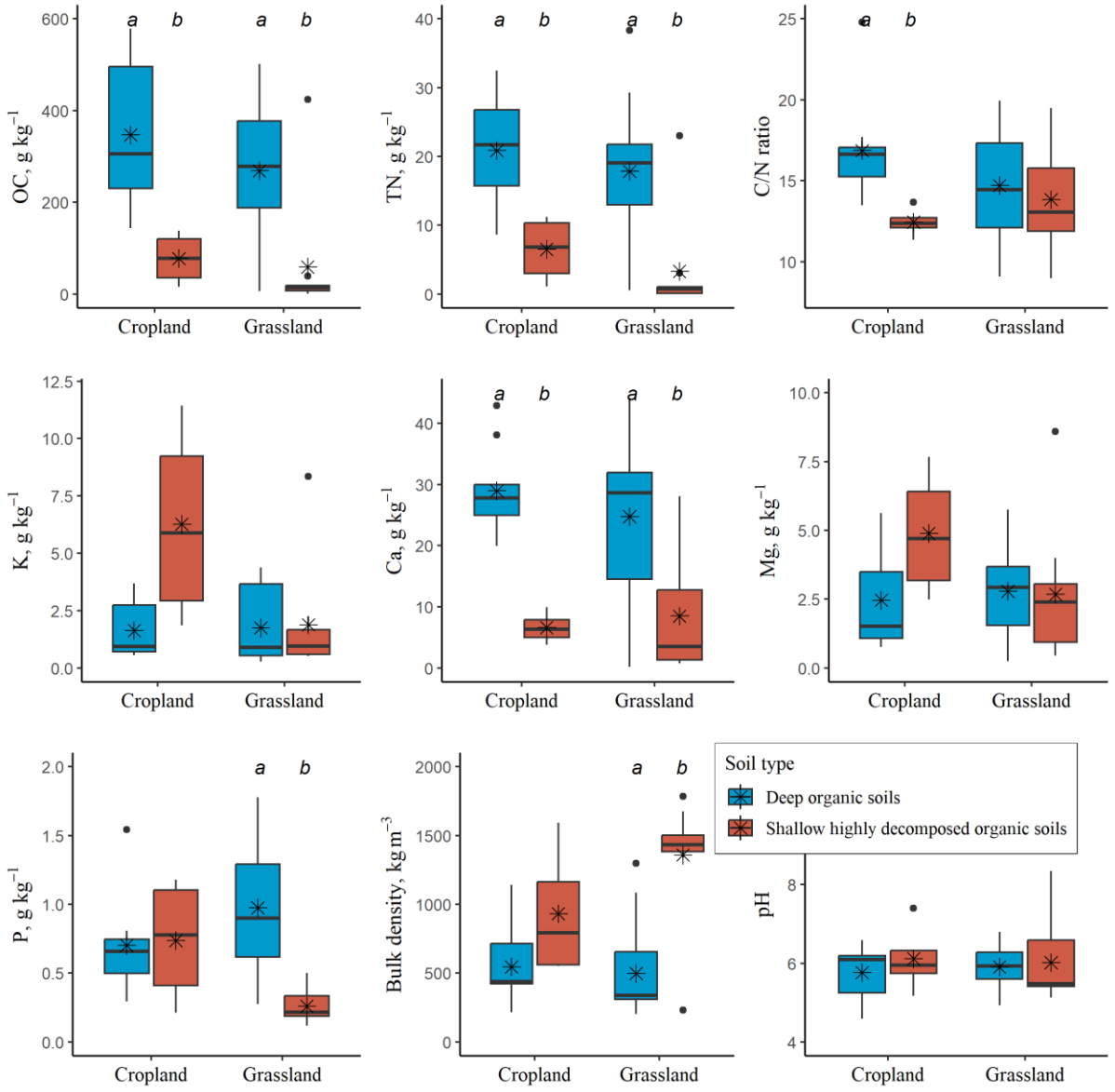

Figure S7: Variation in soil (20–40 cm soil layer) characteristics (organic carbon (OC), total nitrogen (TN), organic carbon/total nitrogen (C/N) ratio, HNO_3-extractable potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P) concentration, soil bulk density, soil pH) in the cropland and grassland sites, separately for the two soil types (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold horizontal lines and asterisks, respectively) are presented; plot mean values were used for analysis. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximum values, and the black dots show outliers. Statistically significant differences ($p < 0.05$, Wilcoxon rank sum exact test) between deep organic soil and shallow highly decomposed organic soil within the type of land use are denoted by lowercase letters a and b.

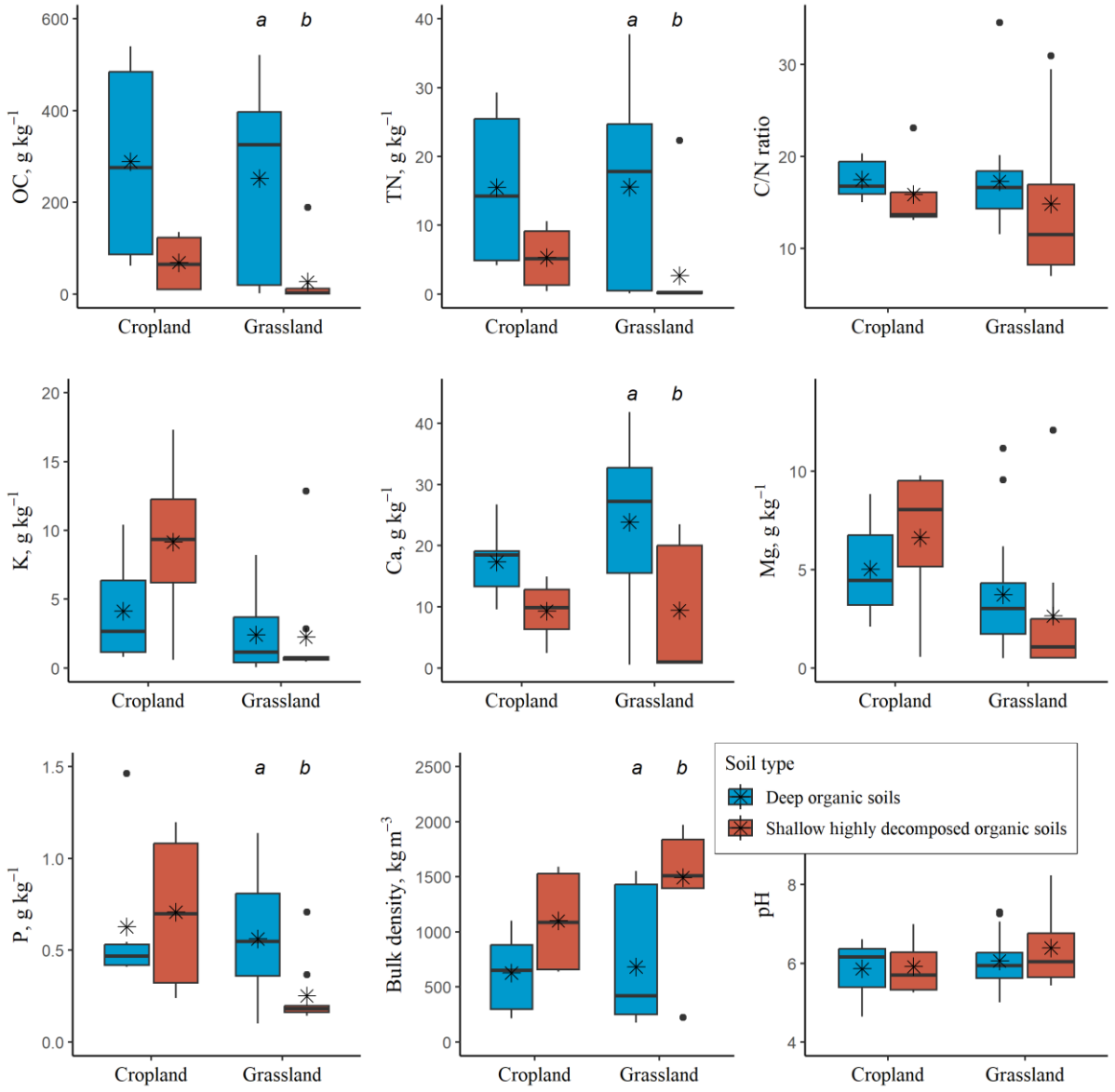

Figure S8: Variation in soil (40–80 cm soil layer) characteristics (organic carbon (OC), total nitrogen (TN), organic carbon/total nitrogen (C/N) ratio, HNO_3-extractable potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P) concentration, soil bulk density, soil pH) in the cropland and grassland sites, separately for the two soil types (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold horizontal lines and asterisks, respectively) are presented; plot mean values were used for analysis. The boxes indicate the interquartile range (from 25^{th} to 75^{th} percentiles), the whiskers denote the minimum and maximum values, and the black dots show outliers. Statistically significant differences ($p < 0.05$, Wilcoxon rank sum exact test) between deep organic soil and shallow highly decomposed organic soil within the type of land use are denoted by lowercase letters a and b.

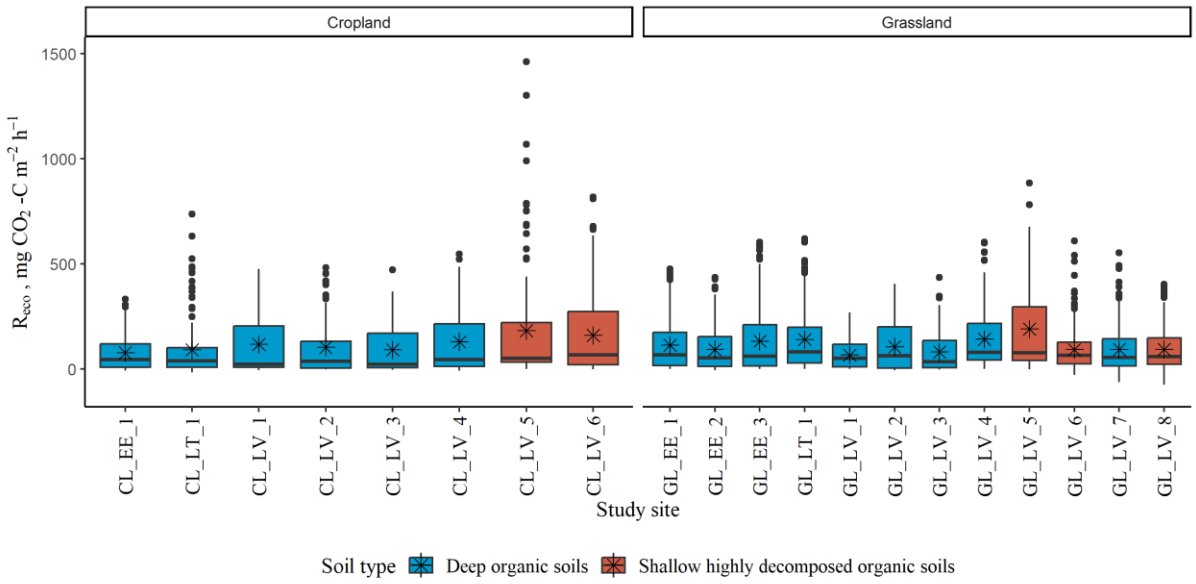

Figure S9: Variation in instantaneous ecosystem respiration (R_{eco}) in cropland (left graph) and grassland (right graph) among different study sites depending on soil type (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold lines and asterisks, respectively) calculated from all performed R_{eco} measurements. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximums values, black dots show outliers.

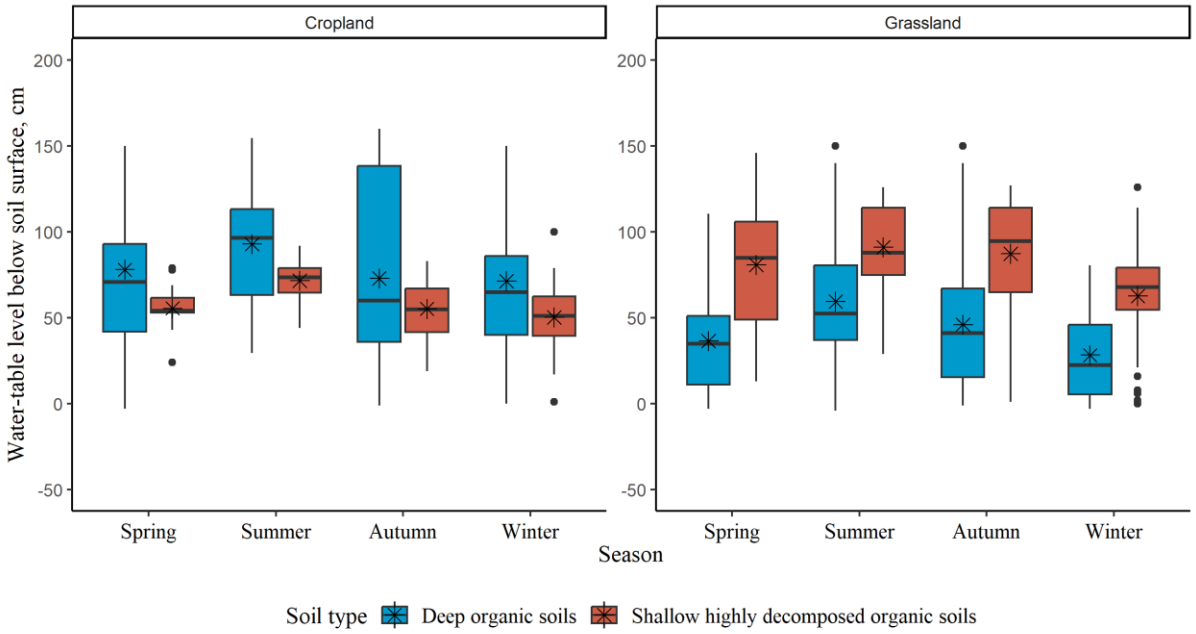

Figure S10: Variation in water-table level below soil surface in cropland (left graph) and grassland (right graph) among different seasons separately for the two soil types (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold lines and asterisks, respectively) calculated from all performed measurements are presented. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximums values, black dots show outliers.

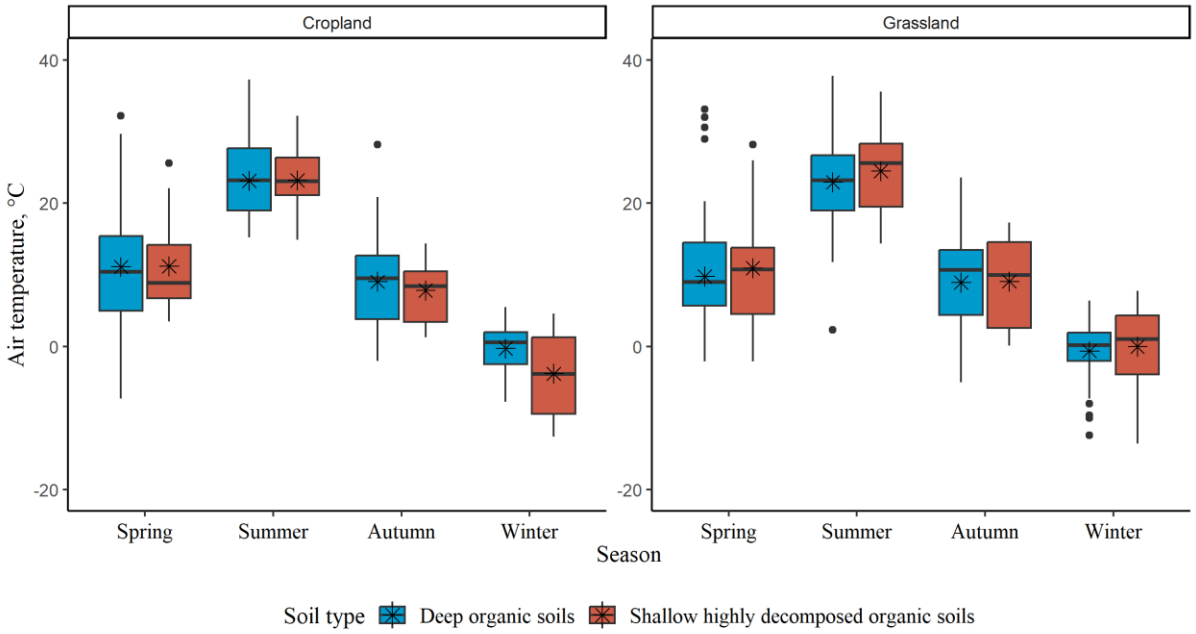

Figure S11: Variation in air temperature in cropland (left graph) and grassland (right graph) among different seasons separately for the two soil types (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold lines and asterisks, respectively) calculated from all performed measurements are presented. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximums values, black dots show outliers.

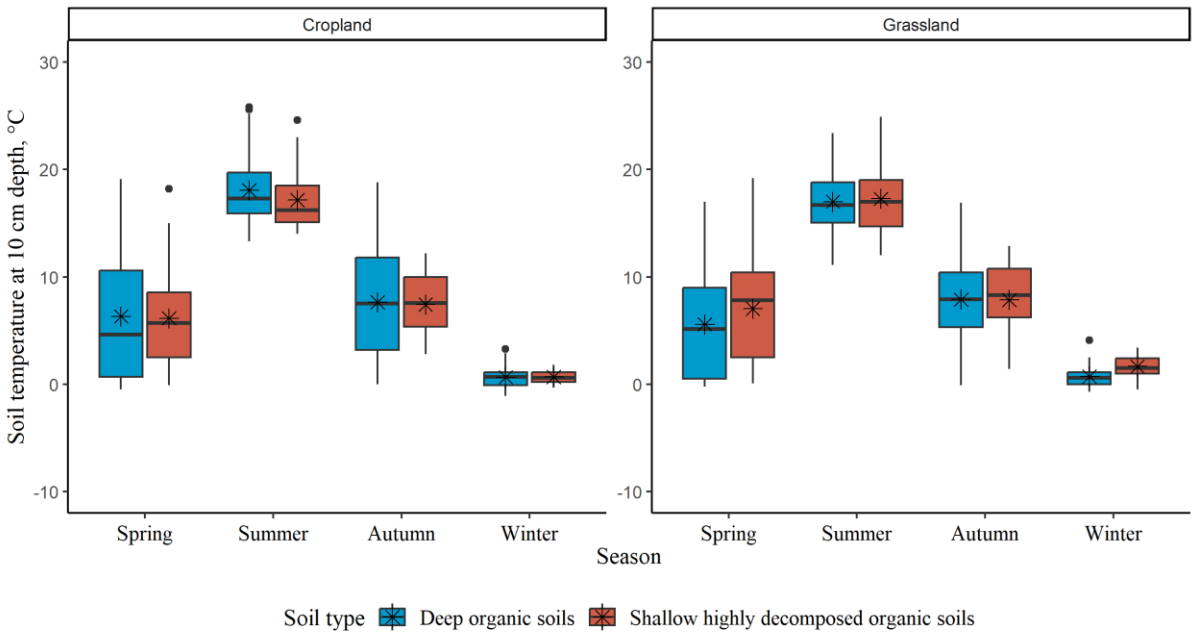

Figure S12: Variation in soil temperature at 10 cm depth in cropland (left graph) and grassland (right graph) among different seasons separately for the two soil types (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold lines and asterisks, respectively) calculated from all performed measurements are presented. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximums values, black dots show outliers.

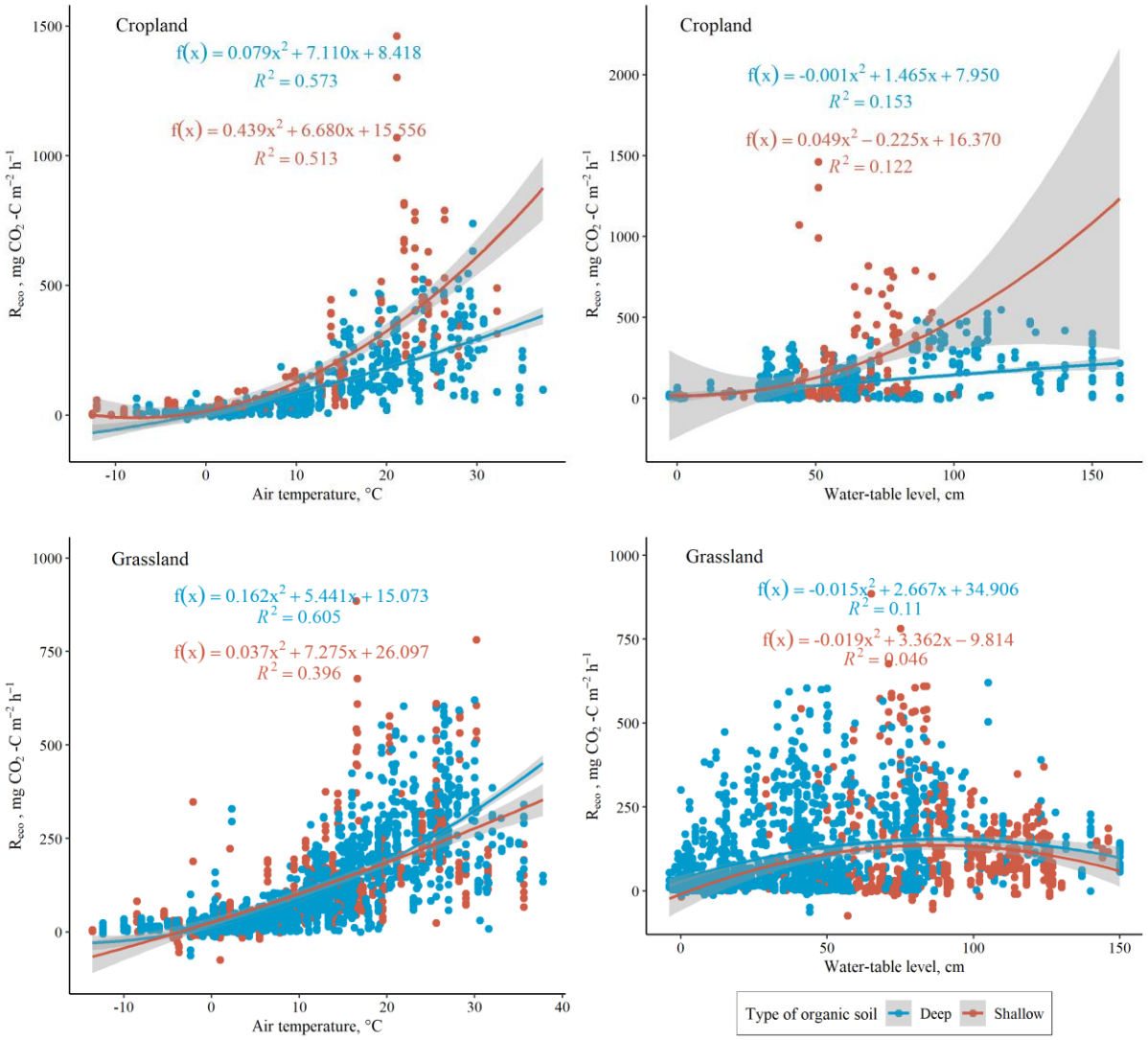

Figure S13: Instantaneous ecosystem respiration (R_{eco}) in cropland and grassland as a function (polynomial regression) of air temperature and water-table level measured during each gas sampling event. Data of instantaneous ecosystem respiration is grouped by soil type (deep organic soil denoted by blue colour and shallow highly decomposed organic soil denoted by red colour). Grey area around regression line reflects the 95% confidence interval of regression.

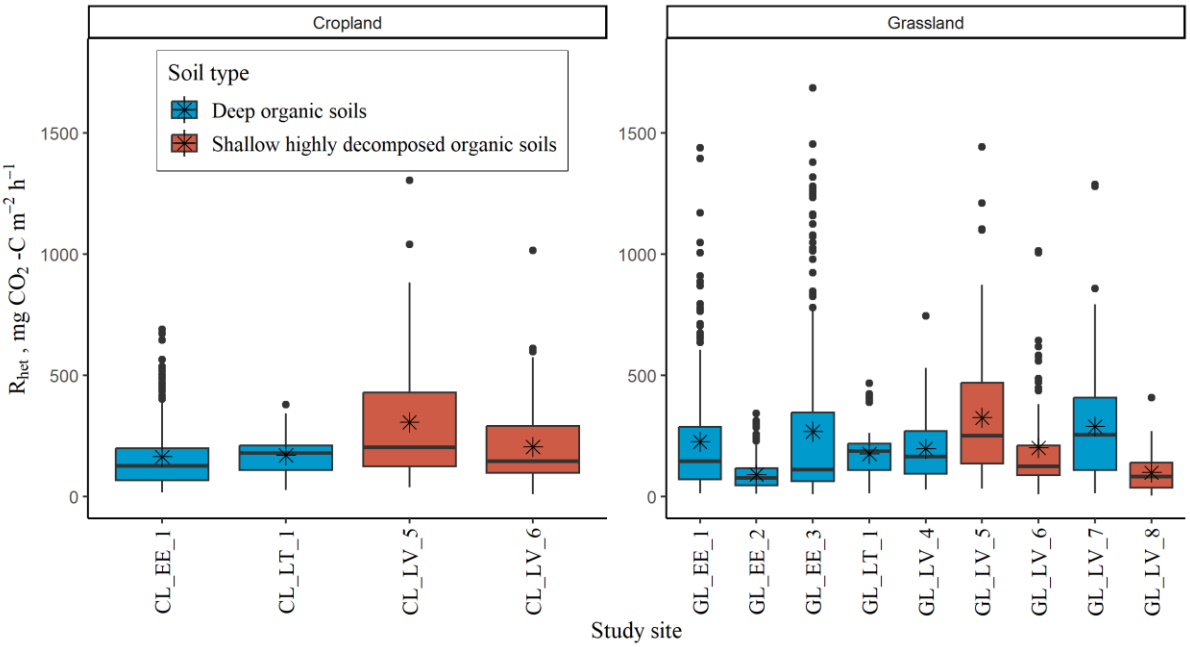

Figure S14: Variation in instantaneous soil heterotrophic respiration (R_{het}) in cropland (left graph) and grassland (right graph) from April to November among different study sites grouped depending on soil type (deep organic soil and shallow highly decomposed organic soil). In the boxplots, median and mean values (bold lines and asterisks, respectively) calculated from all performed R_{het} measurements in four study sites in cropland and nine study sites in grassland are presented. The boxes indicate the interquartile range (from 25th to 75th percentiles), the whiskers denote the minimum and maximums values, black dots show outliers.

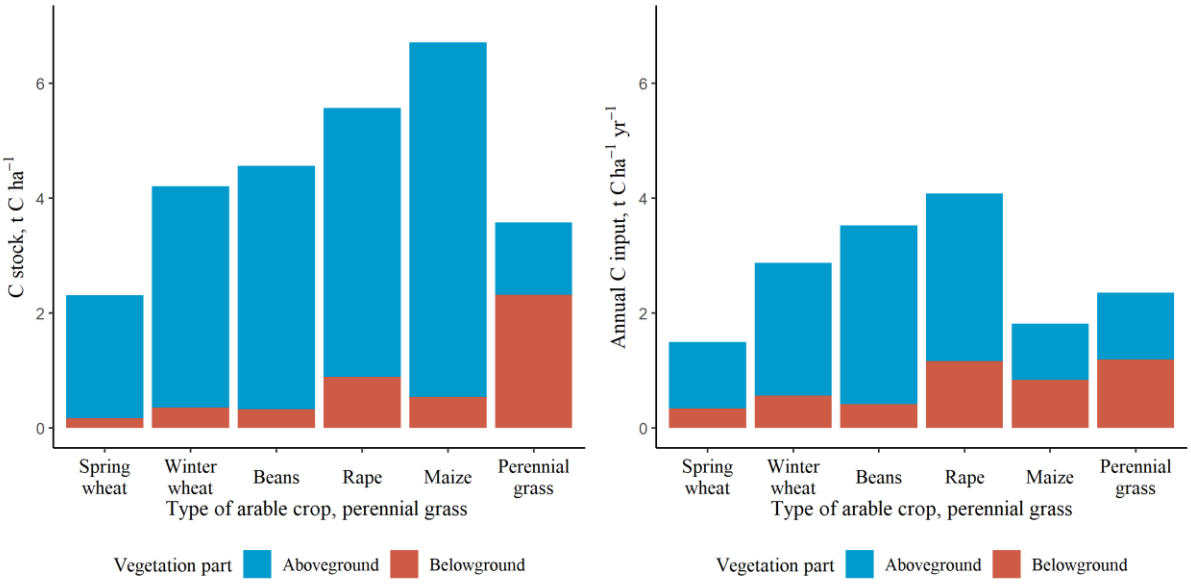

Figure S15: Variation in carbon stock in above- and belowground biomass of vegetation (left graph) and annual carbon input into soil by type of arable crop/perennial grass (right graph).

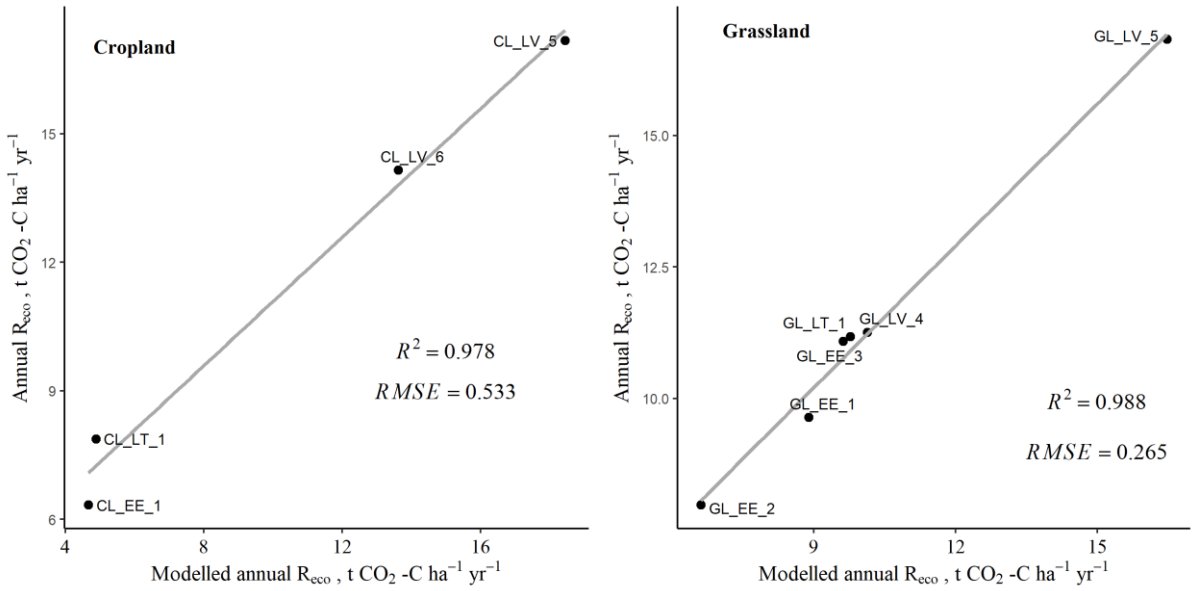

Figure S16: The comparison of estimated annual R_{eco} with the modeled annual R_{eco} based on continuous soil temperature measurements at depths of 10 cm at four study sites in cropland and six study sites in grassland.

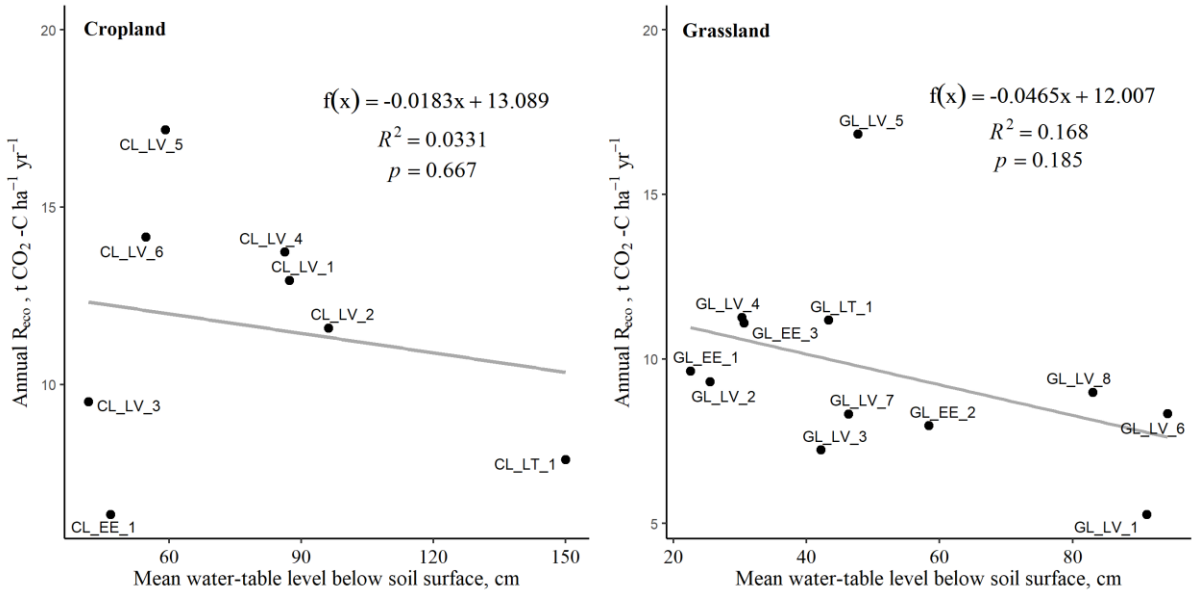

Figure S17: The relationship between annual R_{eco} and mean water-table level in study sites in cropland (left graph) and grassland (right graph).

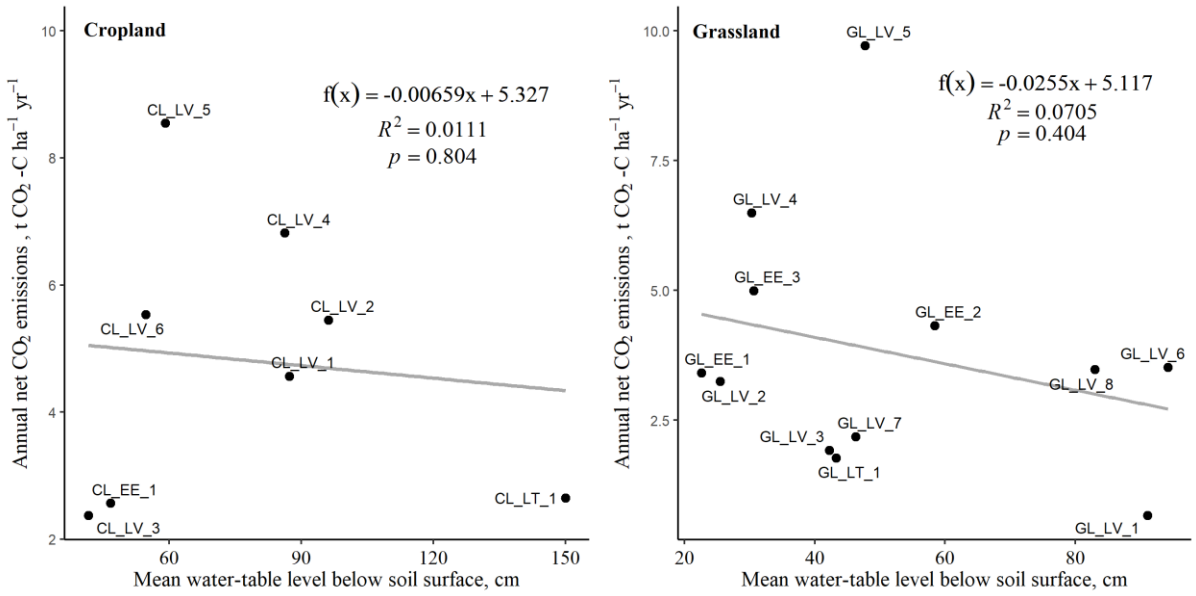

Figure S18: The relationship between annual net soil CO_2 emissions and mean water-table level in study sites in cropland (left graph) and grassland (right graph).