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Relative increases in CH_4 and CO_2 emissions from wetlands under global warming dependent on soil carbon substrates

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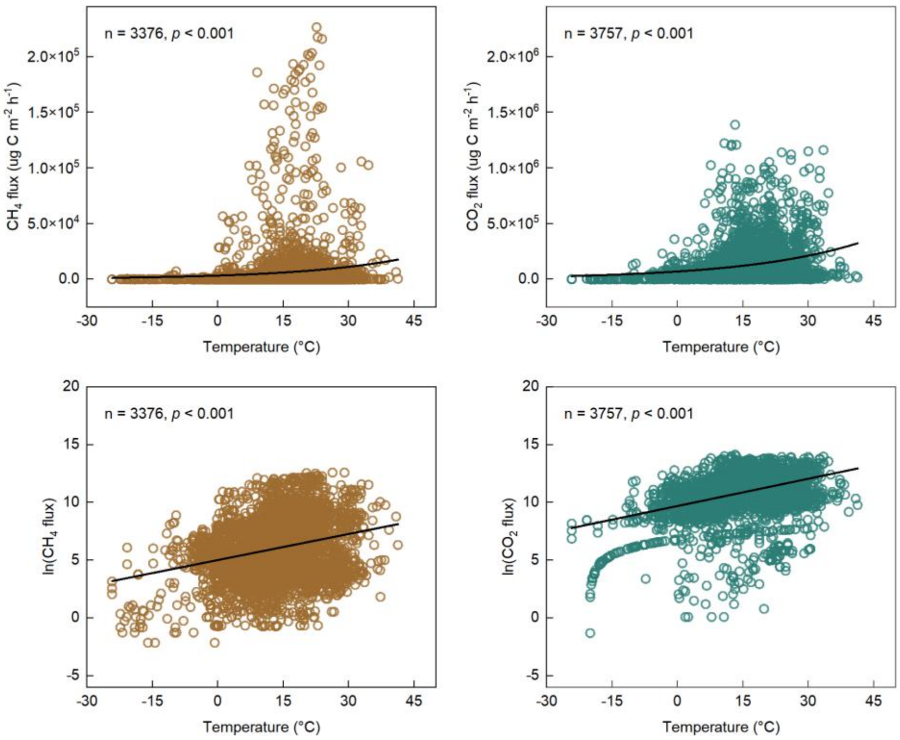
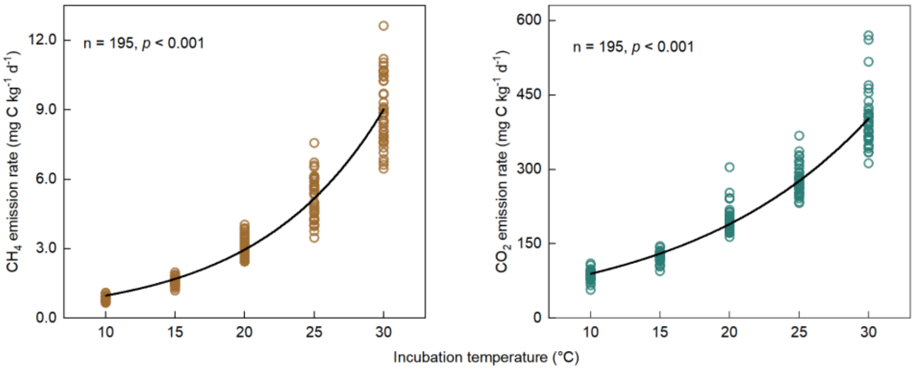
Supplementary Information

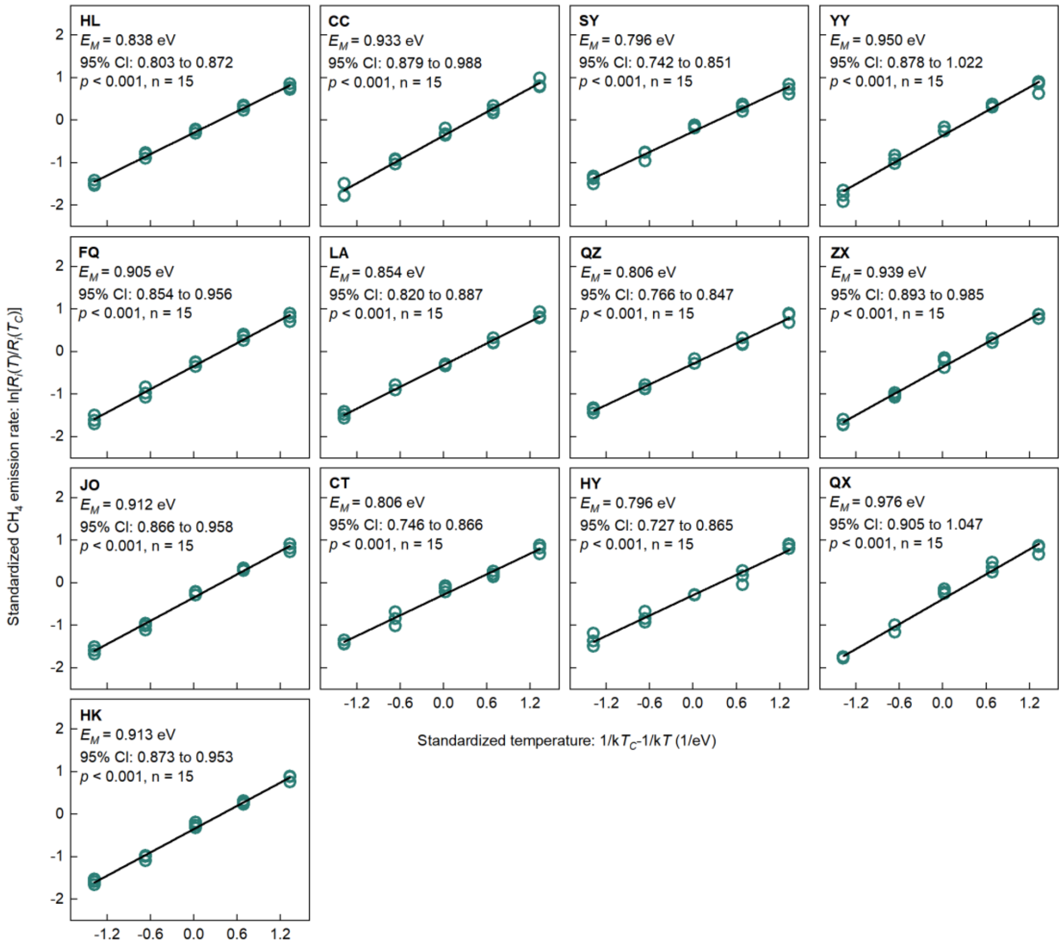
Supplementary Figures



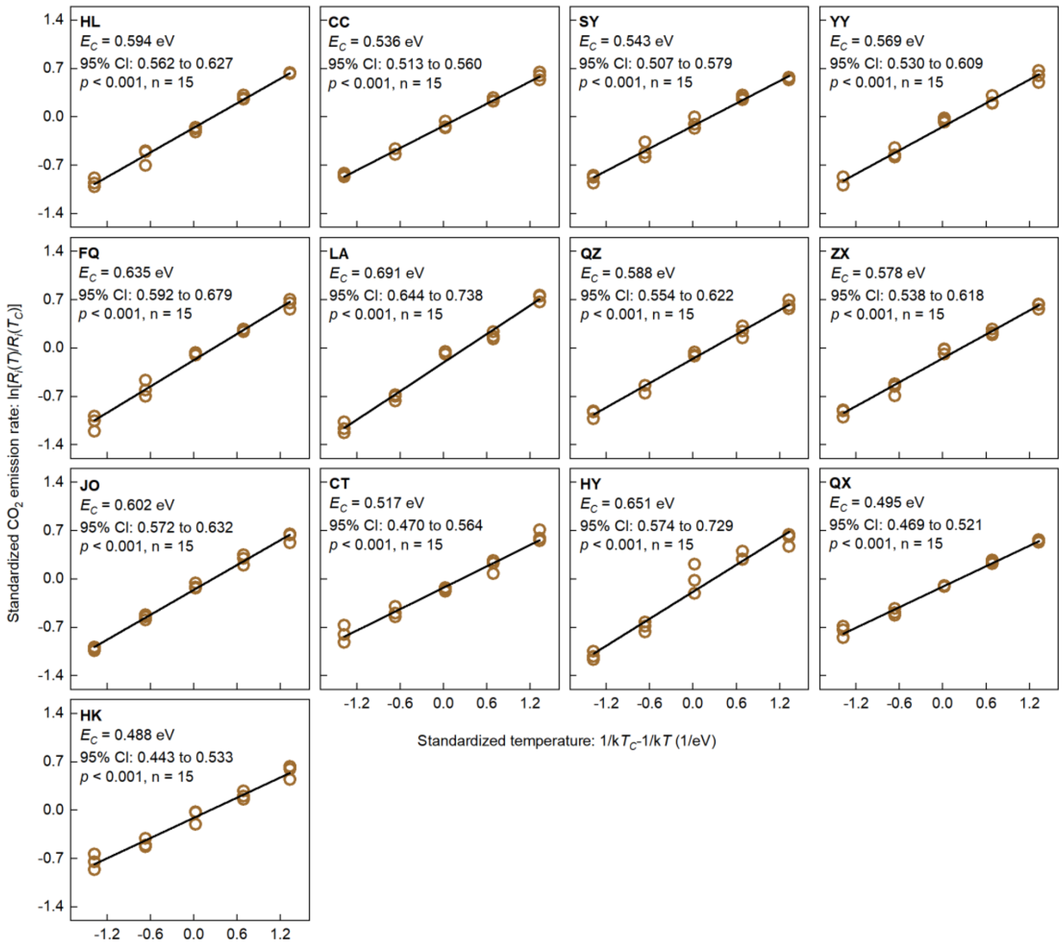
Supplementary Fig. 1. Exponential relationship between wetland CO_2 and CH_4 emission rates and seasonal temperature in the global database. The temperature on the x-axis indicates the soil temperature when measuring the carbon emission rate. The regression lines represent the fitted emission-temperature exponential and linear relationships. n represents the number of samples.



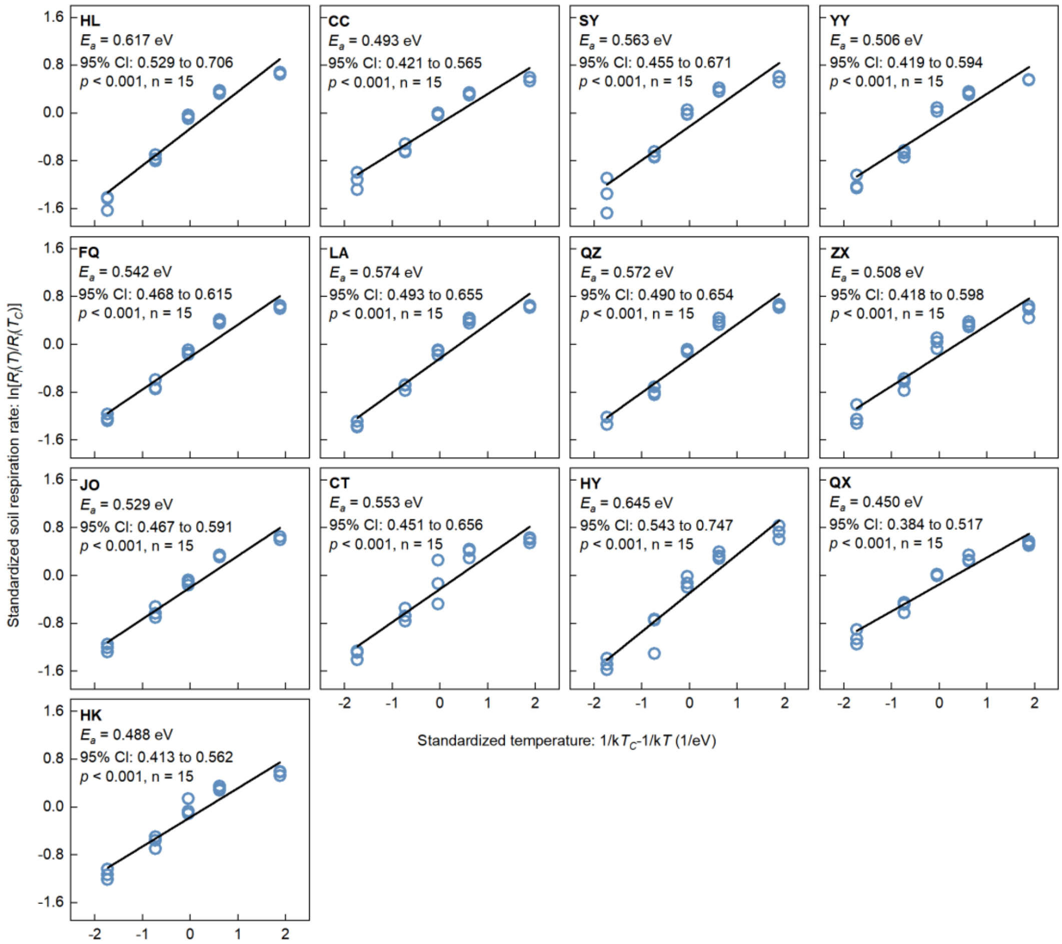
Supplementary Fig. 2. Exponential relationship between wetland CO_2 and CH_4 emission rates and temperature in the incubation experiment. The regression curves represent the fitted emission-temperature exponential relationships. Their significant exponential relationship indicates that the data in our incubation experiment fit the Boltzmann-Arrhenius function well. * represents a significant fit at the level of $p < 0.05$. n represents the number of samples.



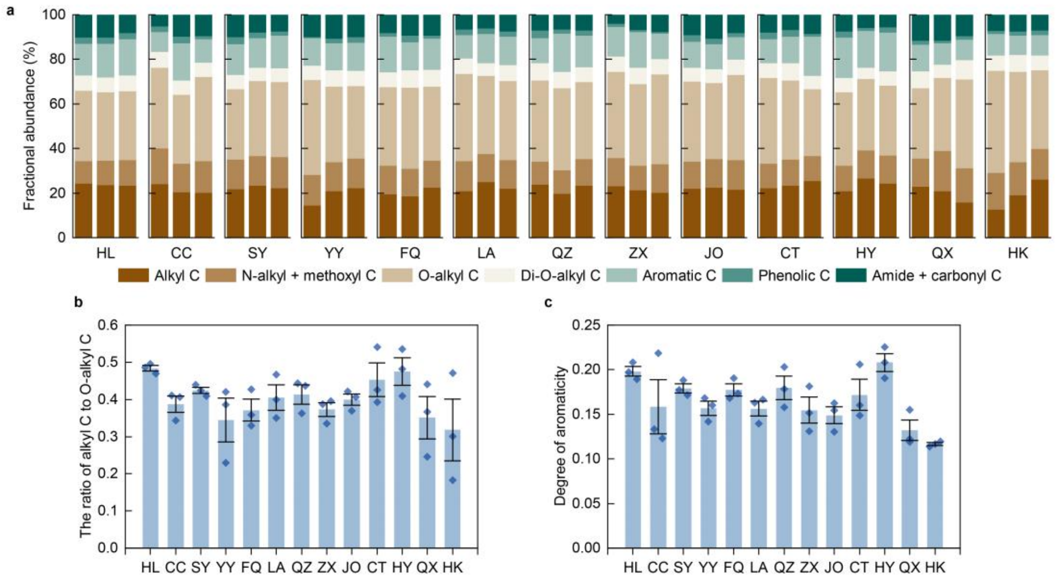
Supplementary Fig. 3. Apparent activation energy of wetland CH_4 emissions (E_M) of 13 regions in the incubation experiment. CH_4 emissions were measured by anaerobic incubation of soil at 10, 15, 20, 25, and 30 °C (n = 3). The temperature dependence of the CH_4 emissions was characterized using the linear mixed effects model after fitting the Boltzmann-Arrhenius function to the data of the CH_4 emission and the standardized temperature (Methods).



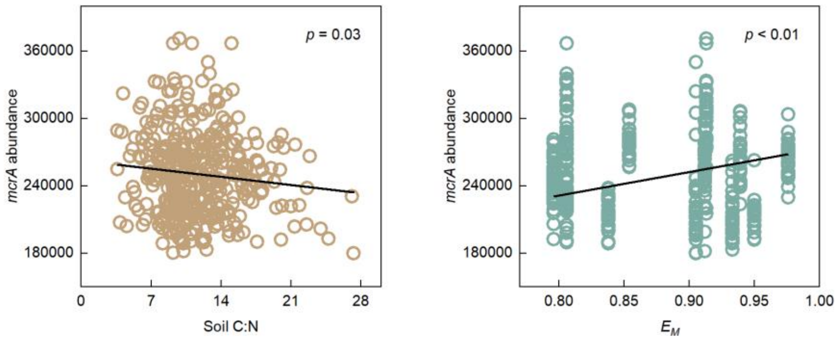
Supplementary Fig. 4. Apparent activation energy of wetland CO_2 emissions (E_C) of 13 regions in the incubation experiment. CO_2 emissions were measured by anaerobic incubation of soil at 10, 15, 20, 25, and 30 °C (n = 3). The temperature dependence of the CO_2 emissions was characterized using the linear mixed effects model after fitting the Boltzmann-Arrhenius function to the data of the CO_2 emission and the standardized temperature (Methods).



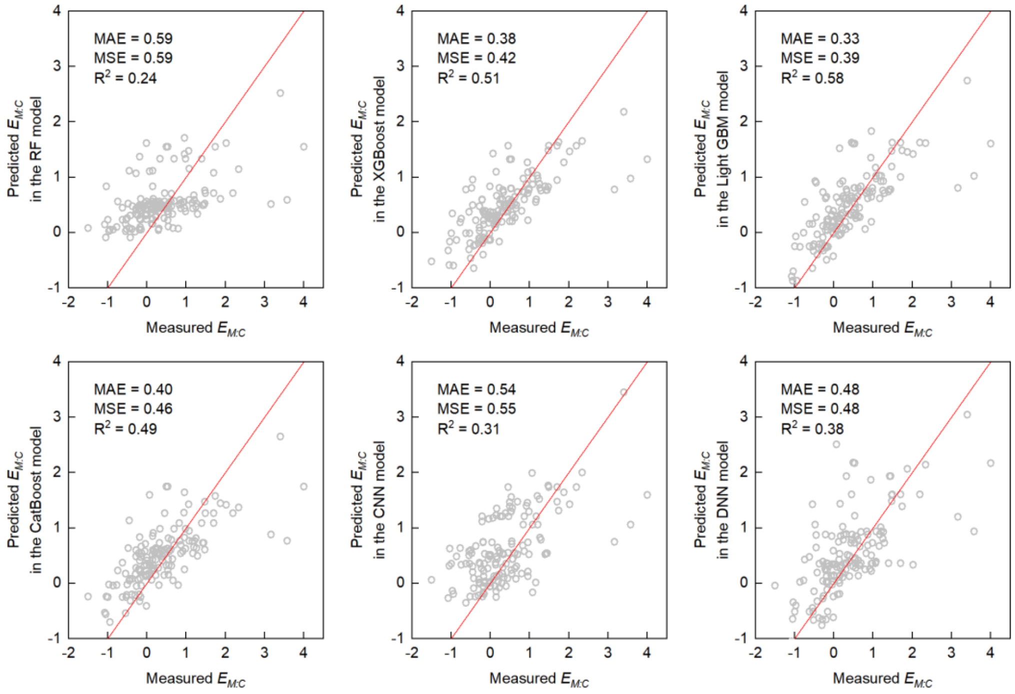
Supplementary Fig. 5. Apparent activation energy (E_a) of soil organic matter (SOM) decomposition in 13 regions in the incubation experiment. The value of E_a is characterized by the temperature dependence of the CO_2 emissions by the decomposition of SOM under aerobic conditions. CO_2 emissions were measured by aerobic incubation of soil at 8, 15, 20, 25 and 35 °C (n = 3). The temperature dependence of the CO_2 emissions was characterized using the linear mixed effects model after fitting the Boltzmann-Arrhenius function to the data of the CO_2 emission and the standardized temperature (Methods).



Supplementary Fig. 6. Relative abundance of functional groups (a), ratio of alkyl carbon to alkoxy carbon (b), and the degree of aromaticity (c) of soil organic matter (SOM) from 13 regions in the incubation experiment. The relative abundance of SOM functional groups was determined by the peak area of ^{13}C cross-polarization magic-angle-spinning nuclear magnetic resonance spectroscopy. After baseline correction, we quantified seven chemical shift regions of the spectrum: 0-45 ppm, 45-60 ppm, 60-95 ppm, 95-110 ppm, 110-145 ppm, 145-160 ppm and 160-220 ppm, assigned to alkyl C, N-alkyl + methoxyl C, O-alkyl C, Di-O-alkyl C, aromatic C, phenolic C, and amide + carbonyl C, respectively. Three columns in the same area indicate replication. HL = Hailun; CC = Changchun; SY = Shenyang; YY = Yuanyang; FQ = Fengqiu; LA = Lin'an; QZ = Quzhou; ZX = Zixi; JO = Jian'ou; CT = Changting; HY = Hengyang; QX = Qingxin; HK = Haikou. **b,** The centre line and error bars are the mean values and standard error, respectively (n = 3). Ratio of alkyl carbon to alkoxy carbon = alkyl C/(O-alkyl C+ N-alkyl + methoxyl C+ Di-O-alkyl C). **c,** The centre line and error bars are the mean values and standard error, respectively (n = 3). The degree of aromaticity = aromatic C + phenolic C/[1- (amide + carbonyl C)].



Supplementary Fig. 7. The linear relationship between the abundance of the *mcrA* gene and soil C:N (a) and the apparent activation energy (E_M) of CH_4 emissions (b). The *mcrA* gene is a key gene in the methanogenic metabolic pathway. The higher abundance of the *mcrA* gene indicates a stronger potential for methane production.



Supplementary Fig. 8. Prediction performance of the random forest (RF) model, extreme gradient boosting (XGBoost) model, light gradient boosting machine (Light GBM) model, gradient boosting decision trees (CatBoost) model, convolutional neural networks (CNN) model, and deep neural networks (DNN) model. The red line represents the 1:1 line. MAE represents the mean absolute error, MSE is the mean-square error, and R^2 represents the coefficient of determination. The optimal model is characterized by the maximum R^2 and the minimum MAE and MSE.

Supplementary Table 1. Comparison among linear mixed effect models with different random effects.

Formula	AIC		
	CH_4 emissions	CO_2 emissions	CH_4:CO_2
R ~ T	11350.52	8083.31	10014.68
R ~ T + (1|site)	10881.23	7412.69	9872.52
R ~ T + (0+T|site)	11225.67	7571.00	9977.75
R ~ T + (1+T|site)	**10748.48**	**6831.14**	**9814.35**

AIC, information-theoretic Akaike information criterion. R is the standardized greenhouse gas. T is the fixed effect, and site is the random effect. (1|site), (0+T|site), and (1+T|site) are the random effects of site on intercept only, on slope only, and on both intercept and slope, respectively. Bold text indicates the model with the minimal AIC.

Supplementary Table 2. Sliding window analysis for the temperature dependence of wetland CO_2 and CH_4 emission ratio ($E_{M:C}$) with a step length of 1 in the global database.

Soil C:N interval	n/site	p for LME model	$E_{M:C}$	Soil C:N interval	n/site	p for LME model	$E_{M:C}$
≤ 1	43/4	0.006	*NS*	**> 1**	2979/155	0.193	*NS*
≤ 2	103/5	0.006	*NS*	**> 2**	2919/154	0.22	*NS*
≤ 3	103/5	0.006	*NS*	**> 3**	2919/154	0.220	*NS*
≤ 4	103/5	0.006	*NS*	**> 4**	2919/154	0.220	*NS*
≤ 5	103/5	0.215	*NS*	**> 5**	2919/154	0.220	*NS*
≤ 6	175/13	0.285	*NS*	**> 6**	2847/146	0.231	*NS*
≤ 7	203/17	0.125	*NS*	**> 7**	2819/142	0.200	*NS*
≤ 8	251/21	**0.006**	0.278	**> 8**	2771/138	0.290	*NS*
≤ 9	444/27	**< 0.001**	0.265	**> 9**	2578/132	0.721	*NS*
≤ 10	956/48	**< 0.001**	0.215	**> 10**	2066/113	0.240	*NS*
≤ 11	1203/65	**< 0.001**	0.198	**> 11**	1819/97	0.218	*NS*
≤ 12	1514/80	**< 0.001**	0.190	**> 12**	1508/82	**0.023**	-0.128
≤ 13	1866/88	**< 0.001**	0.184	**> 13**	1156/73	**0.007**	-0.172
≤ 14	1994/95	**< 0.001**	0.177	**> 14**	1028/65	**0.005**	-0.204
≤ 15	2044/99	**< 0.001**	0.158	**> 15**	978/61	**0.002**	-0.229
≤ 16	2159/106	**0.005**	0.112	**> 16**	863/54	**0.003**	-0.248
≤ 17	2318/121	**0.004**	0.113	**> 17**	704/39	**0.019**	-0.219
≤ 18	2328/121	**0.003**	0.117	**> 18**	694/39	**0.017**	-0.222
≤ 19	2355/124	**0.004**	0.118	**> 19**	667/36	**0.026**	-0.217
≤ 20	2469/129	**0.004**	0.115	**> 20**	553/32	**0.005**	-0.228
≤ 21	2476/130	**0.034**	0.083	**> 21**	546/31	**0.006**	-0.229
≤ 22	2598/137	**0.031**	0.086	**> 22**	424/24	0.055	*NS*
≤ 23	2648/140	0.053	*NS*	**> 23**	374/21	**0.013**	-0.139
≤ 24	2693/143	0.054	*NS*	**> 24**	329/17	0.115	*NS*
≤ 25	2705/144	0.055	*NS*	**> 25**	317/16	0.136	*NS*
≤ 26	2723/145	0.063	*NS*	**> 26**	299/14	0.119	*NS*
≤ 27	2773/147	0.063	*NS*	**> 27**	249/12	0.062	*NS*
≤ 28	2773/147	0.075	*NS*	**> 28**	249/12	0.062	*NS*
≤ 29	2818/148	0.068	*NS*	**> 29**	204/11	0.205	*NS*
≤ 30	2850/150	0.006	*NS*	**> 30**	172/9	**0.038**	-0.200

LME model, linear mixed-effects model; NA, not applicable; NS, not significant. $E_{M:C}$ were separately characterized using LME models after fitting Boltzmann-Arrhenius functions to the emissions data. The slopes of the fitted function in the LME models are the $E_{M:C}$ values.

Supplementary Table 3. The collinearity of soil, climate, and hydrologic independent variables to explain the site-level $E_{M:C}$ and their relative explained variance.

Independent variable	Variance inflation factor	*p* value in LM	Variance partition (%)
SOC	79.46	/	/
TN	110.27	0.89	2.84
TP	2.10	0.08	4.22
Soil C:N	2.70	< 0.01	75.99
Soil C:P	63.98	0.51	26.67
Soil N:P	97.66	/	2.2%
Soil pH	1.61	0.40	-2.11
Soil clay content	6.49	0.25	-0.37
Soil silt content	9.82	0.58	-4.12
Soil sand content	18.36	/	/
Water table depth	1.22	0.21	2.11
Mean annual air temperature	5.57	0.46	-2.20
Mean annual precipitation	7.96	0.52	-3.30
Mean annual evaporation	7.14	0.82	2.93
Aridity index	4.53	0.52	-2.66

Supplementary Table 4. Explaining the Akaike information criterion (AIC) ranking of all possible linear regression models for $E_{M:C}$ at the site level.

Model	AIC
$E_{M:C}$ ~ soil C:N	299.19
$E_{M:C}$ ~ soil C:N + WTD	299.76
$E_{M:C}$ ~ 1	314.67
$E_{M:C}$ ~ WTD	315.12