Universitat Autònoma de Barcelona

Dipòsit digital de documents de la UAB

This is the **accepted version** of the article:

Carey, Joanna C.; Tang, Jianwu; Templer, Pamela H.; [et al.]. «Temperature response of soil respiration largely unaltered with experimental warming». Proceedings of the National Academy of Science, Vol. 113, Issue 48 (November 2016), p. 13797-13802. DOI 10.1073/pnas.1605365113

Temperature response of soil respiration largely unaltered with experimental warming

Authors: Joanna C. Carey[a*], Jianwu Tang[a*], Pamela H. Templer[b], Kevin D. Kroeger[c], Thomas W. Crowther[d,e], Andrew Burton[f], Jeffrey S. Dukes[g], Bridget Emmett[h], Serita Frey[i], Mary Heskel[a], Lifen Jiang[j], Megan Machmuller[k], Jacqueline E. Mohan[l], Anne Marie Panetta[m], Peter B. Reich[n,o], Sabine Reinsch[h], Xin Wang[p], Steven D. Allison[q], Chrisopher Bamminger[r], Scott D. Bridgham[s], Scott L. Collins[t], Giovanbattista de Dato[u], William C. Eddy[v], Brian J. Enquist[w], Marc Estiarte[x,y], John Harte[z], Amanda Henderson[w], Bart R. Johnson[aa], Klaus S. Larsen[bb], Yiqi Luo[j], Sven Marhan[r], Jerry Melillo[a], Josep Peñuelas[x,y], Laurel Pfeifer-Meister[s,cc], Christian Poll[r], Edward B. Rastetter[a], Andy Reinmann[b], Lorien L. Reynolds[s], Inger K. Schmidt[bb], Gaius R. Shaver[a], Aaron L. Strong[dd], Vidya Suseela[ee], Albert Tietema[ff]

Supporting Methods

Dataset Generation and Description

A literature search was conducted on September 22, 2014 using Web of Science, which produced five studies presenting non-aggregated instantaneous data that were extractable (Table S1). Published datasets (16-17) and unpublished values make up the majority of the data in the dataset. We obtained unpublished data by first creating a list of all known experimental warming studies globally and asking the principal investigators to supply soil respiration data with corresponding soil temperature and moisture values. Because of widely variable experimental designs across studies, we averaged all plot-scale values for each sampling event to obtain one average (± SD) for each treatment for each sampling event ('sampling events' typically refer to a single day of sampling, although several studies complete full suites of sampling (i.e., 'sampling events') from all plots in both morning and afternoon). Only soil respiration values with corresponding soil moisture and soil temperature values from experimental warming studies were included in our analysis. Only observations from single-factor treatments (i.e., warming) were used, excluding values that combined warming with other treatments (e.g., precipitation or nitrogen manipulation). Four studies included more than one level of warming treatment (e.g., both 1.5 and 3°C warming treatments); in these cases, data from all levels of warming were used for our temperature response function analyses. All data were reported as instantaneous change in CO_2 efflux over a fixed area, with belowground (i.e., roots and rhizomes), but not aboveground vegetation, included. Thus, soil respiration values presented here include both heterotrophic and autotrophic soil respiration.

Experiment locations ranged from 33.5 to 68.4 °N latitude (Fig. S5) and the duration of warming at experiments ranged from <1 to 22 years (average 5.1 years) (Fig. S6). Depths of soil temperature (1-10 cm) and moisture measurements (5-30 cm) ranged across studies, but were always consistent between warmed and control plots within a particular study. The majority of the observations were taken between 5 and 10 years after warming commenced (n=1534), followed by 2-5 year duration (n=1109), less than 2 years (n=896) and >10 years (n=278). Each site was classified into a particular biome (grassland, northern shrubland (i.e., peatlands and heathlands), southern shrubland (i.e., Mediterranean or sub-tropical shrublands), tundra, desert, meadow, temperate agriculture, temperate forest and boreal forest) by the associated principal investigator. Tropical biomes are not represented in our analysis because no data from experimental warming studies in the tropics are yet available. However, the first known tropical warming experiment, Tropical Responses to Altered Climate Experiment (TRACE), is currently being set up in Luquillo Experimental Forest in Puerto Rico, with heating scheduled to commence during spring 2016.

Seasonality was defined by principal investigators contributing data as those months that fall into the following categories: growing (plants actively growing), non-growing (plants not actively growing), or shoulder (takes into account months of transition and intra-annual variability) season. Data from the growing season accounted for more than half of our observations (n=1840), followed by shoulder season (n=1112), and non-growing season (n=865). Absolute differences in soil temperature, moisture, and respiration across sites were always calculated as values from warmed plots minus values from control plots for each sampling event: e.g., $\Delta T = T_w - T_c$.

Evaluating role of Soil Moisture, Seasonality, and Warming Duration in Controlling Soil Respiration

We investigated the role of soil moisture in controlling the response of soil respiration in four ways. First, we evaluated the significance of soil moisture as a predictor of soil respiration by adding moisture as an additional continuous variable in a multiple linear regression model (Model e in Table S3, Table S2):

$$\ln\left(R\right) = a_0 + a_1 T + a_2 T^2 + a_3 M \quad (2)$$

where *R* is soil respiration (µmol C m^2 s^{-1}), *T* is soil temperature (°C), and *M* is soil moisture (cm^3 cm^{-3}). In cases where significant differences in the response functions of warmed vs. control treatments were observed (boreal and desert biomes), separate models that included moisture were run for each treatment (Table S2). Because respiration rates are often not linearly related to moisture content, we also conducted our analysis with an additional model (Eq. 4), which resulted in no differences in our conclusions (Table S6). Next, we created partial regression plots (i.e., added-variable plots) for both temperature and moisture (Fig. S7), allowing for visual inspection of the role of moisture compared to temperature in controlling the respiration response. Third, we examined how moisture alters the temperature sensitivity of respiration by running a separate model of respiration as a function of temperature with moisture as the interaction term (Model f in Table S3). To evaluate this response visually, we then partitioned the data into moisture quantiles and plotted the temperature sensitivities of respiration at these four different moisture levels (Fig. S3), reporting the coefficients in Table S4. Finally, we normalized each instantaneous difference in respiration between warmed and control plots (ΔR) by ΔT, and binned those values by amount of moisture available in warmed plots as a fraction of control plots (Fig. 3). Moisture bins containing less than 5% of total observations from each biome are not shown (not applicable in Fig. 3, where all bins represent at least 5% total data). This analysis allowed us to understand how differences in the magnitude of respiration between treatments change with moisture availability (Fig. S3).

We evaluated the influence of warming duration and seasonality on the respiration response between treatments in two ways: 1) by partitioning the observations into categories of warming duration (<2, 2-5, 5-10, and >10 years) and season (growing, non-growing, and shoulder) and running the multivariate regression model shown in Table 1 for each category separately, and 2) by running additional multivariate models (Models h and i in Table S3) that included duration or season as a fixed factor, with an interaction with warming treatment.

Supporting Results

Magnitudes of Temperature and Respiration Change with Experimental Warming

Experimental warming generally stimulated soil respiration, with a larger ΔT significantly correlated to a larger respiration effect size ($p<0.01$ and $r=0.66$; Fig. S2B, Table S1). Across all sites, experimental warming increased soil temperatures by 1.91 ^{0}C on average, although average soil warming by biome ranged from 0^{0}C in southern shrublands to 4.09 ^{0}C in temperate forests, with relatively large inter-biome differences (Table S1). On average, the magnitude of soil warming at many sites was too low (when ΔT <1.72 °C) to statistically increase respiration rates (Fig. S2B). In turn, the relatively low degree of average warming across many sites resulted in an insignificant grand mean effect size for soil respiration (RR= 0.05 [95% CI: -0.03-0.14], n=26), regardless of season and warming duration, with just five sites (Site IDs 2, 6, 7, 8, 27 Table S1) having a significantly positive response of respiration in the warmed plots. Methodological differences in warming methods resulted in a range of ΔT, and thus, ΔR across sites. In our dataset, experiments that warmed via electric cables observed the greatest average soil warming (ΔT =3.6 °C, n=5), compared to infrared (ΔT =2.3°C, n=11) and passive (ΔT = 0.4°C, n=11) warming methods. Electric cable was the dominant warming method in the temperate forest (4 out of 5 sites) and temperate agriculture (one site) biomes and in turn, these biomes were the only ones when analyzed individually to display a significant increase in respiration (ΔR) with warming using traditional meta-analysis (temperate forest: RR=0.18; 95% CI: 0.06-0.30, temperate agriculture: RR=0.21; 95% CI: 0.06-0.37).

Standardized Mean Difference of Temperature Sensitivity

Beyond investigating differences in the log-quadratic temperature response function (Eq. 1) between warming treatments, we also conducted a traditional meta-analysis on site-level temperature sensitivity parameters using the standardized mean difference (SMD) as our index of effect size, which normalizes raw mean differences by the pooled standard deviation. Examining data from across all sites, the grand mean effect size was not significantly different from zero (SMD= -0.29 [95% CI: -1.21, 0.64], n=27), demonstrating further evidence for the general lack of difference in temperature sensitivities between warmed and control plots with experimental warming (Fig. S8). Although the grand mean effect size was not significantly different from zero, 12 sites showed significantly higher SMDs of temperature sensitivity in warmed plots (Site IDs 5, 8, 9, 13, 14,16, 19, 21, 23, 26-28), while eight sites (Site ID 1, 2, 11, 12, 15, 20, 22, 24) demonstrated significantly lower SMD in warmed plots compared to control plots.

Role of Moisture in Controlling Respiration Rates

Meta-analysis of soil moisture data reveals that moisture was significantly reduced with warming (RR=-0.08, [95% CI:-0.12- -0.03]), with 7 out of 27 sites having significantly less soil moisture at the warmed compared to control plots. However, such decreases were only marginally significantly correlated with ΔT (r= -0.32, p=0.08) (Fig. S2A). Multivariate linear regression highlights that moisture typically explains a much smaller fraction (0-8%) of the total respiration response compared to temperature (34-82%), except in the case of southern shrublands, where moisture is a stronger predictor of respiration than soil temperature (R^2 model a or b versus Model e in Table S3, Fig. S7). We used partial regression plots (Fig. S7) to help visualize the effect of adding an additional variable (i.e., soil moisture) to a multiple regression model. Partial regression with temperature and moisture highlight the more important role of temperature in driving the soil respiration response compared to moisture (Fig. S7). This response is demonstrated by the lower slopes on the added-variable moisture plots (right hand panels). An exception to this is southern shrublands, where moisture added-variable plot has a much steeper slope compared to other biomes, aligning with the multivariate regression output showing moisture playing a more important role in predicting respiration compared to temperature in the southern shrublands.

Ambient soil moisture is a critical factor in mitigating the respiration-temperature relationship. For example, a negative ΔR/ΔT response with soil drying is only apparent in the desert, grassland, and southern shrubland biomes (Fig. S9), likely because these biomes have the lowest ambient soil moisture content (Table S1) and thus, even minor desiccation with warming suppresses C fluxes. On the other hand, in the forest biomes where soil drying with warming was most severe (warmed plots have on average 84% and 87% of the moisture that was observed in control plots in the boreal and temperate forests, respectively), fluxes were still consistently higher from warmed plots despite drying (Fig. S9), due in part to relatively elevated ambient soil moisture conditions at these sites (Table S1).

Soil moisture often has a non-linear relationship with soil respiration. In order to determine if our multivariate linear model (Table S2) was a factor influencing our results, we re-ran our analysis using an additional function (Eq. 4, see below), which shows little difference in model fits (Table S6). Our study does not take into account differences in soil type between sites, as differences in soil type between warmed and control plots within a site should be minimal. In addition, soil moisture content largely reflects soil type across sites, as sandier soils hold less water than more clay-type soils. We see this in our data, as average soil moisture content in several biomes was negatively related to percent sand (r=0.98, 0.62, r=0.55 in northern shrublands, grasslands and forests, respectively). Our analyses of soil moisture are based on soil water content (SWC), otherwise known as soil moisture concentrations. However, soil matric potentials are a much better indicator of water availability in soils, as this metric takes into account soil texture and organic matter content, which can affect relative water availability at the site level (1, 2). Because both factors undoubtedly change across sites, soil matric potentials are likely a more sensitive metric to evaluate how differences in moisture availability influence soil respiration rates.

Role of Warming Duration and Seasonality on Soil Respiration Rates

Multivariate analysis of respiration that included warming duration as a predictor, with an interaction with warming treatment (Model h in Table S3) revealed a significant interaction between duration and warming treatment in four biomes: desert, boreal forest, temperate forest, and northern shrubland. Except for northern shrublands, the other three biomes displayed significantly depressed soil respiration rates with increasing warming duration. Considering that it is in these three biomes where we observed moderate (temperate forest) to strong (boreal forest and desert) evidence of altered temperature response functions to soil warming, it appears that duration of experimental warming is an important factor in driving these results. We also evaluated how duration of warming changes the temperature response function of respiration in warmed versus control treatments by re-running our analysis shown in Table 1 with data partitioned into the following groupings of years of warming duration (<2, 2-5, 5-10, and >10). This analysis continues to support prior conclusions, with no significant differences in the temperature response function in any biome regardless of warming duration, except the boreal forests and desert, and moderate ($p=0.06$) differences from 2-5 years of warming duration in temperature forest.

We investigated how season influenced soil respiration rates in a similar fashion to duration. First, we added season as a predictor to our multilinear regression model, with an interaction with warming treatment (Model i in Table S3). Here we found a significant interaction between season and warming treatment in the desert and boreal forest biomes only, indicating that in these two biomes respiration from warmed and control plots responds differently to temperature depending on the time of year. Next, we re-ran our analysis shown in Table 1 with data partitioned into season (non-growing, growing, shoulder) and found a similar result; for all biomes except the desert and boreal forests, no differences in temperature sensitivity were observed when analyzing any particular season in isolation. In the boreal forest, differences in temperature sensitivity were driven by growing season data, which make up the majority of the data (70%) for the boreal forest biome. On the other hand, the differences in sensitivity observed in the desert biome are driven by data from the non-growing season; this was the only season, when examined in isolation, where significant differences in the temperature sensitivity of respiration from warmed versus control plots are observed in the desert biome.

Model Choice

We used several different multivariate models (Table S3) to answer specific questions during our analysis. To address our first objective (i.e., determine whether respiration response from warmed plots paralleled that from control plots), we used a temperature-treatment interaction model (Models c or d in Table S3, depending on whether the 2^{nd}-order temperature term was significant when including the treatment interaction term). We also compared the fits (specifically AICs) of Models c or d with models excluding warming treatment as a predictor (Models a or b) to determine if warming treatments had an effect on the respiration response (Table S3). Lower AICs in Models a or b (Table S3) compared to Models c or d (Table S3) provides further evidence that experimental warming does not alter the shape of the curve to a large degree in those biomes. Parameter values for Models a and b (Table S3) also shown in Table S5. Next, to evaluate our second objective (i.e., investigate the role of soil moisture in influencing how respiration responds to temperature across treatments), we included soil moisture as a predictor, with an interaction term with temperature in our multivariate models (Models e and f in Table S3). Finally, to determine how warming duration and seasonality were influencing our results, we ran three additional models with these terms as predictors (Model g in Table S3), with an interaction term with warming treatment (Models h and i in Table S3).

We did not use the traditional exponential model (the Q_{10} model) or the Arrhenius model to fit our data as these models cannot adequately reflect our findings that the temperature sensitivity decreased when temperature is above ~25°C. The inability of these models to represent varying temperature sensitivities across the temperature gradient has been discussed previously (3, 4). This study focused on understanding the temperature response of soil respiration with experimental warming, rather than modeling soil respiration. However, we also simulated our data using the following equation (5):

(4)

$$R = e^{\alpha (T - T_o)} \left(\frac{T_m - T}{T_m - T_o} \right)^{\alpha (T_m - T_o)} \left(\frac{M}{k_m + M} \right)$$

With R = non-transformed soil respiration rate, T= soil temperature (°C), T_o = optimum soil temperature (°C), T_m = maximum soil temperature (°C), M = soil moisture concentration (cm^3 cm^{-3}). T_o, T_m, $k_{m'}$ and α were solved individually for each biome. Irrespective of having a similar or better overall performance (R^2 in Table S6), we selected the log-linear or log-quadratic equations to fit our data (Table 1, Eq. 1, Models c and d in Table S3) because it facilitated use of the binary categorical variable to evaluate differences in temperature response functions with warming treatment.

Cross-Biome Differences

Temperature response functions of soil respiration were not equal across biomes; not only were the temperature sensitivities different (γ_1 and γ_2, Table 1), but the magnitudes of respiration (γ_o, Table 1) also differed, with highest fluxes from boreal forests and lowest fluxes from deserts (Fig. S4). Multivariate regression output highlights these across-biome differences, as adding 'biome' as a predictor to the larger multivariate regression of all non-desert data increased the predictive power of the model by 28% (Model j in Table S3).

Supporting References

1. Reynolds LL, Johnson BR, Pfeifer-Meister L, Bridgham SD (2015) Soil respiration response to climate change in Pacific Northwest prairies is mediated by a regional Mediterranean climate gradient. *Glob Chang Biol* 21(1):487–500.

2. Vicca S, et al. (2012) Urgent need for a common metric to make precipitation manipulation experiments comparable. *New Phytol* 195(3):518–22.

3. Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. *Funct Ecol*:315–

323.

4. Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440(7081):165–73.

5. Rastetter EB, et al. (1991) A general biogeochemical model describing the responses of the C and N cycles in terrestrial ecosystems to changes in CO_2, climate, and N deposition. *Tree Physiol* 9(1-2):101–126.

6. Lellei-Kovács E, et al. (2008) Experimental warming does not enhance soil respiration in a semiarid temperate forest-steppe ecosystem. *Community Ecol* 9(1):29–37.

7. de Dato GD, De Angelis P, Sirca C, Beier C (2009) Impact of drought and increasing temperatures on soil CO2 emissions in a Mediterranean shrubland (gariga). *Plant Soil* 327(1-2):153–166.

8. Saleska SR, Harte J, Torn MS (1999) The effect of experimental ecosystem warming on CO_2 fluxes in a montane meadow. *Glob Chang Biol* 5(2):125–141.

9. Flanagan LB, Sharp EJ, Letts MG (2013) Response of plant biomass and soil respiration to experimental warming and precipitation manipulation in a Northern Great Plains grassland. *Agric For Meteorol* 173:40–52.

10. Jarvi MP, Burton AJ (2013) Acclimation and soil moisture constrain sugar maple root respiration in experimentally warmed soil. *Tree Physiol* 33(9):949–959.

11. Suseela V, Conant RT, Wallenstein MD, Dukes JS (2012) Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. *Glob Chang Biol* 18(1):336–348.

12. Allison SD, Treseder KK (2008) Warming and drying suppress microbial activity and carbon cycling in boreal forest soils. *Glob Chang Biol* 14(12):2898–2909.

13. Allison SD, McGuire KL, Treseder KK (2010) Resistance of microbial and soil properties to warming treatment seven years after boreal fire. *Soil Biol Biochem* 42(10):1872–1878.

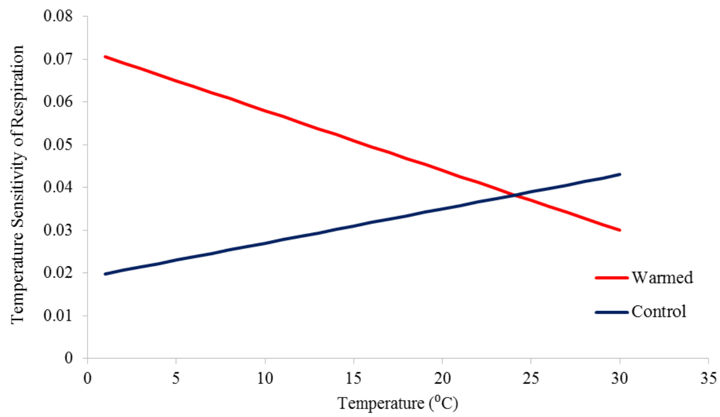
14. Poll C, Marhan S, Back F, Niklaus PA, Kandeler E (2013) Field-scale manipulation of soil temperature and precipitation change soil CO2 flux in a temperate agricultural ecosystem. *Agric Ecosyst Environ* 165:88–97.

15. Johnson LC, et al. (2000) Plant carbon - nutrient interactions control CO_2 exchange in Alaskan wet sedge tundra ecosystems. *Ecology* 81(2):453–469.

16. Reinsch, S., Sowerby, A., Emmett, B.A. (2016) Fortnightly soil respiration data from Climoor fieldsite in Clocaenog Forest 1999 – 2015. DOI: 10.5285/[2]c0822023-0ec2-425f-8bf9-a546ce281ee0

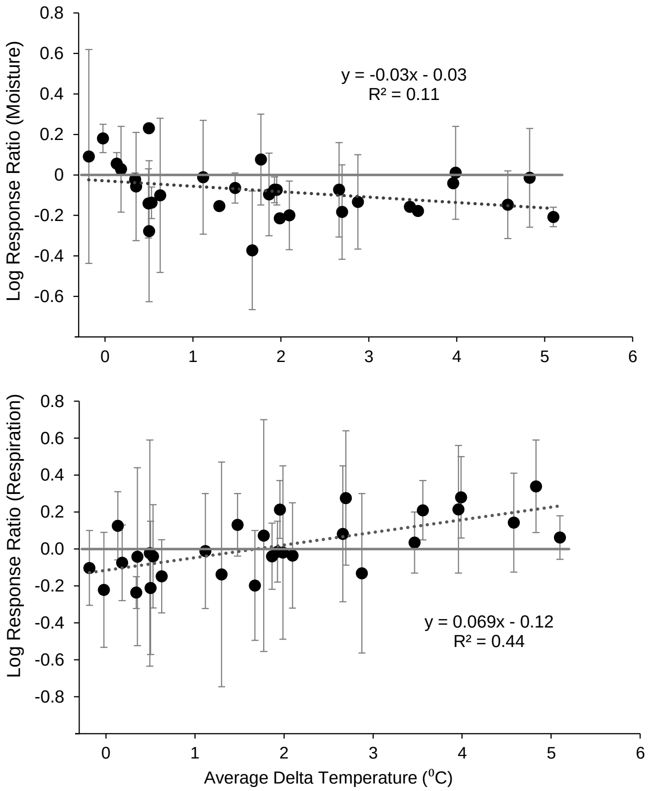
17. Reinsch, S., Sowerby, A., Emmett, B.A. (2016) Daily plot level (micro meteorological) data at Climoor field site in Clocaenog Forest 1998-2015. DOI: http://doi.org/10.5285/afb994e5-b33d-48b4-ad29-d374b1f9f3c8

Fig. S1.



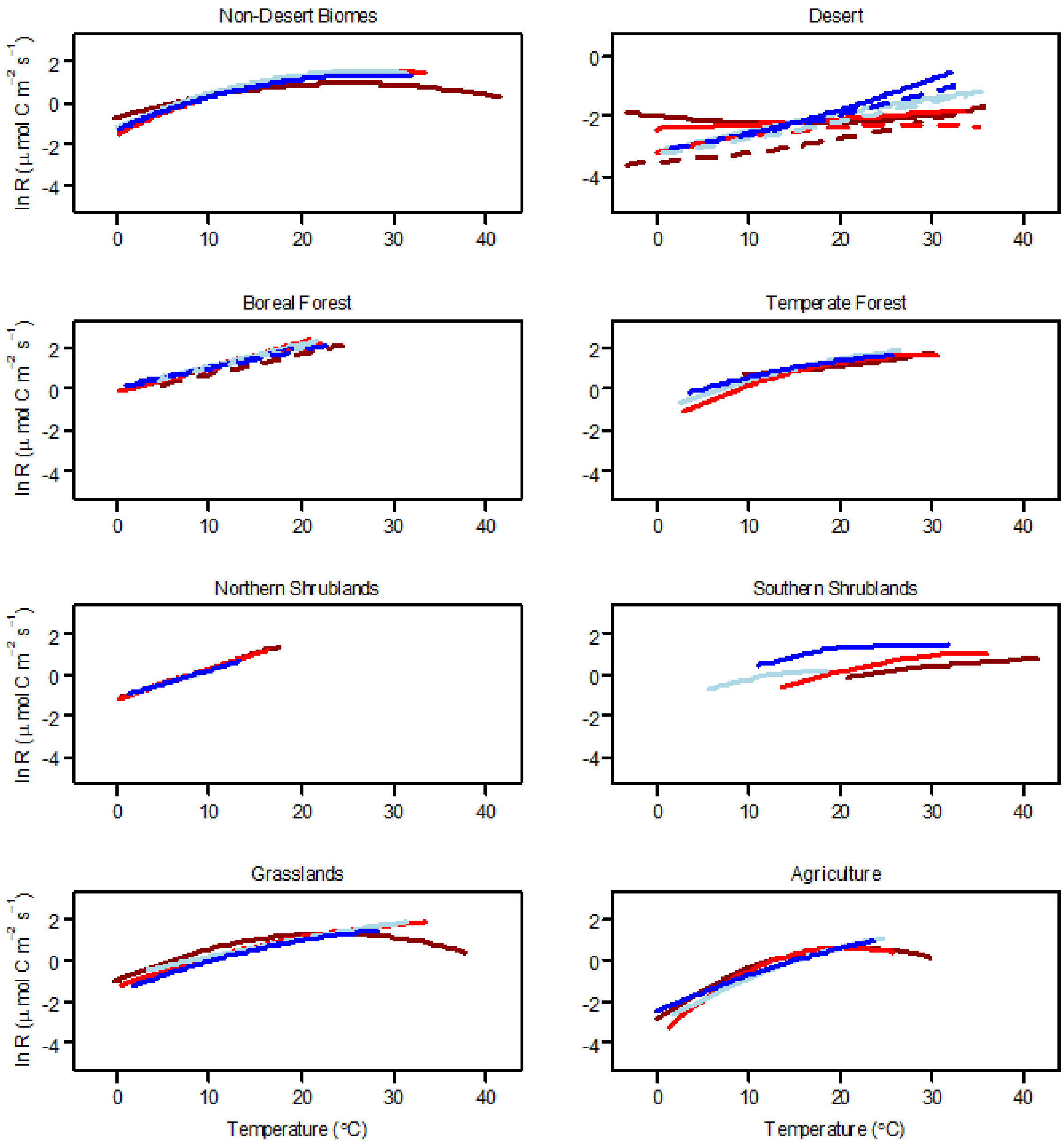
Temperature sensitivities for desert calculated as the linear functions describing the derivative of the log-quadratic fit of ln respiration as a function of soil temperatures: $\frac{\partial y}{\partial t}$ = -0.0014 *T* + 0.072 (warmed) and $\frac{\partial y}{\partial t}$ =0.0008 *T*+ 0.019 (control), where y refers to ln of respiration (µmol C m^{-2} s^{-1}) and *T* refers to temperature (°C).

Fig. S2.



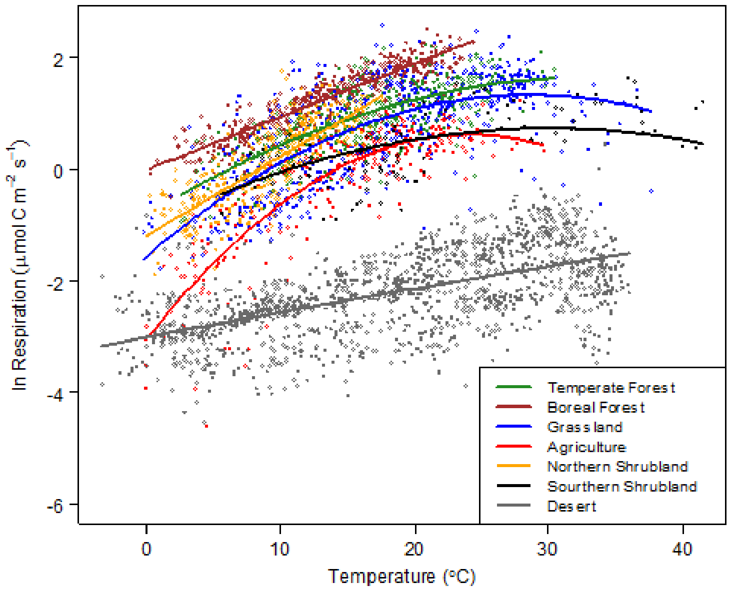
Effect size (log response ratio) as a function of degree of experimental warming (ΔT (°C)) for moisture (A) and respiration (B). Data from all biomes plotted here.

Fig. S3.



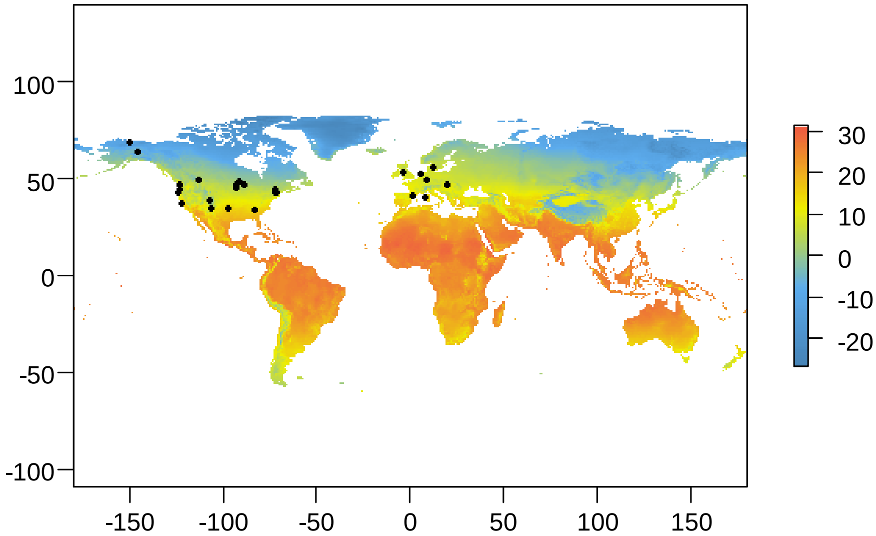
Best fit regression lines of natural log (ln) of respiration (μmol C m^{-2} s^{-1}) as a function of soil temperature (°C) across biome types, with data partitioned into moisture quantiles: dark red (1st (lowest) quartile), red (2nd quartile), light blue (3rd quartile), dark blue (4th (highest) quartile). For model parameters, see Table S3. Separate fits were calculated for control and warmed treatments where statistically different temperature sensitivities were observed (boreal forest and desert), with dashed lines for warmed data and solid lines for control data. Solid lines on all other plots represent both warmed and control data, as their fits were not statistically different from one another. Note the scale of Y-axis are all equal, except for desert, which had lower respiration rates compared to all other biomes.

Fig. S4.



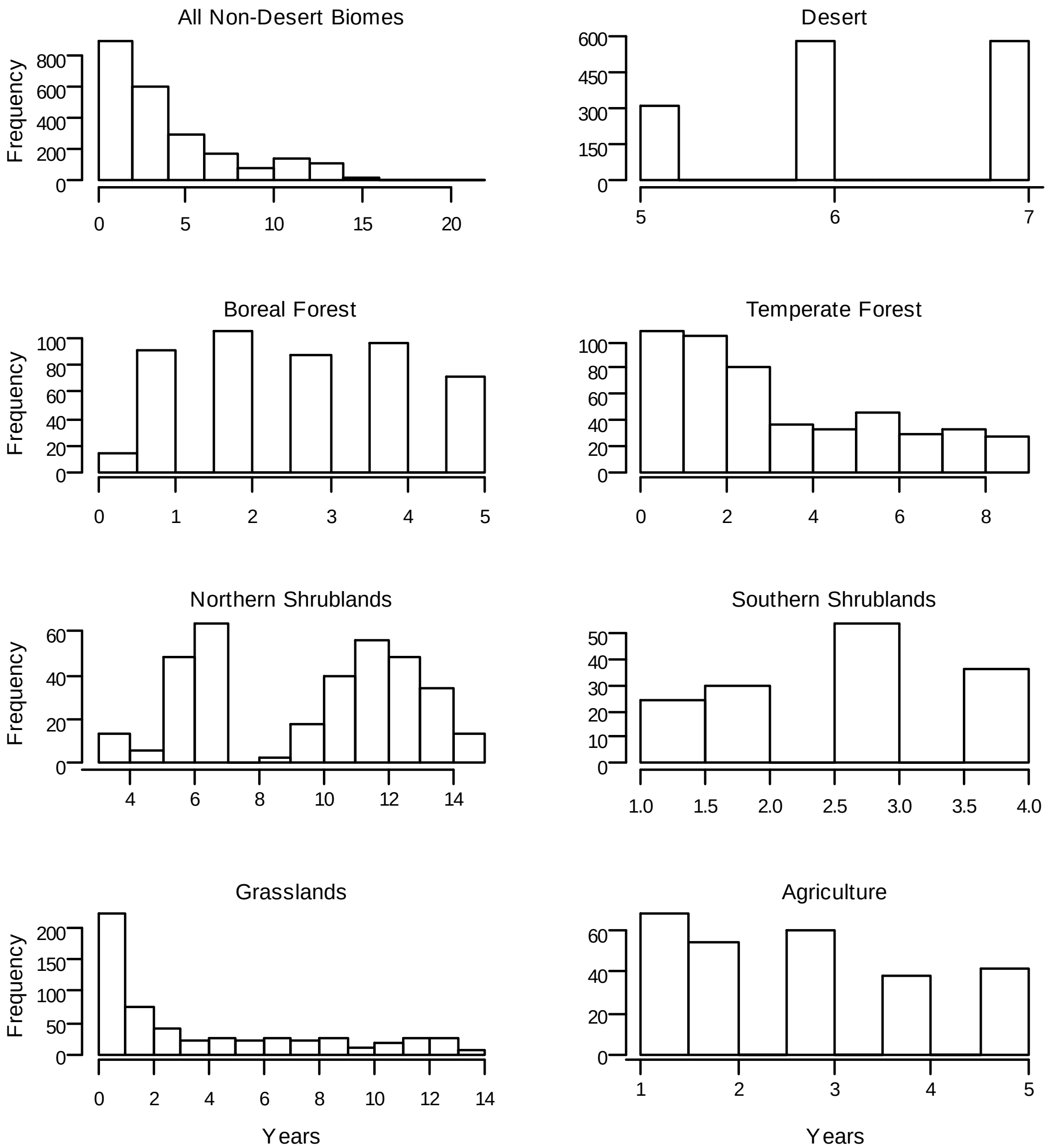
Ln respiration (μmol C m^{-2} s^{-1}) as a function of soil temperature (°C) for all data included in our study. Each dot represents an individual data point, including data from both control and warmed treatments (n=3817). Lines are best-fit regression lines using the log-quadratic temperature response functions for all biomes, except the boreal forest and northern shrublands, where log-linear functions were used (for coefficients, see Table S5).

Fig. S5.



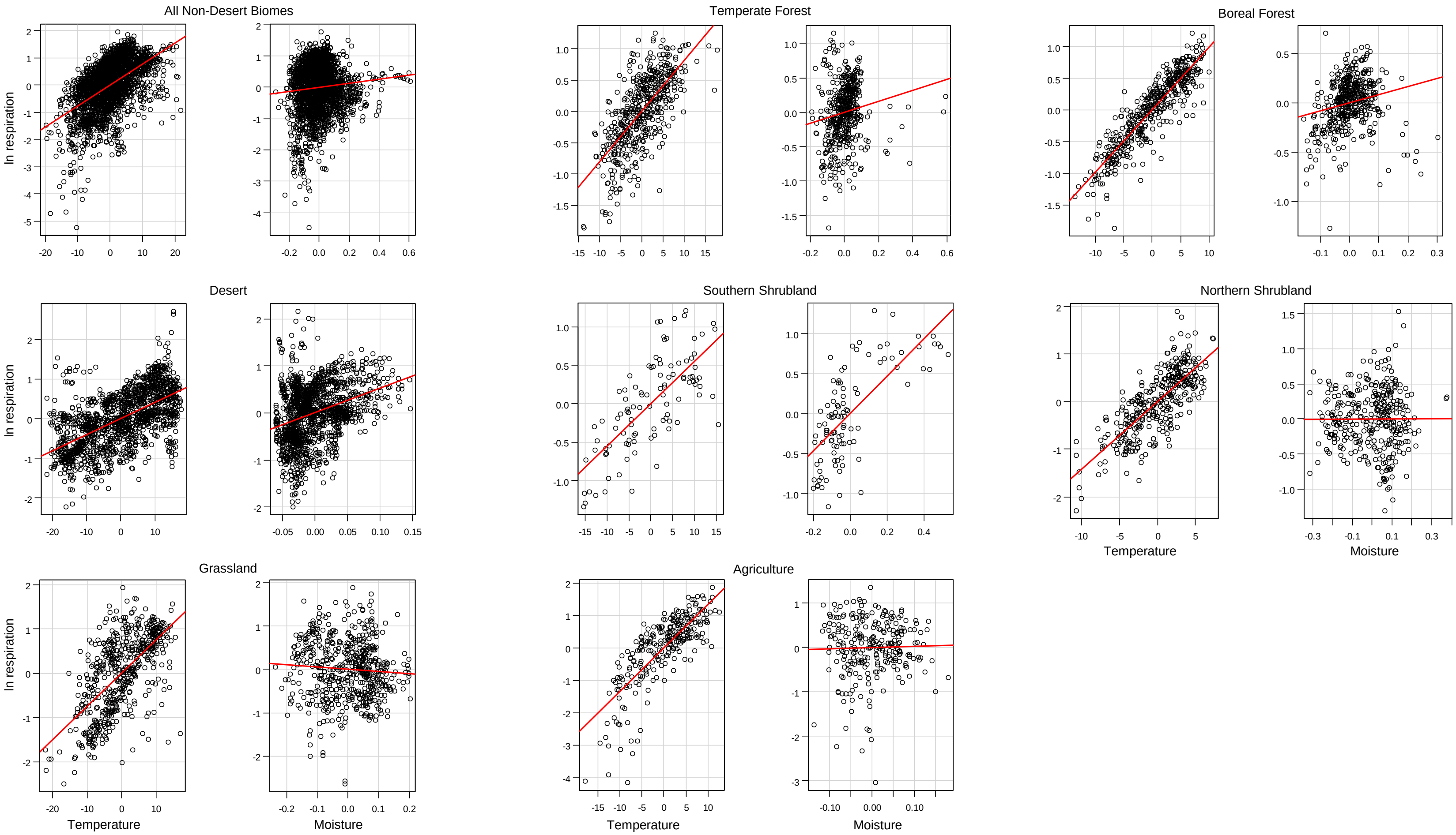
Map of study sites. Color refers to mean annual temperature (°C). Map created using ‘maps’, ‘mapdata’, and ‘raster’ packages in R.

Fig S6.



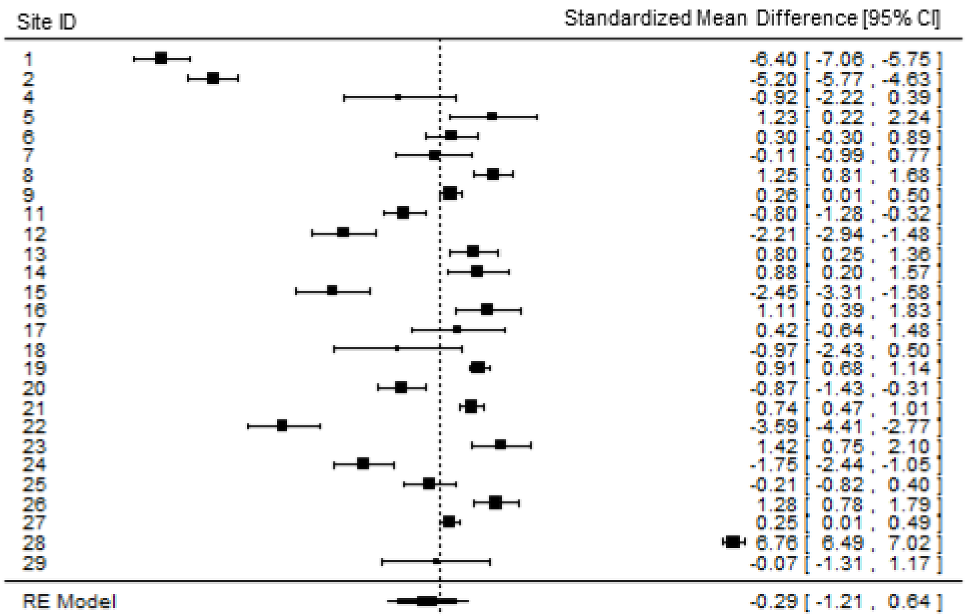
Histogram of duration of warming within each biome.

Fig. S7.



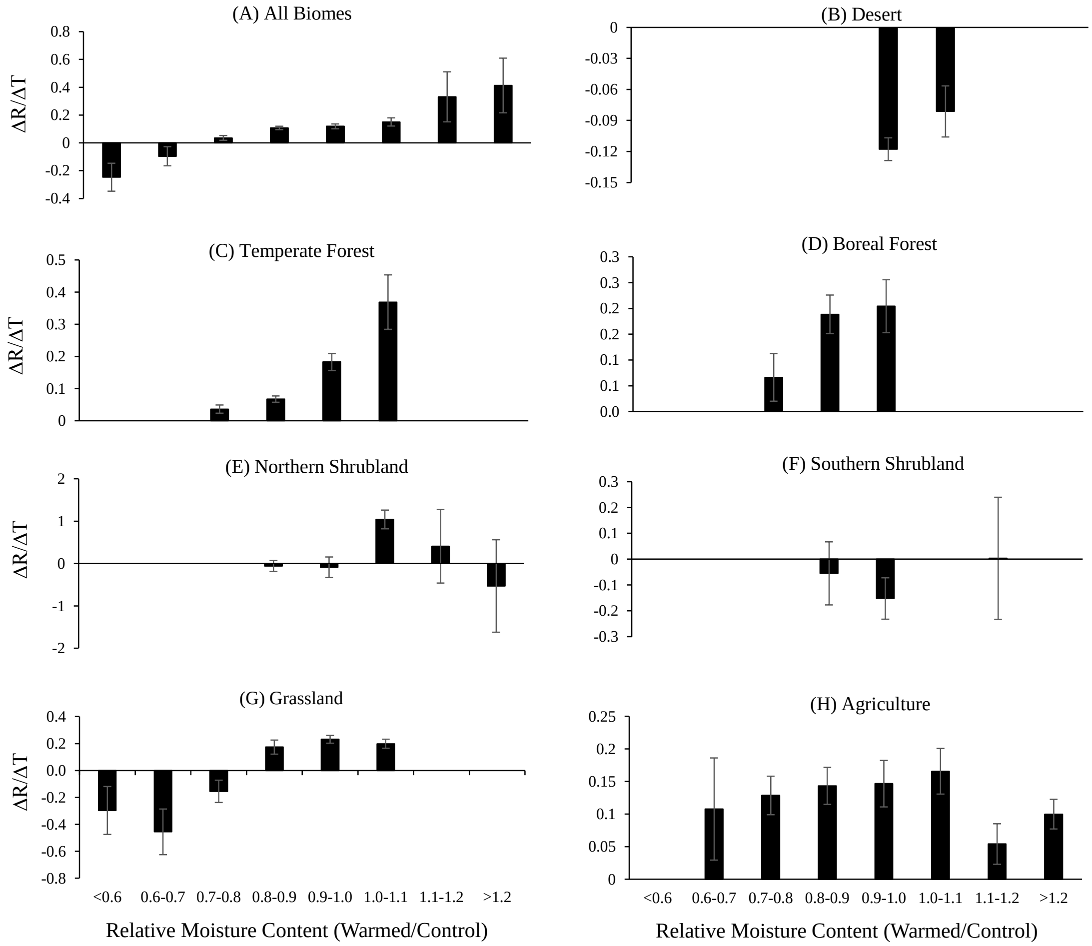
Partial regression plots of soil respiration as a function of temperature and moisture across all biomes. Plots created using the ‘car’ package and AvPlots function in R.

Fig. S8



Forest plot of first-order temperature sensitivities (γ_1 in Eq. 1) at each site. Size of filled squares indicates number of observations. Error bars represent 95% confidence intervals. Error bars that do not cross zero line indicate significant differences in temperature sensitivity between warmed and control plots. Values on right of zero line indicate higher sensitivity in warmed plots, while values on left of zero line indicate lower sensitivity of warmed plots.

Fig. S9.



Difference in respiration (μmol C m^{-2} s^{-1}) between warmed and control plots (ΔR) normalized by degree of warming (ΔT °C), binned by amount of soil desiccation with warming (soil moisture content in warmed plots divided by soil moisture content in control plots) for each individual biome. X axis values <1 indicate warmed plots have less moisture available than control plots. Y axis values <0 indicate that respiration rates were lower from warmed plots, despite warmer soil temperatures. Respiration data not log transformed. Note the scales of the Y-axes are different. For number of observations by biome see Table S3.

Supplementary Tables

Table S1.

						Control		Warmed Treatment (multiple levels)										
Site ID	Name	Ecosystem Type	Warming Method	n	Average Delta Temperature (^{0}C)	Average Respiration (μmol m^{-2} s^{-1})	SE	Average Respiration (μmol m^{-2} s^{-1})	SE	Average Ambient Moisture (cm^3 cm^{-3})	Average Delta Moisture (cm3 cm-3)	MAP (mm)	MAT (^{0}C)	Elevation (m)	Duration Range* *	%Sand	%Silt	%Clay
1	B4W_CFC	Boreal Forest	Infrared	75	1.87	4.38	0.29	4.21	0.25	0.213	0.020	752	4.23	413	5	60.9	30.5	8.6
1	B4W_CFC	Boreal Forest	Infrared	75	3.47			4.53	0.24		-0.031							
2	B4W_HWRC	Boreal Forest	Infrared	71	1.93	4.08	0.26	4.02	0.22	0.278	0.020	665	3.57	383	5	62.3	23.5	14.2
2	B4W_HWRC	Boreal Forest	Infrared	71	3.56			5.03	0.25		-0.045							
4	Tower_Burn	Boreal Forest	Passive	5	0.49	1.68	0.40	1.65	0.34	0.475	0.062	303	-2	457	2	31.6	56.8	11.8
5	Tower_Control	Boreal Forest	Passive	9	0.50	2.40	0.19	1.94	0.33	0.202	0.049	303	-2	499	2	34.1	53.5	12.4
6	Ford^	Temperate Forest	Infrared	22	4.58	2.89	0.28	3.33	0.31	0.240	0.033	879	4.9	402	5	62.1	29.0	9.0
7	HBEF	Temperate Forest	Electric Cable	10	4.83	5.18	0.52	7.28	0.61	0.144	0.002	1400	5.2	252	1	60.0	30.0	10.0
8	HF_Frey	Temperate Forest	Electric Cable	48	3.99	1.91	0.16	2.53	0.19	0.243	-0.003	1100	7	1026.5	8	62.0	22.0	15.0
9	HF_Melillo	Temperate Forest	Electric Cable	130	5.10	3.03	0.14	3.22	0.13	0.276	0.052	1080	7	1026.5	9	62.0	22.0	15.0
11	Whitehall	Temperate Forest	Electric Cable	29	2.10	3.10	0.34	3.00	0.29	0.171	0.031	99	17.6	207	4	63.9	18.0	18.1
11	Whitehall	Temperate Forest	Electric Cable	19	3.96			4.24	0.50		-0.007							
12	BACE^	Temperate Grassland	Infrared	14	0.35	3.22	0.59	3.09	0.51	0.225	0.013	1194	9.5	17	2	45.0	46.0	9.0
12	BACE^	Temperate Grassland	Infrared	14	1.99			3.16	0.49		-0.044							
12	BACE^	Temperate Grassland	Infrared	14	2.93			3.26	0.45		-0.070							
13	BioCON	Temperate Grassland	Infrared	27	1.67	5.30	0.59	4.35	0.46	0.079	0.025	660	6.7	282	2	94.4	0.0	2.5
14	COR	Temperate Grassland	Infrared	18	2.66	2.75	0.38	2.99	0.37	0.257	0.018	1134	11.4	164	2	36.5	49.0	14.5
15	SOR	Temperate Grassland	Infrared	18	2.88	2.92	0.47	2.56	0.38	0.234	0.029	1434	12.3	395	2	31.5	37.5	31.0
16	WA	Temperate Grassland	Infrared	17	2.70	2.18	0.29	2.87	0.37	0.162	0.027	1196	10.5	134	2	75.0	21.5	3.5
17	FluxnetCanada *	Temperate Grassland	Passive	7	0.50	3.27	0.70	8.44	0.98	0.220	-0.057	386	5.4	960	1	28.8	40.0	31.2
18	JasperRidge	Temperate Grassland	Infrared	4	1.77	4.87	1.53	5.23	0.35	0.076	-0.006	531	15.3	120	1	37.0	48.0	15.0
19	Kessler	Temperate Grassland	Infrared	164	1.48	2.20	0.13	2.51	0.15	0.255	0.016	914	16.3	335	13	36.0	55.0	10.0
20	MontainMeadow^	Meadow	Infrared	27	1.12	2.49	0.29	2.46	0.27	0.109	0.001	750		2920	20	na	na	na
21	Clocaenog	Northern Shrubland	Passive	114	0.13	1.23	0.09	1.40	0.09	0.421	-0.024	1289	8.2	490	13	40.2	50.0	9.8
22	Garraf	Southern Shrubland	Passive	30	0.18	1.11	0.09	1.03	0.07	0.185	-0.005	570	15.6	215	2	42.9	38.7	18.4
23	Hungary*	Southern Shrubland	Passive	21	0.63	0.42	0.03	0.37	0.03	0.051	0.005	505	10.4		3			
24	Oldbroek	Northern Shrubland	Passive	22	-0.02	1.39	0.16	1.11	0.12	0.215	-0.043	1072	10.1	25	3	93.5	6.0	0.5
25	PCCC^	Southern Shrubland	Passive	21	-0.18	3.08	0.22	2.78	0.20	0.328	-0.031	640	16.8	40	3	75.6	11.2	13.4
26	Brandbjerg	Northern Shrubland	Passive	36	0.53	1.73	0.17	1.66	0.17	0.178	0.023	757	8.7	9	2	91.0	7.0	2.0
27	HoCC	Temperate Agriculture	Electric Cable	131	1.95	1.07	0.06	1.32	0.07	0.210	0.015	679	8.7	395	5	9.0	69.0	22.0
28	Sevilleta	Desert	Passive	737	0.34	0.16	0.00	0.13	0.00	0.112	0.003	250	13.2	1525	3	68.0	22.0	10.0
29	Toolik	Wet Sedge Tundra	Passive	5	1.30	0.76	0.20	0.66	0.11	0.700	0.100	331	-8.5	717	1	na	na	na

*data from published literature only
^ data from both published and unpublished data
**Years of observations since warming started

Characteristics of each site included in study, including both published and unpublished sources (6–17).

Table S2

Parameters for models: $\ln(R) \sim \alpha_0 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 M$						
Model	**$\alpha_0 \pm$ SE**	**$\alpha_1 \pm$ SE**	**$\alpha_2 \pm$ SE**	**$\alpha_3 \pm$ SE**	**n**	**R^2**
All Biomes Except Desert	-1.547 ± 0.078	0.210 ± 0.008	-0.004 ± 0.0022	0.692 ± 0.142	2343	0.39
Desert						
Control Treatment	-2.875 ± 0.069	0.009 ± 0.007	0.001 ± 0.0002	3.320 ± 0.474	737	0.38
Warming Treatment	-4.065 ± 0.078	0.005 ± 0.008	<0.0001 ± 0.0002	7.228 ± 0.549	737	0.53
Boreal Forest						
Control Treatment	0.020 ± 0.085	0.108 ± 0.003	na	-0.286 ± 0.256	160	0.88
Warming Treatment	-0.368 ± 0.074	0.098 ± 0.003	na	1.301 ± 0.231	306	0.82
Temperate Forest	-1.082 ± 0.157	0.152 ± 0.017	-0.002 ± 0.0005	0.817 ± 0.234	497	0.52
Northern Shrubland	-1.180 ± 0.106	0.142 ± 0.006	na	0.020 ± 0.187	344	0.63
Southern Shrubland	-1.825 ± 0.244	0.109 ± 0.022	-0.001 ± 0.0005	2.236 ± 0.234	102	0.6
Grassland	-1.338 ± 0.145	0.201 ± 0.015	-0.004 ± 0.0004	-0.708 ± 0.299	566	0.52
Temperate Agriculture	-3.076 ± 0.206	0.304 ± 0.022	-0.006 ± 0.0078	0.202 ± 0.597	262	0.72

Parameters for multivariate regression model of soil respiration (natural log, in μmol C m^{-2} s^{-1}) (R) as a function of soil temperature (°C) (T) and soil moisture (cm^3 cm^{-3}) (M). In biomes with significantly different temperature sensitivities between warming and control treatments (boreal and desert biomes), control and warmed data were run in model separately. n= number of observations, R^2 = coefficient of determination. Parameter units: α_0 = ln μmol C m^{-2} s^{-1}; α_1= $°C^{-1}$; α_2 = $°C^{-2}$, α_3 = cm^{-3} cm^3.

Table S3.

Model ID	Model Terms	Significant Interaction?	df	R^2	Δ AICc
All Biomes Except Desert (n=2343)					
a	R~**T**	NA	2341	0.30	1745
b	R~**T** + **T^2**	NA	2340	0.39	1436
c	R~**T***W	No	2339	0.30	1744
d	R~**T***W + **T^2***W	No	2327	0.39	1437
e	R~**T** + **T^2** + **Moisture**	NA	2339	0.39	1415
f	R~**T***Moisture + **T^2***Moisture	No	2337	0.41	1359
g	R~**T** + **T^2** + **Moisture** + **Duration**	NA	2338	0.40	1393
h	R~**T** + **T^2** + **Duration***W	No	2337	0.39	1429
i	R~**T** + **T^2** + **Season***W	No	2335	0.44	1222
j	R~**T***Biome + **T^2***Biome + **Moisture**	Yes	2321	0.67	0
Desert (n=1474)					
a	R~**T**	NA	1472	0.34	318
b	R~**T** + T^2	NA	1471	0.34	320
c	R~**T*W**	Yes	1470	0.41	153
d	R~**T*W** + **T^2*W**	Yes	1468	0.42	144
e	R~**T** + **T^2** + **Moisture**	NA	1470	0.42	140
f	R~T***Moisture** + T^2*Moisture	Yes	1468	0.47	0
g	R~**T** + **T^2** + **Moisture** + Duration	NA	1469	0.42	139
h	R~**T** + T^2 + **Duration*W**	Yes	1468	0.42	143
i	R~**T** + **T^2** + **Season*W**	Yes	1466	0.44	76
Boreal Forest (n=466)					
a	R~**T**	NA	464	0.82	52
b	R~**T** + **T^2**	NA	463	0.82	43
c	R~**T*W**	Yes	463	0.84	2
d	R~**T***W + T^2*W	No	460	0.84	0
e	R~**T** + **Moisture**	NA	463	0.82	34
f	R~**T***Moisture	Yes	462	0.83	21
g	R~**T** + **Moisture** + **Duration**	NA	462	0.83	29
h	R~**T** + **Duration*W**	Yes	461	0.83	8
i	R~**T** + **T^2** + **Season***W	Yes	459	0.83	12
Temperate Forest (n=497)					
a	R~**T**	NA	495	0.49	92
b	R~**T** + **T^2**	NA	494	0.51	77
c	R~**T***W	No	493	0.52	62
d	R~**T***W + **T^2***W	No	491	0.54	46
e	R~**T** + **T^2** + **Moisture**	NA	493	0.52	67
f	R~**T***Moisture + T^2*Moisture	No	491	0.52	69
g	R~**T** + **T^2** + **Moisture** + Duration	NA	492	0.52	69
h	R~**T** + **T^2** + Duration***W**	Yes	491	0.54	45
i	R~**T** + **T^2** + **Season***W	No	489	0.58	0
Northern Shrubland (n=344)					
a	R~**T**	NA	342	0.63	60
b	R~**T** + T^2	NA	341	0.63	62
c	R~**T***W	No	340	0.63	64
d	R~**T***W + T^2*W	No	338	0.63	65
e	R~**T** + Moisture	NA	341	0.63	62
f	R~**T***Moisture	No	340	0.63	63
g	R~**T** + **Moisture** + **Duration**	NA	340	0.69	0
h	R~**T** + **Duration*W**	Yes	339	0.69	7
i	R~**T** + Season*W	No	337	0.63	66

Table S3 Continued.

Model ID	Model Terms	Significant Interaction?	df	R^2	Δ AICc
Southern Shrubland - no Hungary (n=102)					
a	R~**T**	NA	100	0.15	92
b	R~**T** + T^2	NA	99	0.23	85
c	R~**T***W	No	98	0.16	96
d	R~**T***W + $\mathbf{T}^2$*W	No	96	0.25	88
e	R~**T** + $\mathbf{T}^2$ + **Moisture**	NA	98	0.60	19
f	R~**T***Moisture + T^2*Moisture	No	96	0.60	23
g	R~**T** + $\mathbf{T}^2$ + **Moisture** + **Duration**	NA	97	0.68	0
h	R~**T** + $\mathbf{T}^2$ + **Duration***W	No	96	0.47	46
i	R~**T** + $\mathbf{T}^2$ + Season*W	No	94	0.18	93
Southern Shrubland - with Hungary (n=144)					
a	R~T	NA	142	0.06	124
b	R~T + $\mathbf{T}^2$	NA	141	0.09	120
c	R~**T***W	No	140	0.06	127
d	R~T*W + T^2*W	No	138	0.11	123
e	R~**T** + $\mathbf{T}^2$ + **Moisture**	NA	140	0.6	4
f	R~T*Moisture + $\mathbf{T}^2$*Moisture	No	128	0.62	0
g	R~T + T^2 + **Moisture** + **Duration**	NA	139	0.62	1
Grassland (n=566)					
a	R~**T**	NA	564	0.45	151
b	R~**T** + $\mathbf{T}^2$	NA	563	0.52	82
c	R~**T***W	No	562	0.45	154
d	R~**T***W + $\mathbf{T}^2$*W	No	560	0.51	87
e	R~T + $\mathbf{T}^2$ + **Moisture**	NA	562	0.52	78
f	R~**T***Moisture + $\mathbf{T}^2$*Moisture	Yes	560	0.54	51
g	R~**T** + $\mathbf{T}^2$ + Moisture + **Duration**	NA	561	0.56	24
h	R~**T** + $\mathbf{T}^2$ + **Duration***W	No	560	0.56	24
i	R~**T** + $\mathbf{T}^2$ + **Season***W	No	558	0.58	0
Temperate Agriculture (n=262)					
a	R~**T**	NA	260	0.66	73
b	R~**T** + $\mathbf{T}^2$	NA	259	0.72	17
c	R~**T***W	No	258	0.66	75
d	R~**T***W + T^2*W	No	256	0.73	22
e	R~**T** + $\mathbf{T}^2$ + Moisture	NA	258	0.72	19
f	R~**T*Moisture** + $\mathbf{T}^2$***Moisture**	Yes	256	0.74	9
g	R~**T** + $\mathbf{T}^2$ + Moisture + **Duration**	NA	257	0.73	16
h	R~**T** + $\mathbf{T}^2$ + Duration*W	No	256	0.73	18
i	R~**T** + $\mathbf{T}^2$ + **Season***W	No	254	0.74	0

Summary of various models and their fits of soil respiration as a function of multiple variables. R = soil respiration (natural log, in μmol C m^{-2} s^{-1}), T = soil temperature (°C), M= soil moisture content (cm^3 cm^{-3}), W = treatment (control or warmed), df=degrees of freedom, R^2= coefficient of determination, ΔAICc = delta Akaike information criterion, with zero as best and all other model values presented relative to zero. Bold indicates significant predictor of respiration. Asterisk indicates interaction term in model.

Table S4.

Parameters for models: $LnR \sim \alpha_o + \alpha_1 T + \alpha_2 T^2$					
Moisture Quartile ($cm^3 cm^{-3}$)	α_o	α_1	α_2	n	R^2
Non-desert biomes					
First quartile (<0.163)	-0.897	0.147	-0.0029	585	0.13
Second quartile (0.163-0.228)	-1.410	0.211	-0.0038	580	0.49
Third quartile (0.228-0.29)	-1.224	0.201	-0.0036	559	0.42
Fourth quartile (>0.29)	-1.276	0.188	-0.0033	605	0.46
Desert - Control					
First quartile (<0.082)	-2.010	-0.032	0.0011	184	0.01
Second quartile (0.082-0.102)	-2.418	0.016	0.0002	185	0.23
Third quartile (0.102-0.139)	-3.200	0.074	-0.0005	183	0.59
Fourth quartile (>0.139)	-3.170	0.046	0.0012	185	0.88
Desert - Warmed					
First quartile (<0.082)	-3.544	0.023	0.0008	184	0.60
Second quartile (0.082-0.102)	-3.220	0.066	-0.0012	183	0.17
Third quartile (0.102-0.14)	-3.300	0.051	0.0002	184	0.46
Fourth quartile (>0.14)	-3.155	0.049	0.0054	186	0.76
Boreal Forest - Control					
First quartile (<0.21)	-0.147	0.110	na	40	0.90
Second quartile (0.21-0.245)	-0.150	0.120	na	40	0.94
Third quartile (0.245-0.284)	-0.014	0.108	na	40	0.94
Fourth quartile (>0.284)	0.026	0.100	na	40	0.72
Boreal Forest - Warmed					
First quartile (<0.186)	-0.308	0.099	na	77	0.85
Second quartile (0.186-0.226)	-0.069	0.100	na	77	0.82
Third quartile (0.226-0.263)	-0.067	0.103	na	76	0.90
Fourth quartile (>0.263)	0.106	0.087	na	76	0.75
Temperate Forest					
First quartile (<0.176)	0.530	0.002	0.0013	124	0.20
Second quartile (0.176-0.233)	-1.800	0.232	-0.0040	128	0.68
Third quartile (0.223-0.279)	-1.126	0.176	-0.0024	120	0.64
Fourth quartile (>0.279)	-0.672	0.140	-0.0019	125	0.54
Northern Shrubland					
First quartile (<0.2157)	-1.183	0.145	na	86	0.83
Second quartile (0.2157-0.389)	-1.167	0.144	na	86	0.57
Third quartile (0.389-0.458)	-1.106	0.128	na	86	0.37
Fourth quartile (>0.458)	-1.115	0.132	na	86	0.45
Southern Shrubland					
First quartile (<0.1128)	-1.990	0.114	-0.0012	26	0.31
Second quartile (0.1128-0.199)	-3.200	0.230	-0.0031	25	0.54
Third quartile (0.199-0.2898)	-1.505	0.167	-0.0040	25	0.37
Fourth quartile (>0.2898)	-1.560	0.228	-0.0042	26	0.55
Grassland					
First quartile (<0.141)	-0.990	0.195	-0.0040	141	0.29
Second quartile (0.141-0.23)	-1.240	0.156	-0.0020	142	0.68
Third quartile (0.23-0.29)	-0.827	0.104	0.0006	142	0.47
Fourth quartile (>0.291)	-1.570	0.175	-0.0020	141	0.52
Temperate Agriculture					
First quartile (<0.151)	-2.816	0.310	-0.0070	65	0.74
Second quartile (0.151-0.198)	-3.810	0.431	-0.0100	66	0.78
Third quartile (0.198-0.25)	-3.126	0.264	-0.0039	65	0.62
Fourth quartile (>0.25)	-2.530	0.207	-0.0026	66	0.76

Parameters for models of natural log (ln) respiration (µmol C m^{-2} s^{-1}) as a function of soil temperature (°C) by moisture quartile for each biome. Data also shown in Fig. S3.

Table S5

Model	$\gamma_0 \pm SE$	$\gamma_1 \pm SE$	$\gamma_2 \pm SE$	n	R^2
All Biomes Except Desert					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-0.445 ± 0.038	0.072 ± 0.002	na	2343	0.30
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-1.302 ± 0.059	0.204 ± 0.008	-0.0041 ± 0.0002	2343	0.39
Desert					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-2.970 ± 0.032	0.042 ± 0.002	na	1474	0.34
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-2.993 ± 0.047	0.046 ± 0.006	-0.0001 ± 0.0002	1474	0.34
Boreal Forest					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	0.003 ± 0.031	0.095 ± 0.002	na	466	0.82
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-0.170 ± 0.060	0.127 ± 0.010	-0.0012 ± 0.0004	466	0.82
Temperate Forest					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-0.288 ± 0.061	0.076 ± 0.004	na	497	0.49
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-0.803 ± 0.136	0.146 ± 0.017	-0.0022 ± 0.0005	497	0.51
Northern Shrubland					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-1.171 ± 0.057	0.142 ± 0.006	na	344	0.63
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-1.176 ± 0.100	0.143 ± 0.024	-0.0001 ± 0.0013	344	0.63
Southern Shrubland					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-0.132 ± 0.145	0.026 ± 0.006	na	102	0.15
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-1.020 ± 0.317	0.118 ± 0.030	-0.0020 ± 0.0006	102	0.23
Grassland					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-0.654 ± 0.070	0.077 ± 0.004	na	566	0.45
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-1.531 ± 0.120	0.202 ± 0.015	-0.0035 ± 0.0004	566	0.51
Temperate Agriculture					
$\ln(R) \sim \gamma_0 + \gamma_1 T$	-2.166 ± 0.097	0.134 ± 0.006	na	262	0.66
$\ln(R) \sim \gamma_0 + \gamma_1 T + \gamma_2 T^2$	-3.025 ± 0.138	0.304 ± 0.022	-0.0063 ± 0.0008	262	0.72

Parameters for multivariate regression model of soil respiration (natural log, in μmol C m^{-2} s^{-1}) (*R*) as a function of soil temperature (°C) (*T*), including data from both control and warmed treatments (Models a and b in Table S3). Parameters shown for both the log-linear and log-quadratic temperature response functions. n = sample size, R^2= correlation coefficient. Parameter units: γ_0 = ln μmol C m^{-2} s^{-1}; γ_1 = °C^{-1}, γ_2 = °C^{-2}. All models significant (p<0.001). For comparison of model fits, see Table S3. For model parameters of control versus warmed plots, see Table 1.

Table S6.

Comparison of Model Fits (R^2)		
Biome Type	Eq. 2	Eq. 4
All non-desert	0.39	0.33
Desert	0.42	0.40
Boreal Forest	0.82	0.80
Temperate Forest	0.51	0.44
Northern Shrubland	0.63	0.53
Southern Shrubland (no Hungary)	0.60	0.13
Southern Shrubland (includes Hungary)	0.60	0.03
Grassland	0.52	0.39
Agriculture	0.72	0.63

Comparison of model fits (Eq. 2, Eq. 4) evaluating role of soil moisture in driving soil respiration.