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3 **Full Title: Temperature response of soil respiration largely unaltered with experimental warming**

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5 **Short Title: Soil respiration largely unaltered with experimental warming**

6  
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62  
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64 response  
65

66 **Abstract:**

67 The respiratory release of carbon dioxide (CO<sub>2</sub>) from soil is a major and yet, poorly understood flux in the  
68 global carbon cycle. Climatic warming is hypothesized to increase rates of soil respiration, potentially  
69 fueling further increases in global temperatures. However, despite considerable scientific attention in  
70 recent decades, the overall response of soil respiration to anticipated climatic warming remains unclear.  
71 We synthesize the largest global dataset to date of soil respiration, moisture, and temperature  
72 measurements, totaling >3800 observations representing 27 temperature manipulation studies, spanning  
73 nine biomes and over two decades of warming. Our analysis reveals no differences in the temperature  
74 sensitivity of soil respiration between control and warmed plots in all biomes, with the exception of  
75 deserts and boreal forests. Thus, our data provide limited evidence of acclimation of soil respiration to  
76 experimental warming in several major biome types, contrary to the results from multiple single-site  
77 studies. Moreover, across all non-desert biomes, respiration rates with and without experimental warming  
78 follow a Gaussian response, increasing with soil temperature up to a threshold of ~25°C, above which,

79 respiration rates decrease with further increases in temperature. This consistent decrease in temperature  
80 sensitivity at higher temperatures demonstrates that rising global temperatures may result in regionally  
81 variable responses in soil respiration, with colder climates being considerably more responsive to  
82 increased ambient temperatures compared to warmer regions. Our analysis adds a unique cross-biome  
83 perspective on the temperature response of soil respiration, information critical to improving our  
84 mechanistic understanding of how soil carbon dynamics change with climatic warming.

85

86 **Significance Statement:** One of the greatest challenges in projecting future shifts in the global climate is  
87 to understand how soil respiration rates will change with warming. Multiple experimental warming  
88 studies have been conducted to explore this response, but no consensus has been reached. Based on a  
89 global synthesis of 27 experimental warming studies spanning nine biomes, we find that although  
90 warming increases soil respiration rates, there is limited evidence for a shifting respiration response with  
91 experimental warming. We also note a universal decline in the temperature sensitivity of respiration at  
92 soil temperatures  $>25^{\circ}\text{C}$ . Together, our data indicate that future respiration rates will often follow the  
93 current temperature response function, but higher latitudes will be more responsive to warmer  
94 temperatures.

95

96 **Text:**

97 **\body**

98 Compared to anthropogenic emissions, roughly nine times more carbon dioxide ( $\text{CO}_2$ ) is released from  
99 soils to the atmosphere via soil respiration on an annual basis (1). Both plant root respiration and  
100 microbial respiration during the decomposition of organic matter contribute to this efflux of carbon (C)  
101 from soils, cumulatively estimated at  $\sim 90 \text{ Pg C yr}^{-1}$ (2). Rising temperatures are expected to stimulate soil  
102 respiration (3), both by accelerating rates of C cycling via autotrophic respiration and by providing a  
103 potentially powerful positive feedback to climatic warming via heterotrophic decomposition of organic  
104 matter. However, due to a suite of factors beyond temperature that control soil respiration rates (e.g., soil

105 moisture, C substrate quality and quantity, nutrient availability), the interaction between temperature and  
106 respiration remains uncertain (3–5). As such, soil respiration is a major and poorly understood flux in the  
107 global C cycle.

108  
109 Experimental warming of soils is one approach used to understand the complex relationship between  
110 respiration and temperature, as it allows scientists to separate the effects of warming from confounding  
111 environmental variation (e.g., soil type, plant species composition). Results of experimental studies reveal  
112 a range of responses of soil respiration to warming, with few unifying trends observed across biomes (6–  
113 8). Although warming has been shown to stimulate soil respiration within many sites, several studies  
114 show neutral, or even negative responses to warming, often attributed to moisture limitation (9, 10), shifts  
115 in microbial physiological response or composition (11–13), or depletion of labile C pools (14–17). As  
116 such, multiple single-site analyses find evidence of acclimation (sometimes termed thermal adaptation) of  
117 soil respiration to experimental warming (10–14, 16, 17), although others report no evidence for such  
118 shifts in respiration response over time (18–20). Moreover, the response of soil respiration to temperature  
119 is not consistent across all temperature ranges, as the temperature sensitivity of respiration typically  
120 decreases under warmer conditions (21, 22). As a result, the interaction between soil respiration and  
121 climate warming remains one of the greatest sources of uncertainty in climate projections, despite being  
122 an important boundary condition in current Earth system models (ESMs) (4, 23, 24).

123  
124 Current understanding of how soil respiration responds to experimental warming stems from single-site  
125 warming experiments, or traditional meta-analyses based on average or cumulative soil respiration values  
126 in control versus warmed plots. To date, no cross-biome synthesis efforts of experimental warming have  
127 evaluated how temperature and moisture interact at high temporal frequencies to determine rates of soil  
128 respiration. Therefore, the goals of this study were to: (i) synthesize the results of experimental warming  
129 studies to understand how the temperature response function of soil respiration changes with experimental  
130 warming treatments across biomes, with respect to both warming duration and seasonality; (ii) investigate

131 the role of soil moisture in driving these responses; and (iii) examine whether a uniform model exists that  
132 can describe the response of soil respiration to temperature across all biomes. To do this, we generated an  
133 unprecedented global dataset of >3800 observations of instantaneous soil respiration, soil temperature,  
134 and soil moisture based on data from 27 individual warming experiments spanning nine biomes and up to  
135 22 years of experimental warming. Our analysis is unique among soil respiration synthesis efforts focused  
136 on warming experiments, in that we used instantaneous observations (i.e., plot-scale measurements of soil  
137 respiration averaged from individual sampling events) rather than annual or monthly averaged values to  
138 evaluate the temperature response function of soil respiration and the interaction with soil moisture at the  
139 global scale.

140

## 141 **Results and Discussion**

### 142 *Evaluating Differences in Temperature Response Function with Experimental Warming*

143 We first sought to determine whether respiration responses from experimentally warmed plots paralleled  
144 those of control plots over the seasonal range of temperature variation at the biome scale. After evaluating  
145 multiple functional forms, we used a log-quadratic temperature response function, as this was the best  
146 supported model for most biomes (Table S3):

147

$$148 \quad (1) \quad \ln(R) = \gamma_0 + \gamma_1 T + \gamma_2 T^2$$

149

150 where  $R$  is soil respiration ( $\mu\text{mol C m}^{-2} \text{s}^{-1}$ ) and  $T$  is soil temperature ( $^{\circ}\text{C}$ ). Using this basic model, we  
151 included warming treatment as an interaction term in order to evaluate differences in the temperature  
152 response between warmed versus control plots (Table 1). We used this log-quadratic model for all biomes  
153 (Model d in Table S3), except the boreal forest and northern shrublands, where a log-linear model ( $\ln(R)$   
154  $= \gamma_0 + \gamma_1 T$ ) was the better fit when including the warming treatment interaction term (Model c in Table  
155 S3). We evaluated two specific features of the temperature response function: (i) the temperature

156 sensitivity (i.e., the shape of the curve denoted by the first derivative of Eq. 1:  $\equiv d \ln(\mathbf{R})/dT$ , Table 1)  
157 and (ii) the magnitude of the respiration response when  $T = 0$  (i.e., the y-intercept of Eq. 1:  $\gamma_0$ , Table 1).

158  
159 Including data from all warming durations and seasons, we observed no significant differences in the  
160 temperature sensitivity of soil respiration between warmed or control treatments within each individual  
161 biome, with the exception of boreal forest and desert (Table 1, Fig. 1). In the boreal forest and desert  
162 biomes, where significant differences in the temperature sensitivities between warmed versus control  
163 plots were observed, trends between treatments were not consistent; compared to control plots, warmed  
164 plots in the boreal forest had consistently lower temperature sensitivity, while in the desert warmed plots  
165 had slightly higher temperature sensitivity at temperatures  $<24^\circ\text{C}$ , but lower sensitivity at temperatures  
166  $>24^\circ\text{C}$  (SI Appendix, Fig. S1, Fig. 2).

167  
168 The lack of difference in the temperature sensitivity of respiration between control and warmed plots in  
169 all biomes except the desert and boreal forests cannot be attributed to an insufficient magnitude of  
170 warming. Across our studies, the desert plots were subjected to a relatively small degree of warming ( $0.34$   
171  $^\circ\text{C}$  on average), but showed the largest differences in sensitivity between treatments. By contrast,  
172 grasslands experienced larger amounts of experimental warming ( $1.9^\circ\text{C}$  on average) (Table S1), but did  
173 not display altered sensitivity between treatments.

174  
175 In addition to evaluating changes in the temperature sensitivities with respiration, (i.e., the shape of the  
176 temperature response function denoted by  $\gamma_1$  and  $\gamma_2$  in Table 1), we also evaluated differences in the  
177 magnitude of respiration rates between treatments (denoted by the y-intercept,  $\gamma_0$ , in Table 1). The desert  
178 was the only biome to display a significantly different y-intercept between warmed versus control plots,  
179 with warmed plots having a lower y-intercept than control plots. Thus, compared to desert control plots,  
180 warmed plots emitted less  $\text{CO}_2$  at a given temperature, despite being generally more sensitive to changes

181 in soil temperature (Fig. 2C). Similar to the desert, temperate forests showed a marginally significant  
182 ( $p=0.06$ ) trend of emitting less CO<sub>2</sub> from warmed plots compared to control plots at a given temperature  
183 ( $\gamma_0$  in Table 1, Fig. 2D). Therefore, although the shapes of the temperature response functions with and  
184 without experimental warming were similar in temperate forests, the magnitude of respiration from  
185 warmed plots was typically lower than from control plots. In turn, despite little difference in temperature  
186 sensitivities between treatments, the reduced fluxes from warmed plots provide evidence of acclimation to  
187 experimental warming in the temperate forest.

188  
189 The lack of difference in temperature response between warmed and control plots in most biomes persists  
190 regardless of warming duration or season. For example, by partitioning the observations into categories of  
191 warming duration (<2, 2-5, 5-10, and >10 years) and season (growing, non-growing, and shoulder) and  
192 running the model described by Eq. 1, we continued to find no differences in the temperature response  
193 function between warmed and control plots, except in the boreal forest and desert. We then ran two  
194 additional multivariate regression models that added duration or season as predictors of soil respiration  
195 with interactions with warming treatment to our temperature response functions (Table S3). Here we  
196 found similar outcomes, with significant interactions between season and warming treatment observed  
197 only in the boreal forest and desert. Significant interactions between duration and warming treatment  
198 were also observed in the boreal forest and desert, in addition to the temperate forest and northern  
199 shrubland. Thus, over time respiration from warmed plots appears to respond differently to temperature  
200 compared to respiration from control plots in these four biomes (see SI Appendix).

201  
202 Together, our results show a similar temperature response of soil respiration from warmed and control  
203 plots across several major biome types, providing limited support of acclimation with experimental  
204 warming at the biome scale, across seasons and often independent of warming duration. However, the  
205 pronounced difference in the temperature response of respiration between treatments in the boreal forest

206 and desert ecosystems suggests that acclimation of soil communities to warmer conditions is likely to  
207 have greater consequences for soil C dynamics in these biomes.

208

### 209 *Changes in Soil Moisture with Experimental Warming*

210 Reductions in soil moisture that accompany experimental warming can influence the soil respiration  
211 response to elevated temperatures (25, 26). Using log response ratios as our index of effect size, we found  
212 that soil moisture was significantly ( $p < 0.05$ ) reduced in warmed plots across all sites, with the magnitude  
213 of this soil drying being weakly correlated to the amount of soil warming at each site ( $p = 0.08$ ;  $r = -0.32$ ;  
214 SI Appendix, Fig. S2A). In situations of severe soil drying, we found evidence that soil respiration  
215 becomes limited by moisture, which in turn changes the respiration-temperature relationship. For  
216 example, not only are the lowest moisture quartiles typically associated with a depressed temperature  
217 response function (Fig. S3,  $\gamma_0$ ,  $\gamma_1$ ,  $\gamma_2$  in Table S4), but the magnitude of the respiration response to  
218 warming decreased linearly with the degree of soil drying across our entire dataset ( $p < 0.05$ , Fig. 3). In  
219 fact, when moisture of warmed plots dropped by at least 30% relative to control plots, respiration rates  
220 were actually lower from warmed plots, despite experiencing higher soil temperatures (Fig. 3; see SI  
221 Appendix).

222

### 223 *A Universal Decline in Temperature Sensitivity at Seasonally Elevated Temperatures*

224 Our dataset of instantaneous soil respiration and temperature measurements allowed us to evaluate the  
225 temperature response function of soil respiration across biomes. We observed a similar Gaussian response  
226 pattern (expressed as a log-quadratic function, Eq. 1) in the soil respiration response across temperature  
227 gradients in most non-desert biomes, with respiration rates increasing with temperature up to  $\sim 25^\circ\text{C}$  (23-  
228  $34^\circ\text{C}$ , depending on the biome), above which respiration rates level off and decrease (Table 1, Fig. 1, Fig.  
229 S4). This common functional form applies to all the non-desert biomes that reach temperatures above  
230  $25^\circ\text{C}$  (thus, excluding boreal forests and northern shrublands), despite variation in temperature response  
231 function parameters among biomes (Table 1, Fig. S4). Low soil moisture at high temperatures partially



232 explains this decreasing sensitivity at elevated temperatures (Fig. S3). Nevertheless, respiration rates  
233 continue to reach a plateau or even slightly decrease at elevated soil temperatures, even under the wettest  
234 conditions in most biomes (Fig. S3, Table S4). In turn, we hypothesize that decreased autotrophic demand  
235 for ATP and enzyme capacity (27), in addition to microbial enzymatic activities reaching their  
236 physiological thermal limit (13, 28), play important roles in the reduced temperature sensitivity under  
237 warmer conditions. The desert was again unique among biomes in that control plots did not display  
238 decreased sensitivity at such high temperatures, and warmed plots displayed dramatically higher  
239 temperature threshold for reduced respiration (55°C) (Table 1, Fig. 1). The fundamentally different  
240 response of soil respiration to temperature in deserts could be due to several factors, namely higher  
241 respiration temperature optima and maxima of plant and microbial communities in the desert compared to  
242 other ecosystems (28), or the importance of abiotic (i.e., UV-driven) decomposition as a major component  
243 of litter decomposition in deserts (29).

244

#### 245 *Regionally Variable Response to Global Change*

246 The reversal in the direction of the temperature response at temperatures greater than ~25°C observed in  
247 most non-desert biomes suggests that warmer global temperatures will result in regionally variable  
248 responses in soil respiration rates, as different regions occupy different positions on the shared  
249 temperature-response function. Compared to lower latitudes, higher latitude sites more often experience  
250 soil temperatures <25°C, where the relationship between soil respiration and temperature is nearly  
251 exponential. As such, our data indicate that higher latitude sites will be more responsive to increased  
252 ambient temperatures compared to warmer regions that more frequently experience soil temperatures  
253 >25°C. Our results also support the idea that models of soil respiration based on fixed parameters (e.g.,  
254 fixed  $Q_{10}$  in an exponential function) are inadequate for describing the respiration response across the full  
255 temperature range (4, 21, 22). Without accounting for reduced temperature sensitivity at elevated  
256 temperatures, ESMs will likely over-estimate soil respiration rates in response to climate warming,  
257 particularly from lower latitude regions.

258

259 *Limited Evidence of Acclimation of Soil Respiration to Experimental Warming*

260 Acclimation of soil respiration to soil warming can manifest itself in different ways, both via changing the  
261 shape of the temperature response curve (i.e., temperature sensitivity) and position of the curve on the y-  
262 axis (i.e., y-intercept). Our analyses addressed both of these factors, finding evidence of shifting  
263 sensitivities only in the desert and boreal forest biomes, and lower fluxes at a given temperature (i.e., y-  
264 intercepts) from warmed plots in the desert ( $p < 0.01$ ) and temperate forest ( $p = 0.06$ ) biomes. Such reduced  
265 fluxes from warmed plots in the desert and temperate forests could be a consequence of soil drying, as  
266 desert and temperate forest warmed plots had less soil moisture than control plots (3% and 13%  
267 difference in soil moisture between warmed and control plots in desert and temperate forests,  
268 respectively). However, reduced C substrate supply (14) and microbial acclimation (11, 13) could be  
269 factors contributing to reduced fluxes at a given temperature in these biomes.

270

271 The lack of difference in the respiration temperature response functions that we observe between warmed  
272 versus control treatments within most biomes highlights a commonality among treatments often not  
273 observed in single-site studies (10–14, 16, 17). This finding suggests that, in many regions of the globe,  
274 simply measuring ambient respiration rates across a seasonal temperature gradient within a site will yield  
275 a similar temperature response to measurements made in a soil warming experiment (Fig. 2A). That is,  
276 seasonally-driven soil respiration-temperature response curves appear to be largely adequate at predicting  
277 how future warming will alter fluxes of CO<sub>2</sub> from soils to the atmosphere. Nevertheless, the relative roles  
278 of autotrophic versus heterotrophic soil respiration and how these processes change with warming  
279 remains poorly defined, but critical to understanding the strength of soil respiration feedbacks to climate  
280 change (30). In addition, it is unclear if the lack of difference in respiration response between control  
281 versus warmed treatments that we observe here will persist over the long-term, as the majority of the  
282 extant experiments have a relatively short duration (<5 years). Considering that significant interactions  
283 between experiment duration and warming treatment were observed in several biome types, long-term

284 studies are necessary to fully disentangle interactions between warming, soil respiration and other  
285 ecosystem components (e.g., C substrate quality and quantity, nutrient and water availability, shifts in  
286 microbial community) (31).

287  
288 Our conclusions are based on the largest and highest resolution global dataset of soil respiration response  
289 to experimental warming in existence, to our knowledge. The scale and magnitude of our dataset provide  
290 a unique opportunity to enhance our understanding of the sensitivity of global C stocks to warming.  
291 However, current understanding of how soil respiration will respond to warmer temperatures is restricted  
292 to the types of biomes where experimental warming studies occur, predominantly in North America and  
293 Europe. We stress the importance of expanding experimental warming studies to underrepresented  
294 regions, specifically the Arctic and the tropics. Northern latitudes are warming faster than other parts of  
295 the globe (32) and store extremely large amounts of C in soils (33). However, measurements of ecosystem  
296 respiration are far more common than those of soil respiration in the Arctic, making it challenging to  
297 tackle the roles of plant versus microbial responses to global change in these systems. Plant and microbial  
298 communities in tropical latitudes, where no experimental warming manipulations have been published,  
299 may be pushed past their physiological temperature optima with even slight warming. As we demonstrate  
300 here, major changes to the shape of the seasonal response curve at higher ambient temperatures are  
301 common, but not well defined. Thus, exploring the biome-specific responses of soil respiration as  
302 temperatures shift beyond the historical range of variability is critical to understanding soil C dynamics in  
303 a warmer world.

304

## 305 **Methods**

306 Data for this study were obtained from a combination of unpublished data and published literature values  
307 (SI Appendix). Our synthesis generated a dataset that includes 3817 observations, from control (n=1812),  
308 first (i.e., lowest or sole) level warming (n=1812), second (higher) level warming (n=179, four studies),  
309 and third-level warming (n=14, one study) (Table S1).

310  
311 *Evaluating Temperature Response Functions*  
312 Our models investigated the role of warming treatment, moisture, season, and warming duration in  
313 controlling the temperature response function of soil respiration across biomes (SI Appendix). Individual  
314 biomes represented by >100 data points were analyzed individually, which excluded montane meadow  
315 and tundra ecosystems from being analyzed in isolation. Different multivariate models (Table S3) were  
316 used to investigate different questions (SI Appendix). To evaluate whether respiration responses from the  
317 warmed plots paralleled those from control plots, we used multiple linear regression to model respiration  
318 as a function of soil temperature, with temperature as a continuous variable and warming treatment as a  
319 binary categorical variable (warming (“W=1”) or control (“W”=0) treatment) (Table 1) (Model c and d,  
320 Table S3). The categorical term was accompanied by an interaction with soil temperature, which allowed  
321 us to analyze the influence of warming treatment on soil respiration while taking into account the  
322 influence of temperature. Our criteria for the warming treatment interaction model selection (Model c vs d  
323 in Table S3) were to 1) include only significant temperature terms, and 2) in models with significant  
324 temperature terms, use Akaike information criterion (AIC) for model selection. We examined differences  
325 in the temperature sensitivity between warmed and control plots using the first derivative of Eq. 1 (Table  
326 1). This model is equivalent to  $R = \exp(\gamma_0 + \gamma_1 T + \gamma_2 T^2)$ . However, for boreal forest and northern  
327 shrubland data, we used a log-linear model (i.e.,  $R = \exp(\gamma_0 + \gamma_1 T)$ ), because the second order temperature  
328 term was not significant in models including the treatment interaction for these biomes (Fig. 1, Table S3).  
329 These two models nearly approximate one another when T is <25 °C, as in the cases of the boreal and  
330 northern shrubland. Thus, the better fit of the monotonic log-linear model in the boreal forest and northern  
331 shrubland biomes verifies our model choice of the log-quadratic function, as the log-quadratic function  
332 shows a decreasing trend in soil respiration when temperature is higher than 25 °C. We calculated the  
333 temperature threshold of maximum respiration in each biome by setting the derivate of Eq. 1 equal to zero  
334 (Table 1). We also compared the AICs of Models c or d with models excluding warming treatment as a

335 predictor (Models a or b) to further investigate whether warming treatments had an effect on the  
336 respiration response (Table S3); lower AICs for models without the warming treatment term indicate that  
337 experimental warming does not alter the shape of the curve to a large degree. One southern shrubland site  
338 (“Hungary”, Table S1) (34) contained limited data across its temperature gradient and therefore was not  
339 included in our analysis of temperature response functions, although the model results with and without  
340 inclusion of this site are included in Table S3 for comparison. To test for a difference in sensitivity  
341 between biomes, we ran a multiple linear regression with biome type as a predictor and as an interaction  
342 term with temperature (Model j in Table S3).

343

#### 344 *Data Transformation and Model Diagnostics*

345 Respiration data were transformed using natural log (which transforms exponential functions into linear  
346 functions) in order to meet assumptions of regression models and to minimize the role of outliers in  
347 altering the response functions. In turn, model outputs must be transformed to represent the actual values  
348 (i.e., y-intercepts in Table 1 should be anti-logged to represent the soil respiration flux at 0°C). All model  
349 residuals fit the assumption of normal distributions, except the models of all non-desert biomes together  
350 and the temperate agriculture biome in isolation, where residuals were left-tail skewed. Because the desert  
351 had significantly lower respiration rates compared to all other biomes (Fig. S4), models were never run  
352 with all data together, as combined residuals were distinctly bi-modal. For all models included in our  
353 analysis, co-linearity between soil moisture and soil temperature was evaluated by calculating variance  
354 inflation factors (VIF) (35), which were always <1.5, indicating extremely limited co-linearity. Power  
355 analysis (36) revealed power = 1 for all models, except multivariate regression of the southern shrubland  
356 warming interaction, where power=0.95.

357

#### 358 *Meta-Analysis*

359 We used meta-analysis to quantify 1) how warming altered the magnitude of soil respiration and moisture  
360 across sites (SI Appendix, Fig. S2) and 2) whether first-order temperature sensitivities were different

361 between warmed and control plots at the site level (SI Appendix, Fig. S8). We used the log response ratio  
362 (RR) as our index of effect size (37) in determining how warming altered the magnitudes of temperature,  
363 respiration, and moisture, which was calculated as the natural log proportional change in the means of the  
364 treatment ( $X_T$ ) and the control ( $X_C$ ) groups:

365

366 (3) 
$$RR = \ln(X_T/X_C)$$

367

368 and a random effect model (38). We used the standardized mean difference (raw mean difference divided  
369 by pooled standard deviation) and random effect model to determine differences in temperature  
370 sensitivities between treatments across sites. All meta-analysis was done using the metafor package in R  
371 (39). Effect sizes with 95% confidence intervals overlapping zero indicate no significant effect of  
372 warming on the factor in question. Values greater than zero indicate that warming increased soil  
373 temperature, soil moisture, soil respiration, and/or temperature sensitivity, while values lower than zero  
374 indicate that warming decreased these values. In studies with multiple levels of warming treatment (4  
375 studies, Table S1), data from the warmest treatment were used to compute effect sizes. Data from Site ID  
376 17(40) were excluded from Fig. S2 due to extremely high effect size ( $RR=0.95$ ) and small difference in  
377 temperature between treatments ( $\Delta T = 0.5$ ). All tests of significance level used alpha ( $\alpha$ ) of 0.05. All  
378 analysis and statistics were done in R (version 3.2.0) (41).

379

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398

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531  
532

### 533 **Figure Legends**

534 Fig. 1. Ln respiration ( $\mu\text{mol C m}^{-2} \text{ s}^{-1}$ ) as a function of soil temperature ( $^{\circ}\text{C}$ ) across biome types. Data are  
535 instantaneous measurements from control (blue circles) and warmed (red circles) treatments, with best fit  
536 regression lines fitted through control and warmed values (for coefficients, see Table 1). Temperature  
537 sensitivity in control versus warmed plots was not significantly different, except in desert and boreal  
538 forest biomes (Table 1). Note, Y-axis scales are all equal, except for desert, which had lower respiration  
539 rates compared to all other biomes (Fig. S4). For partial regression plots of respiration on temperature and  
540 moisture, see Fig. S7.

541

542 Fig. 2. Conceptual diagram of instantaneous delta respiration ( $\Delta R$ ) and temperature ( $\Delta T$ ) response  
543 between warmed (red symbols) and control (blue symbols) treatments on a given day of measurements at  
544 the lower end of the temperature range ( $<25^{\circ}\text{C}$ ). Circles represent sampling date in spring, while stars

545 represent sampling date in summer. A) All non-desert biomes, except boreal forests: Despite the increase  
546 of respiration with warming on a given day of measurements, the temperature response function (the  
547 dotted line) across the different colors (the warming effect) is similar to that across the different symbols  
548 (the seasonal temperature variation). B) Boreal forests: Warmed plots (dashed line) had lower sensitivity  
549 compared to control plots (solid line). However, no significant differences in the y-intercept were  
550 observed c) Desert: Warmed plots (dashed line) had a lower y-intercept, but higher sensitivity compared  
551 to control plots (solid line). D) Temperate forest: Despite displaying similar temperature sensitivities, y-  
552 intercepts of warmed plots (dashed line) were marginally ( $p=0.06$ ) lower than control plots (solid line).  
553 Delta response was always calculated as warmed value minus control value.

554

555 Fig. 3. Difference in respiration ( $\mu\text{mol C m}^{-2} \text{ s}^{-1}$ ) between warmed and control plots normalized by degree  
556 of warming ( $\Delta T$  °C), binned by amount of soil desiccation with warming (soil moisture content warmed  
557 plots divided by soil moisture content control plots) across the entire dataset. X axis values  $<1$  indicate  
558 warmed plots have less moisture available than control plots. Y axis values  $<0$  indicate that respiration  
559 rates were lower from warmed plots, despite warmer soil temperatures. Respiration data were not log  
560 transformed. Delta respiration was always calculated as warmed values minus control values.

561