

How do climate change experiments alter plot-scale climate?

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December 3, 2018

Statement of authorship All authors conceived of this manuscript, which was inspired by our discussions at a Radcliffe Exploratory Seminar in 2016, and all authors contributed to manuscript revisions. AKE and EMW conceived of the idea for the literature review, database compilation, and related Radcliffe Exploratory Seminar. AKE compiled the datasets; AKE and CRR analyzed the data and created the figures; AKE wrote the manuscript.

Data Accessibility The MC3E database will be available at KNB (Ettinger & Wolkovich, 2018), along with all R code from the analyses included in this paper. (Currently, metadata are published there; the full database and R code are available to reviewers on github.)

Running title Experimental climate change

Key words global warming, warming experiment, microclimate, soil moisture, spring phenology, budburst, direct and indirect effects, structural control, hidden treatment, active-warming, target temperature, feedback

Type of article Review and Synthesis

Number of words in abstract 233

Number of words in main text 5,543

Number of references 98

Number of figures 7

Number of tables 1

Number of text boxes 2

Number of words in Box 1 517

Number of words in Box 2 626

¹ Abstract

² To understand and forecast biological responses to climate change, scientists frequently use field experiments
³ that alter temperature and precipitation. Climate manipulations can manifest in complex ways, however,
⁴ challenging interpretations of biological responses. We reviewed publications from active-warming experi-
⁵ ments to compile a database of daily plot-scale climate data from 15 experiments that use forced air, infrared
⁶ heaters, or soil cables to warm plots. We find that the common practices of analyzing primarily mean
⁷ changes among treatments and analyzing treatments as categorical variables (e.g., warmed verses unwarmed)
⁸ masks important variation in treatment effects over space and time. Our synthesis showed that measured
⁹ mean warming, in plots with the same target warming, differed considerably: for example, by 1.1°C per
¹⁰ °C of target warming (10%), on average, for experiments with feedback control and by 2.2°C (120 %) for
¹¹ those using constant wattage. Warming treatments produce non-temperature effects as well, such as soil
¹² drying. The combination of these direct and indirect effects is complex and can have important biological
¹³ consequences. With a case study of plant phenology across four experiments in our database, we show how
¹⁴ accounting for drier soils with warming tripled the estimated sensitivity of budburst to temperature. Our
¹⁵ synthesis yields recommendations for future analyses, experimental design, and data sharing to improve our
¹⁶ mechanistic understanding of what drives variation across studies, and thus improve the utility of climate
¹⁷ change experiments to accurately identify and forecast species' responses.

¹⁸ Introduction

¹⁹ Climate change is dramatically altering earth's biota, shifting the physiology, distribution, and abundance
²⁰ of organisms, with cascading community, ecosystem, and climate effects (Shukla & Mintz, 1982; Cox *et al.*,
²¹ 2000; Thomas *et al.*, 2004; Parmesan, 2006; Field *et al.*, 2007; Sheldon *et al.*, 2011; Urban *et al.*, 2012). Much
²² uncertainty exists about how particular individuals, populations, species, communities, and ecosystems will
²³ respond as warming becomes more extreme (Thuiller, 2004; Friedlingstein *et al.*, 2014). Predicting biolog-
²⁴ ical responses to current and future climate change—and their feedbacks to earth's climate and ecosystem
²⁵ services—is one of the most significant challenges facing ecologists today.

²⁶ Two common approaches for understanding biological effects of climate change are observational studies,
²⁷ which correlate recorded biological patterns with measured climate, and process-based modeling; yet these

28 approaches are insufficient for several reasons. Observational studies and correlative models cannot disen-
29 tangle the causal effects of warming (one aspect of climate) from other factors that have also changed over
30 time, such as successional stage or land use. In addition, models based on correlative data may fail to make
31 useful predictions for future conditions that fall outside the range of historical variability (e.g., Pearson &
32 Dawson, 2004; Hampe, 2004; Ibanez *et al.*, 2006; Swab *et al.*, 2012; Chuine *et al.*, 2016). Climate change will
33 yield warmer temperatures than the previous 150 years, and possibly warmer than at any time in the last
34 2000 years (Ohlemüller *et al.*, 2006; Williams & Jackson, 2007; Williams *et al.*, 2007; Stocker *et al.*, 2013).
35 Process-based models overcome some of these challenges through inclusion of explicit mechanistic relation-
36 ships between climate and biological outcomes. However, they are limited by the processes they include (i.e.,
37 our understanding of mechanism), as well as by the data available to parameterize those processes (Moorcroft,
38 2006; Kearney & Porter, 2009).

39 Experimental data from field-based climate change experiments are crucial to fill these knowledge gaps and
40 determine mechanistic links between climate change and biological responses. Experiments can quantify
41 biological responses to different levels of climate change, and can create the “no-analog” climate scenarios
42 forecasted for the future, particularly when they employ active-warming methods, such as forced air heaters,
43 soil warming cables, or infrared heaters (Shaver *et al.*, 2000; Williams *et al.*, 2007; Aronson & McNulty,
44 2009). In addition, active-warming can be combined with precipitation manipulations (e.g., snow removal,
45 water additions or reductions), offering the ability to assess individual and interactive effects of temperature
46 and precipitation, separate from other environmental changes (e.g., Price & Waser, 1998; Cleland *et al.*,
47 2006; Sherry *et al.*, 2007; Rollinson & Kaye, 2012). Compared with indoor growth-chamber experiments,
48 field-based experiments offer the possibility of preserving important but unknown or unquantified feedbacks
49 among biotic and abiotic components of the studied systems.

50 With climate change experiments, ecologists often aim to test hypotheses about how projected warming
51 will affect species’ growth, survival, and future distributions (Dukes & Mooney, 1999; Hobbie *et al.*, 1999;
52 Morin *et al.*, 2010; Pelini *et al.*, 2011; Chuine *et al.*, 2012; Reich *et al.*, 2015; Gruner *et al.*, 2017). Recent
53 research suggests, however, that climate manipulations may not always alter plot-scale climate (hereafter,
54 microclimate) in ways that are consistent with observed changes over time (Wolkovich *et al.*, 2012; Menke
55 *et al.*, 2014; Polgar *et al.*, 2014; Andresen *et al.*, 2016). For extrapolation of experimental findings to the real
56 world, we need detailed assessments of how active-warming experiments alter the microclimate conditions
57 experienced by organisms, and the extent to which these conditions are similar to current field conditions or

58 anticipated climate change.

59 Here, we investigate the complex ways that active-warming treatments alter microclimate, both directly and
60 indirectly, across multiple studies. The qualitative challenges and opportunities of climate change experi-
61 ments have been summarized previously (e.g., De Boeck *et al.*, 2015) and effects of these manipulations on
62 some aspects of microclimate have been published for individual sites (e.g., Harte *et al.*, 1995; McDaniel
63 *et al.*, 2014b; Pelini *et al.*, 2011). However, our quantitative meta-analysis allows us to examine trends across
64 sites and warming designs (Box 1, Table 1), and make recommendations based on this information. Using
65 plot-level daily microclimate data from 15 active-warming experiments (yielding 59 experiment years and
66 14,913 experiment days; Table S1), we show the direct and indirect ways that experimental manipulations
67 alter microclimate. We use a case study of spring plant phenology to demonstrate how analyses that assume
68 a constant warming effect and do not include non-temperature effects of warming treatments on biological
69 responses may lead to inaccurate quantification of plant sensitivity to temperature shifts. Finally, we syn-
70 thesize our findings to make recommendations for future analysis and design of climate change experiments
71 (Box 2).

72 MicroClimate from Climate Change Experiments (MC3E) database

73 To investigate how climate change experiments alter microclimate, we first identified published, active-
74 warming field experiments, many of which included precipitation manipulations. We focused on *in situ*
75 active-warming manipulations because recent analyses indicate that active-warming methods are the most
76 controlled and consistent methods available for experimental warming (Kimball, 2005; Kimball *et al.*, 2008;
77 Aronson & McNulty, 2009; Wolkovich *et al.*, 2012). We do not include passive-warming experiments because
78 they have been analyzed extensively already and are known to have distinct issues, including reduction in
79 wind, overheating, and great variation in the amount of warming depending on irradiance and snow depth
80 (Marion *et al.*, 1997; Shaver *et al.*, 2000; Wolkovich *et al.*, 2012; Bokhorst *et al.*, 2013, see also Table S2).

81 We carried out a full literature review to identify potential active-warming field experiments to include in
82 the database. We followed the methods and search terms of Wolkovich *et al.* (2012) for their Synthesis of
83 Timings Observed in iNcrease Experiments (STONE) database (Wolkovich *et al.*, 2012), but restricted our
84 focus to active-warming experiments. Further, because our goal was to tease out variation in microclimate

(including temperature and soil moisture), we focused on warming studies that included both/either multiple levels of warming and/or precipitation treatments. These additional restrictions constrained the list to 11 new studies published after the STONE database, as well as six of the 37 studies in the STONE database. We contacted authors to obtain daily microclimate and phenological data for these 17 studies and received data (or obtained publicly available data) for 10 of them, as well as datasets from five additional sites offered or suggested to us over the course of our literature review and data analysis. The daily temperature and soil moisture data from these 15 experiments comprise the MicroClimate from Climate Change Experiments (MC3E) database (Figures 1 and S1, Table S1), which is available at KNB (Ettinger & Wolkovich, 2018). We examined how these experiments altered microclimate, using mixed-effects models that allowed for inherent differences among studies (through a random effect of study on the intercept), while also estimating various across-study effects, such as degree of warming or warming type.

Complexities in interpreting experimental climate change

Climate change experiments often include detailed monitoring of climate variables at the plot-level, yielding large amounts of data, such as daily or hourly temperature and other climate variables, over the course of an experiment. Ecologists, however, are generally interested in the ecological responses (e.g., community dynamics, species' growth, abundance, or phenology), which are collected on much coarser timescales (e.g., seasonally or annually). Not surprisingly then, when analyzing ecological responses, authors typically provide detailed information on the observed biological responses, and report only the mean change in climate over the course of the experiment and whether it matched their target level of change (e.g., Price & Waser, 1998; Rollinson & Kaye, 2012; Clark *et al.*, 2014a,b). Several studies have conducted detailed, independent analyses of microclimate data from warming experiments (e.g., Harte *et al.*, 1995; Kimball, 2005; Kimball *et al.*, 2008; McDaniel *et al.*, 2014b; Pelini *et al.*, 2011). While these detailed analyses provide valuable case studies of experimental effects on microclimate data alone, they have generally not been incorporated into analyses of ecological responses.

In interpreting ecological responses to climate change manipulations, the focus has been primarily on mean shifts in microclimate, but the imposed manipulations result in much more complex shifts. The magnitude of change in these manipulations varies in time and space, and the presence of experimental equipment alone (with no heat added) often alters environmental conditions. These factors, discussed below, challenge

113 our interpretation of how experimental warming studies forecast effects of climate change on organisms and
114 ecosystems. When possible, we compare and contrast these factors across different study methodologies, such
115 as infrared warming versus forced air chambers and constant wattage versus feedback control, because effects
116 on microclimate may vary across these different methodologies (Figure 2, Box 1).

117 **Effects on microclimate vary over time and space**

118 Reporting only the mean temperature difference across the duration of a warming study masks potentially
119 important temporal variation in temperature among treatments (compare Figure 3 to Figure S2). Using
120 the MC3E database, we found that active-warming reduces the range of above-ground daily temperature
121 by 0.37°C per $^{\circ}\text{C}$ of target warming (Table S3, see also Table S1, which details the different methods used
122 to measure and warm temperatures). Active-warming decreased above-ground daily temperature range by
123 differentially affecting maximum and minimum temperatures: warming increased daily minima by 0.81°C
124 per $^{\circ}\text{C}$ of target warming, but only increased daily maxima by 0.48°C per $^{\circ}\text{C}$ of target warming (Table S3).
125 These effects varied by site (Table S3), but we found no clear patterns by warming type (e.g., infrared versus
126 forced air) or warming control (feedback versus constant). Soil daily temperature range was not affected by
127 experimental warming, as warming altered minimum and maximum daily temperatures similarly (Table S4).

128 We observed strong seasonal and annual variations in the effects of experimental warming (Figures 1, 3, Table
129 S5). Warming generally appears close to targets in winter and early spring, and farthest below targets in
130 summer (day of year 150-200, when evapotranspiration within a robust plant canopy can dissipate energy
131 and act to cool vegetation surfaces), though patterns differ among sites (Figure 1). The variation in warming
132 effectiveness may be driven by interactions between warming treatments and daily, seasonal, and annual
133 weather patterns, since the magnitude of warming can vary as weather conditions change. Both infrared
134 heaters and soil cables fail to achieve target temperature increases during rainstorms (Peterjohn *et al.*, 1993;
135 Hoeppner & Dukes, 2012) and with windy conditions (Kimball, 2005; Kimball *et al.*, 2008). Differences
136 between target and actual warming are likely to be particularly great for studies employing constant wattage,
137 rather than feedback control (Box 1, Figure 2). In addition, treatments are often applied inconsistently within
138 or across years. Heat applications are frequently shut off during winter months, and some heating methods,
139 even if left on throughout the year, do not warm consistently (e.g., Clark *et al.*, 2014a,b; Hagedorn *et al.*,
140 2010).

141 Treatment effects also vary spatially, further complicating interpretation of climate change experiments. The
142 MC3E database contains six studies that used blocked designs, allowing us to examine spatial variation in the
143 amount of warming (i.e., the difference between treatment and control plots within a block). These studies
144 include two infrared with feedback control, three infrared with constant wattage, and one soil warming cable
145 with feedback control experiments. We found that the amount of observed warming frequently varied by
146 more than 1°C (mean= 1.6°C, maximum = 4.9°C) among blocks (Figure 3, Table S6). This variation in
147 warming is substantial, as it is equivalent to the target warming treatment for many studies, and appears
148 to vary substantially among sites, which differ in warming methodologies and environmental characteristics,
149 though low sample sizes make disentangling the effect of warming method difficult (Box 1). The differences in
150 warming among blocks may be caused by fine-scale variation in vegetation, slope, aspect, soil type, or other
151 factors that can alter wind or soil moisture, which in turn affect warming (Peterjohn *et al.*, 1993; Kimball,
152 Kimball *et al.*, 2005; Kimball *et al.*, 2008; Hoepfner & Dukes, 2012; Rollinson & Kaye, 2015).

153 Of course, identical experimental treatments across space and time are neither necessary, nor realistic, for
154 robust analysis of experimental results and forecasting. Indeed, the spatial and temporal variation we re-
155 port could improve and refine models, and—at least in some regions—may be consistent with contemporary
156 patterns of climate change (Stocker *et al.*, 2013). Taking advantage of this variation, though, requires under-
157 standing and reporting it (e.g., Milcu *et al.*, 2016). However, because fine-scale and temporal variations in
158 warming treatments are rarely analyzed explicitly with ecological data, the implications for interpretation of
159 experimental findings are unclear.

160 Experimental infrastructure alters microclimate

161 Experimental structures themselves can alter temperature and other important biotic and abiotic variables in
162 ways that are not generally examined in experimental climate change studies. The importance of controls that
163 mimic a treatment procedure without actually applying the treatment is widely acknowledged in biology (e.g.,
164 Dayton, 1971; Spector, 2001; Johnson & Besselsen, 2002; Quinn & Keough, 2002). Though some experimental
165 climate change studies include treatments with non-functional warming equipment as well as ambient controls,
166 the magnitude and effects of experimental infrastructure alone on climate are rarely interpreted or analyzed.
167 To investigate the magnitude of infrastructure effects, we compared temperature and soil moisture data
168 from five active-warming studies at two sites: Duke Forest and Harvard Forest (Farnsworth *et al.*, 1995;

169 Clark *et al.*, 2014b; Marchin *et al.*, 2015; Pelini *et al.*, 2011)(see Supplemental Materials for model details).
170 These were the only studies in the MC3E database that monitored climate in two types of control plots:
171 structural controls (i.e., ‘shams’ or ‘disturbance controls,’ which contained the warming infrastructure: soil
172 cables (n=1), forced air chambers (n=2), or both (n=2), but with no heat applied) and ambient controls with
173 no infrastructure added. Other studies monitored environmental conditions in only structural controls (n=4)
174 or ambient controls (n=5). We were unable to compare ambient and structural controls for experiments
175 using infrared heating, because no studies in our database included both control types. A separate analysis
176 suggested that there may be infrastructure effects on microclimate for infrared studies in our database (see
177 Supplemental Materials, especially Table S7), and infrastructure effects have been documented in other
178 studies (e.g., shading, Table 1 Kimball *et al.*, 2008).

179 We found that experimental structures altered above-ground and soil temperatures in opposing ways: above-
180 ground temperatures were higher in the structural controls than in ambient controls, whereas soil tempera-
181 tures were lower in structural controls compared with ambient controls (Figure 4a-d). This general pattern
182 was consistent across different temperature models (mean, minimum, and maximum temperatures), although
183 the magnitude varied among seasons, studies, and years (Figure 4a-d, Tables S8-S11). We also found that
184 experimental infrastructure decreased soil moisture relative to ambient conditions across all seasons, studies,
185 and years (Figure 4e, Tables S12, S13).

186 There are several possible reasons for the observed climatic differences between ambient and structural con-
187 trols. Infrastructure materials may shade the plots, reduce airflow, reduce albedo relative to surroundings,
188 or otherwise change the energy balance, particularly in chamber warming (i.e., 4 of the 5 studies included in
189 the above analysis). Specifically, soil temperatures may be cooler in structural controls for forced air studies
190 because the experimental structures block sunlight from hitting the ground surface, causing less radiative
191 heating of the ground in structural controls compared to ambient controls. In addition, above-ground tem-
192 peratures may be warmer in structural controls because the structures radiatively warm the air around them
193 and block wind, inhibiting mixing with air outside of the plot. Structures may also interfere with precipi-
194 tation hitting the ground, thereby reducing local soil moisture and snowpack, with its insulative properties.
195 These effects may be most dramatic in studies that employ chambers, rather than open-air designs, such as
196 infrared heating (Aronson & McNulty, 2009). Finally, for some warming types (e.g., soil cables), structural
197 controls experience increased soil disturbance compared with ambient controls; this may alter water flow and
198 percolation, and introduce conductive material via the cables or posts.

199 To the extent that differences between ambient and structural controls have been reported in previous studies,
200 our findings appear to be consistent. Clark *et al.* (2014b), who used forced air and soil cables with feedback
201 control for warming, state that “control of the air temperature was less precise, in part due to air scooping on
202 windy days.” Marchin *et al.* (2015), who used forced air warming with feedback control, note that structural
203 controls had mean spring air temperatures about 0.5°C or more above ambient temperatures. Peterjohn *et*
204 *al.* (1994), who warmed soil with heating cables and feedback control, reported cooler soil temperatures
205 in structural controls than in ambient controls at shallow soil depths. Similarly, we found the greatest
206 difference in soil temperature between structural and ambient controls in shallow soils (e.g., exp10, in which
207 soil temperature was measured at a depth of 2cm). If addressed, the focus to date has been largely on these
208 abiotic impacts of experimental structures, but structures may also alter herbivory and other biotic conditions
209 (Kennedy, 1995; Moise & Henry, 2010; Wolkovich *et al.*, 2012; Hoeppner & Dukes, 2012).

210 Our analyses suggest that warming experiments that calculate focal response variables relative to ambient
211 controls (e.g., Price & Waser, 1998; Dunne *et al.*, 2003; Cleland *et al.*, 2006; Morin *et al.*, 2010; Marchin *et al.*,
212 2015) may not adequately account for the ways in which infrastructure affects microclimate. Results from
213 studies reporting only structural controls (e.g., Sherry *et al.*, 2007; Hoeppner & Dukes, 2012; Rollinson &
214 Kaye, 2012), should be cautiously applied outside of an experimental context, as—without ambient controls—
215 their inference is technically limited to the environment of the structural controls. Our results suggest that
216 studies aiming to predict or forecast the effects of climate change on organisms and ecosystems would benefit
217 from employing both structural and ambient controls so that they may separate artifacts due to infrastructure
218 from the effects of experimental warming. Increased use of both structural and ambient controls together
219 would also help answer important questions of how infrastructure effects vary across ecosystem types, and
220 warming designs (Box 1, Figure 2).

221 Indirect and feedback effects of climate change manipulations

222 Climate change experiments often seek to manipulate temperature or precipitation separately as well as
223 interactively. Manipulating either of these variables in isolation is notoriously difficult. Treatments involving
224 precipitation additions typically reduce temperatures in climate change manipulations (Sherry *et al.*, 2007;
225 Rollinson & Kaye, 2012; McDaniel *et al.*, 2014b). For example, Sherry *et al.* (2007) observed that a doubling
226 of precipitation reduced mean air temperatures by 0.44°C, on average, during their one-year observation

227 period.

228 In the MC3E database, there are four experiments that manipulated both temperature and precipitation,
229 and provided daily above-ground temperature data (three of these also measured soil temperature). Across
230 these studies, all of which used infrared heating (two with feedback control and one with constant warming),
231 we found that increasing the amount of added precipitation reduced daily minimum and maximum above-
232 ground temperatures, at rates of 0.01 and 0.02°C, respectively, and soil temperatures, at a rate of 0.01°C for
233 both minimum and maximum temperature, per percent increase in added precipitation (Table S14). Thus,
234 a 50% increase in precipitation would be expected to decrease temperature by 0.5°C. This is likely because
235 increasing soil moisture (an effect of precipitation additions) typically shifts the surface energy balance to
236 favor latent (i.e., evapotranspiration) over sensible energy fluxes, reducing heating of the air overlying the
237 soils. Maintaining target warming levels is a challenge even for independent feedback systems, which vary
238 energy inputs using ongoing temperature measurements, particularly during seasons or years with wetter
239 soils and higher evapotranspiration (Rich *et al.*, 2015).

240 In addition to its effects on temperature, experimental warming often increases vapor pressure deficit and
241 reduces soil water content (e.g., Harte *et al.*, 1995; Sherry *et al.*, 2007; Morin *et al.*, 2010; Pelini *et al.*, 2014;
242 Templer *et al.*, 2016). Of the 15 experiments in the MC3E database, we examined the 12 that continuously
243 measured and reported soil moisture. We included target warming, warming type, and their interaction
244 as predictors (excluding data from plots with precipitation treatments) and accounted for other differences
245 among studies by including a random effect of study (see Supplemental Materials for details). We found
246 that experimental warming reduced soil moisture across all warming types, with substantial variation among
247 experiments (Figure 5, Table S15). The drying effect varied by warming type (-0.80% for infrared versus -
248 0.33% for forced air, per °C of target warming, Table S16). Soil moisture can be difficult to measure, with high
249 spatial and temporal variation (Famiglietti *et al.*, 1999; Teuling & Troch, 2005), but these results highlight
250 that changes in soil moisture often accompany temperature changes in active-warming experiments.

251 Warming and precipitation treatments, and their indirect effects on soil moisture and other abiotic factors,
252 can also alter the biotic environment, which may produce cascading effects. Many studies have found shifts
253 from herbaceous to woody plant communities over time with experimental warming (e.g., Rollinson & Kaye,
254 2012; McDaniel *et al.*, 2014b,a; Harte *et al.*, 2015). These community shifts may affect resource levels, such
255 as moisture, carbon, and nutrient levels in the soil (McDaniel *et al.*, 2014b,a; Harte *et al.*, 2015) and feed

256 back to affect microclimate (Harte *et al.*, 2015).

257 The presence of these feedback effects is both a strength of and a challenge for climate change experiments.
258 They may represent important and ecologically realistic effects that became apparent only with the *in situ* field
259 experiment. Alternatively, they may represent artifacts that are unlikely to occur outside of an experimental
260 context. Quantifying, interpreting, and reporting these non-temperature effects in experiments is critical
261 to distinguish these possibilities and to understand mechanisms underlying observed biological responses to
262 climate change.

263 The widespread presence of indirect effects of climate manipulations highlights the importance of measuring
264 environmental conditions at the plot-level, and using these measurements in analysis and interpretation of
265 results. Many papers published on climate change experiments—including 10 of the 15 references listed
266 in Table S1—analyze warming and/or precipitation treatments as simple categorical predictors (e.g., as in
267 a two-way ANOVA). Our findings, however, demonstrate a need for alternative modelling approaches to
268 fully understand the experimental results and to make mechanistic links between changes in climate and
269 ecological responses. One straightforward alternative is to include the continuous climate data (e.g., plot-
270 level temperatures) as predictors of the focal response variable, such as phenological state or species density
271 (e.g., Marchin *et al.*, 2015; Pelini *et al.*, 2014).

272 Ecological implications

273 We have highlighted a suite of factors that complicate interpretation of climate change experiments. These
274 indirect effects are likely to have biological implications for many of the responses studied in warming exper-
275 iments (e.g., Figure 6). Interpretation of experimental climate change effects on biological responses may be
276 misleading because the intended climate treatments (i.e., categorical comparisons or target warming levels)
277 are often used as explanatory variables in analyses (Table S1). The interpretation is likely to be altered by
278 using fine-scale, measured climate as explanatory variables. For example, biological responses may be muted
279 (Figure 6b) or exaggerated (Figure 6c) when direct and indirect effects of climate manipulations interact.

280 To investigate the ecological implications of non-target abiotic responses to climate warming, we used a
281 simple case study of plant phenology. We used the MC3E database to test if estimates of the temperature
282 sensitivity of phenology vary when calculated using target warming versus plot-level climate variables. We

283 fit two separate mixed-effects models, which differed in their explanatory variables: one used target warming
284 and one used measured climate. Both models had budburst day of year as the response variable, and both
285 included random effects of study (which modeled other differences between studies that may have affected
286 phenology), year (nested within study, which modeled differences due to weather variability among years that
287 may have altered phenology), and species (which often vary in their phenology). All random effects were
288 modeled on the intercept only; see Supplemental Materials for details.

289 We found that phenological sensitivities to temperature estimated from the two modeling approaches varied
290 three-fold. The target warming model estimated temperature sensitivity of budburst to be -1.91 days/°C
291 (95% CI -2.17, -1.86; Table S17, solid black line in Figure 7), whereas the measured climate model estimated
292 temperature sensitivity of budburst to be -6.00 days/°C (95% CI: -6.74, -5.26; Table S17). Further, all
293 measured climate models with both temperature and moisture had improved model fit compared to the target
294 warming model (Table S18). The best-fit model included mean daily minimum above-ground temperature,
295 mean winter soil moisture, and their interaction as explanatory variables, suggesting that these variables are
296 important drivers of budburst timing (Tables S17, S18). In addition, the measured climate model estimated
297 a significant effect of soil moisture on budburst of -1.51 days/% VWC (95% CI: -1.76, -1.26; Table S17,
298 Figure 7). This negative effect is expected, if reducing moisture delays budburst (Table S17, Figure 7), and
299 is consistent with previous work showing that budburst requires water uptake (Essiamah & Eschrich, 1986).

300 The increase in estimated temperature sensitivity with measured (rather than target) temperature has two
301 major causes. First, plot-level warming often does not reach target levels (Figure 3), producing a muted effect
302 of temperature in models using target warming. Second, experimental warming's dual effects of decreasing
303 soil moisture and increasing temperature impact budburst in contrasting ways. Decreasing soil moisture
304 has a delaying effect on budburst phenology, opposing the advancing effect of rising temperatures (Figure
305 6b); thus the effect of temperature is underestimated when moisture is not included in the model. This
306 example shows how the common method of using target warming alone, or even measured temperature
307 alone as done in previous analyses of the particular experiments included here (exp01, exp03, exp04, exp10,
308 Clark *et al.*, 2014a,b; Polgar *et al.*, 2014; Marchin *et al.*, 2015), to understand biological responses may yield
309 inaccurate estimates of temperature sensitivity in warming experiments. In this case, the underestimation
310 may be substantial enough to account for previously described discrepancies between phenological responses
311 to warming in observational versus experimental studies (Wolkovich *et al.*, 2012; Polgar *et al.*, 2014), though
312 further investigation is required.

313 Accounting for both direct and indirect effects of warming is critical for accurate interpretation of the conse-
314 quences of climate change (Kharouba *et al.*, 2015). Of particular importance is the extent to which abiotic
315 and biotic effects are realistic forecasts of future shifts that are likely to occur with climate change, or due to
316 artifacts that are unlikely to occur outside of experimental systems (Hurlbert, 1984; Moise & Henry, 2010;
317 Diamond *et al.*, 2013). For many important climatic and ecological metrics, experimental findings of abiotic
318 and biotic effects appear to be consistent with observations. Altered above-ground daily temperature range
319 (i.e., temperature minima changing more than maxima, Table S3) with experimental warming is consistent
320 with observed changes in many places. Global minimum temperatures increased more rapidly than max-
321 imum temperatures from 1950-1980, reducing above-ground daily temperature range (Thorne *et al.*, 2016;
322 Vose *et al.*, 2005). In addition, the acclimation response of leaf respiration to temperature (Aspinwall *et al.*,
323 2016; Reich *et al.*, 2016), responses of soil respiration to warming (Carey *et al.*, 2016), and declines in soil
324 carbon at one site (Harte *et al.*, 2015), also appear to be consistent across experiments and observations.
325 These cases suggest that many responses observed in climate change experiments, including indirect effects of
326 treatments, may be accurate harbingers of future biological responses to climate change.

327 In contrast, some responses documented in climate change experiments may not be in line with future
328 climate change—or may be too uncertain for robust prediction, and thus need explicit analyses and cautious
329 interpretation. Although surface warming inevitably increases soil water evaporation, it does not necessarily
330 translate to a decrease in soil water content. Precipitation forecasts with climate change are more uncertain
331 than temperature forecasts, as are, consequently, future changes in soil moisture (Cook *et al.*, 2018). For
332 example, soil drying is forecasted in some regions, such as the southwestern United States, mainly because of
333 reductions in precipitation and increased evaporative demand associated with warmer air (Dai, 2013; Seager
334 *et al.*, 2013). The northeastern United States, on the other hand, has been trending wetter over time (Shuman
335 & Burrell, 2017), even though temperatures have warmed. Shifts in soil moisture are likely to vary by region,
336 season, vegetation type, and soil depth (Seager *et al.*, 2014; Berg *et al.*, 2017; Cook *et al.*, 2018). The
337 uncertainty associated with forecasting changes to soil moisture makes replicating future water availability
338 regimes in climate change experiments especially challenging; one way to meet this challenge and make
339 predictions—even given high uncertainty—is to quantify soil moisture effects in climate change experiments.
340 The altered light, wind, and herbivory patterns documented under experimental infrastructure (Kennedy,
341 1995; Moise & Henry, 2010; Wolkovich *et al.*, 2012; Hoeppner & Dukes, 2012; Clark *et al.*, 2014b) represent
342 other non-temperature effects that may be potential experimental artifacts and are worth quantifying in

343 future analyses to provide improved estimates of temperature sensitivity.

344 An additional challenge in relating experiments to observations is that experimental findings may not scale
345 up in space and time. Short-term responses to climate change frequently differ from long-term responses
346 (Woodward, 1992; Elmendorf *et al.*, 2012; Andresen *et al.*, 2016; Reich *et al.*, 2018). Differences may be, in
347 part, because many experiments typically impose some mean shift in climate, but patterns of climate change
348 are likely to be more variable. Many climate models project complex shifts in precipitation: more intense
349 extreme precipitation events (e.g., heavy downpours), more dry days (i.e., less total precipitation events),
350 or both (Polade *et al.*, 2014). In addition, the small spatial scale of experiments may result in responses
351 that are unlikely to be observed at larger scales (Woodward, 1992; Menke *et al.*, 2014). Experimental plots
352 range in area from 1.5 to 36 square meters (Table S1), which may be too small to encapsulate, for example,
353 the rooting zones of perennial plants (Canadell *et al.*, 1996), or foraging ranges for animals (Menke *et al.*,
354 2014). One approach to overcome these challenges is to conduct larger, longer experiments (Woodward,
355 1992), though this frequently is not logistically possible and does not easily address how to capture potential
356 shifts in climate variability.

357 Conclusions

358 As climate change continues across the globe, ecologists are challenged to not only document impacts, but
359 also make quantitative, robust predictions. Our ability to meet this challenge requires a nuanced mechanistic
360 understanding of how climate directly and indirectly alters biological processes. Climate change experiments,
361 which have been underway for nearly four decades (e.g., Tamaki *et al.*, 1981; Carlson & Bazzaz, 1982; Melillo
362 *et al.*, 2017), provide invaluable information about biological responses to climate change. Yet the full range
363 of changes in environmental conditions imposed by these experiments is rarely presented, and we need a fuller
364 understanding of the variable effects across different warming methodologies. We have compiled a database
365 of microclimate data from multiple warming experiments and shown how time, space, experimental artifacts,
366 and indirect effects of treatments may complicate interpretations of these experimental results. The relative
367 importance of each of these factors is likely to vary across warming designs (Box 1), as well as myriad other
368 attributes of sites, making more studies that measure climate similarly and include full infrastructure controls
369 important for progress. We hope this work provides a foundation for gaining the most knowledge and utility
370 from existing experiments via robust analyses, for designing new experiments (see Box 2), and for improved

³⁷¹ understanding of biological responses to a changing world.

³⁷² **Acknowledgements**

³⁷³ We are grateful to those who shared their experimental climate data with us, allowing it to be included in
³⁷⁴ the MC3E database. We thank the Radcliffe Institute for Advanced Study at Harvard University, which
³⁷⁵ provided funding for an Exploratory Seminar at which the ideas in this paper were conceived, and we thank
³⁷⁶ three anonymous reviewers. This research was also supported by the National Science Foundation (NSF DBI
³⁷⁷ 14-01854 to A.K.E.). Any opinion, findings, and conclusions or recommendations expressed in this material
³⁷⁸ are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Table 1: **Summary of measured warming and documented non-temperature effects, by warming technique**, for studies included in the MC3E database. Summaries of the target warming treatments ($^{\circ}\text{C}$) and measured warming for above-ground temperature, and soil temperature are given. Measured warming is standardized per degree of target warming, and is shown here for warming treatments only (precipitation treatments are excluded). Thus, measured warming is the difference between mean annual temperature (MAT) of control plots and MAT of each treatment level within year (and block, if applicable) of a study. Mean difference (with standard error) and the range of differences in warming are shown, across all years (and blocks, if applicable). n is the number of studies of each warming technique and control type combination in the MC3E database. ‘Soil drying’ indicates figures showing an effect of warming on soil water content and references of previous studies reporting such effect. ‘Other non-temperature effects’ indicates other effects that have been studied in individual previous studies for each type of warming. See Table S1 for additional details of studies included in the MC3E database.

warming type	warming control	study	target (min-max)	aboveground mean (se)	aboveground range	soil mean (se)	soil range	n	soil drying	other nontemperature effects
infrared	constant	exp05,06,11-14	2.2 (1.2-4)	0.52 (0.03)	-5.22-2.16	0.68 (0.02)	-0.07-1.56	6	Fig. 4, Tab. S15-16, Kimball et al. 2005	+shading (Kimball et al. 2005)
infrared	feedback	exp01,02,09	2.5 (1-4)	0.84 (0.05)	-0.19-1.86	0.96 (0.05)	-0.03-1.85	3	Fig.4, Tables S15-S16, Kimball et al. 2005, Sherry et al. 2007	+freeze-thaw cycles (McDaniel et al. 2013) +shading (Kimball et al. 2005) VPD (Morin et al. 2010)
forced air	feedback	exp07,10,15	3.5 (1.5-5.5)	0.95 (0.02)	0.43-1.73	0.36 (0.02)	-0.42-1.06	3	Fig.3-4 Norby et al. 1997	+VPD (Norby et al. 1997) air flow (Norby et al. 1997)
soil cables	feedback	exp08	5			1.01 (0.02)	0.9-1.08	1	Fig.3-4, Peterjohn et al. 1993	+CO ₂ flux (Peterjohn et al. 1993) +N mineralization (Peterjohn et al. 1993)
force air, soil cables	feedback	exp03,04	4 (3-5)	0.49 (0.06)	-0.02-0.94	0.75 (0.07)	0.01-1.05	2	Fig.3-4	air flow (Clark et al. 2013)

622 **Figures**

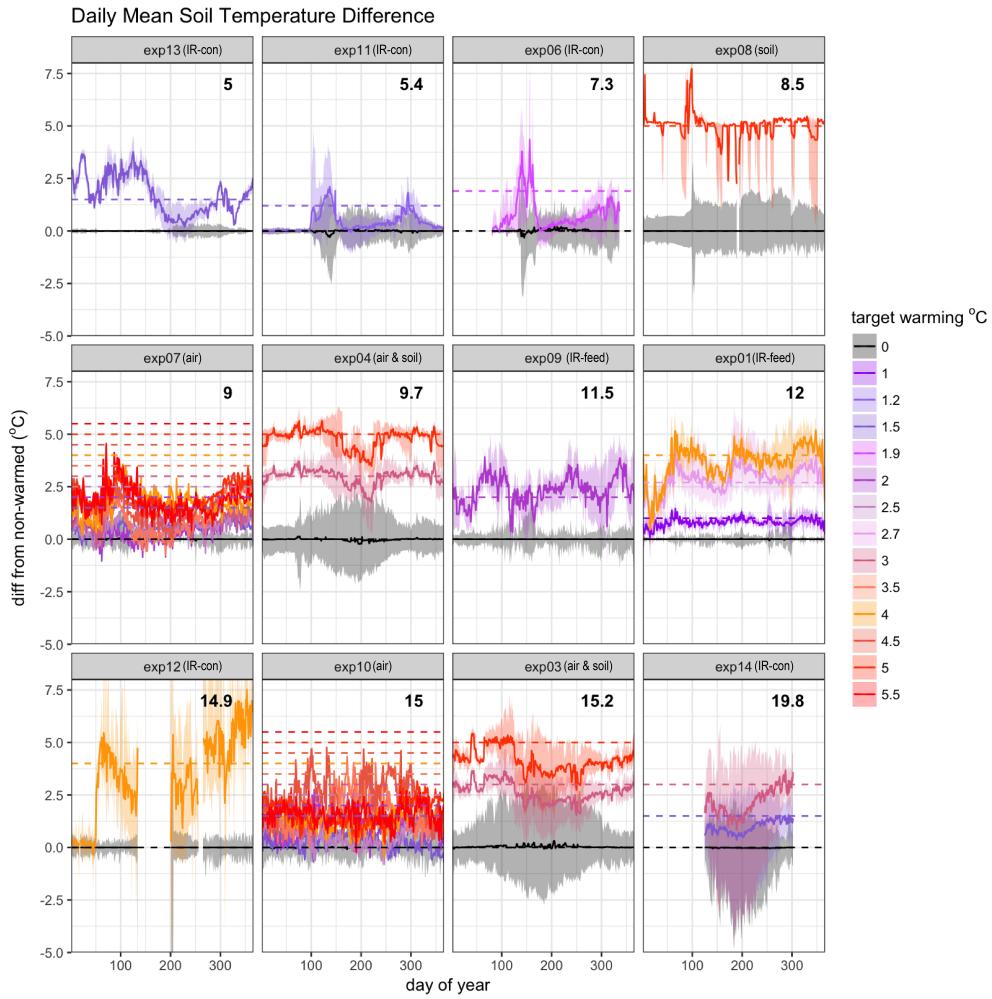


Figure 1: **Deviations in daily observed warming from mean control soil temperature for 12 study sites**, excluding data from plots that manipulated precipitation. We show soil, rather than above-ground, temperature, as this was the most frequently recorded temperature variable in the MC3E database. Solid lines show observed difference between warming treatment (colors) and control (black) plots, averaged across replicates and years; shading shows 95% confidence intervals. Dashed lines represent target warming levels. (Note that the following sites had no explicit target temperature: exp06, exp11, exp12; in exp01, only the highest warming treatment had a target temperature; for these studies and treatments, we used their reported level of warming.) Two sites not shown here did not monitor soil temperature. Sites are ordered by low to high mean annual soil temperature (shown in the upper right corner of each panel). The heating type is listed in parentheses next to the site number (IR= infrared, soil= soil cables, air= forced air; con= constant wattage warming control).



Soil cable warming experiment at Harvard Forest, Petersham, Massachusetts, USA (Melillo et al. 2017). Photograph credit: A. Barker-Plotkin.



Forced air chamber warming experiment at Duke Forest, Hillsborough, North Carolina, USA (exp10, Pelini et al., 2011). Photo credit: A. Ellison.



Infrared warming experiment in Pennsylvania, USA (exp09, Rollinson et al., 2012). Photo credit: C. Rollinson.



Infrared warming experiment in Montpellier, France (exp02, Morin et al., 2010). Photo credit: I. Chuine.

Figure 2: **Photographs of different warming methodologies** used by studies in the MC3E database.

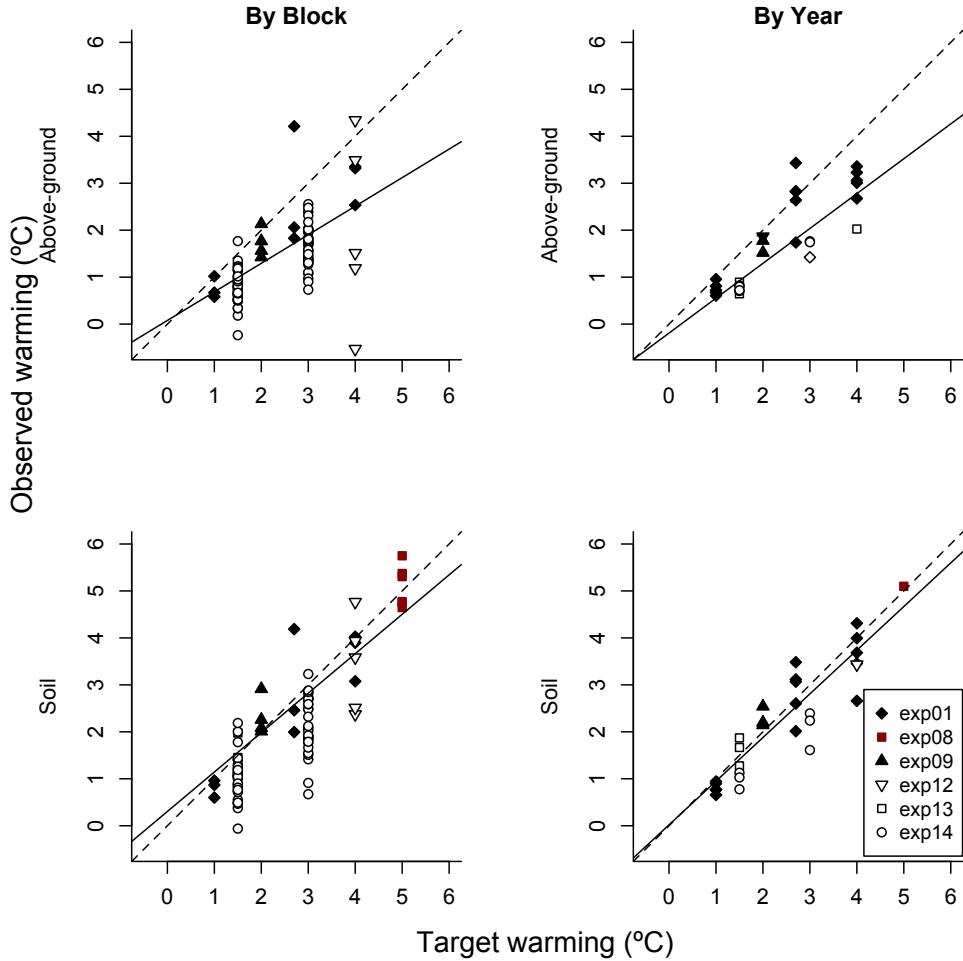


Figure 3: Observed warming over space and time, for above-ground and soil temperatures, excluding data from plots that manipulated precipitation. Above-ground temperature includes air, canopy, and surface temperature. Points represent the difference between treatment and control plots by block (i.e., one data point per block) and by year (i.e., one data point per year). The solid line is the fitted relationship between observed and target warming and the dashed line shows when observed warming is exactly equal to target warming (1:1). Black symbols represent studies using infrared; red represents soil warming cables (only exp08); no studies with forced air heating used a blocked design. Open symbols represent constant wattage control and filled symbols represent feedback control. Note that the following studies had no explicit target temperature: exp06, exp11, exp12; for these studies, we used their reported level of warming. For exp01, only the treatment with the greatest warming had a target temperature. See Supplemental Materials (especially Tables S5 and S6) for details.

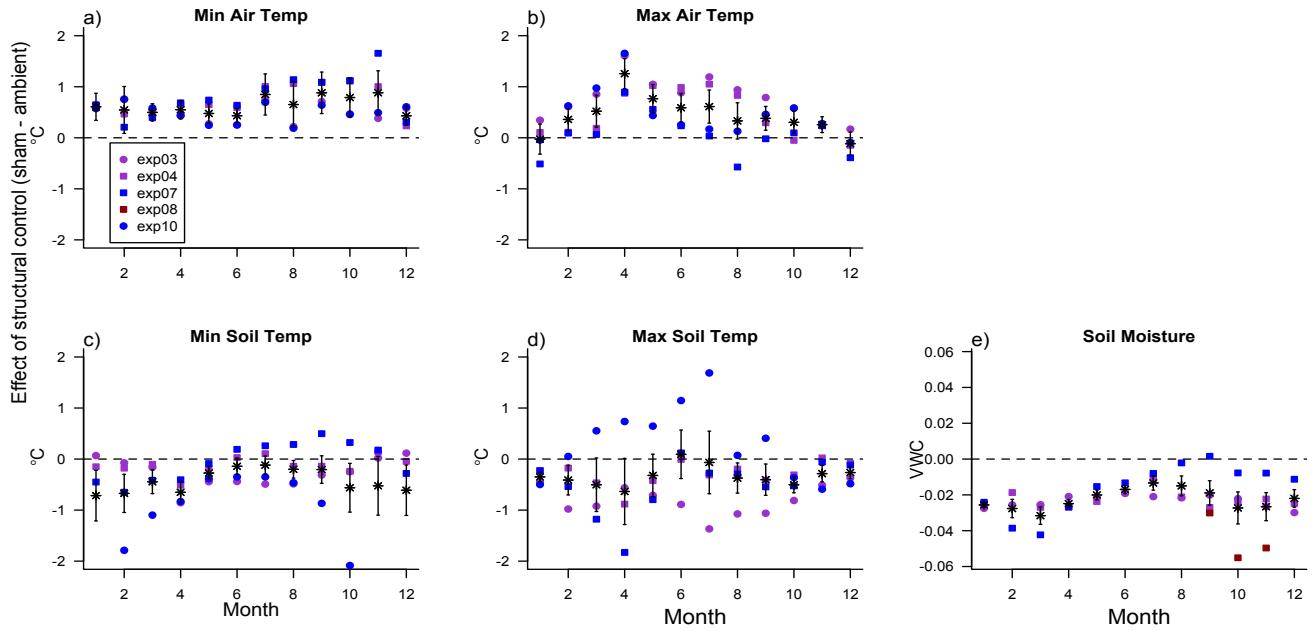


Figure 4: Deviations in measured abiotic variables by month in structural controls compared to ambient controls (i.e., with no control chambers or warming infrastructure in place). Above-ground temperatures (which include includes air, canopy, and surface temperatures) were higher (a,b), whereas soil temperature (c,d) and soil moisture (e) were lower in structural controls compared with ambient controls. We show overall (fixed) effects in black from monthly mixed-effects models; site-level random effects are shown by squares (for the three studies conducted at Harvard Forest in Massachusetts, USA) and circles (the two studies conducted at Duke Forest in North Carolina, USA). Colors vary by heating type: red represents soil warming cables, blue represents forced air; purple represents combined soil warming cables and forced air heating (no studies with infrared heating included both control types). All studies included used feedback warming control. See Supplemental Materials for details (Tables S8-S13).

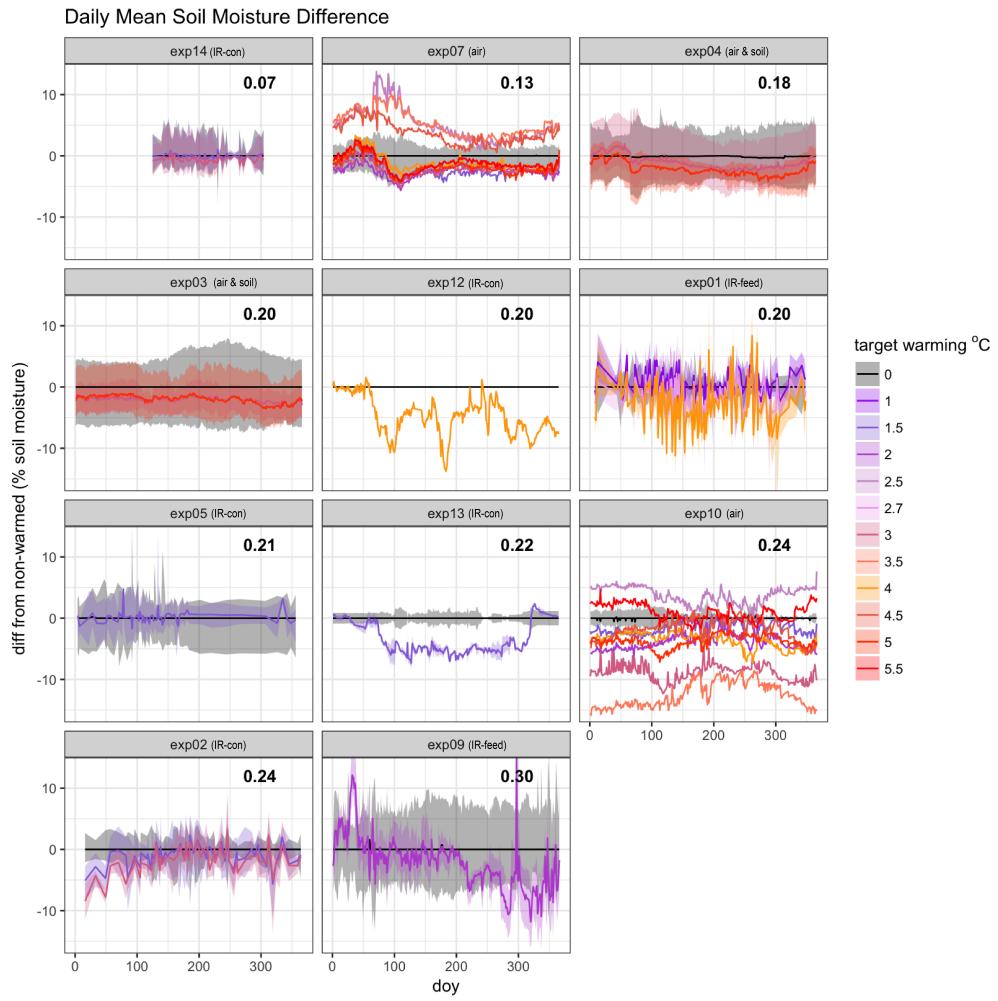


Figure 5: **Deviations in daily observed soil moisture**, shown for the 11 study sites that continuously monitored soil moisture, excluding data from plots that manipulated precipitation. Black lines represent control plots, and colored lines represent warming treatments with various target warming levels (or reported warming, if there was no explicit target temperature). The number of temperature treatment levels vary from one (e.g., exp08, exp11) to nine (exp07 and exp10, which used an unreplicated regression design). Sites are ordered by low to high mean annual soil moisture (shown in the upper right corner of each plot). All experiments measured soil moisture in volumetric water content, as a percentage of the soil volume in the sample, scaled from 0 to 100; the absolute difference between treatment and control plots is shown. Heating type is listed in parentheses next to the site number: IR-con= infrared with constant wattage, IR-f= infrared with feedback control), soil= soil cables, air= forced air.

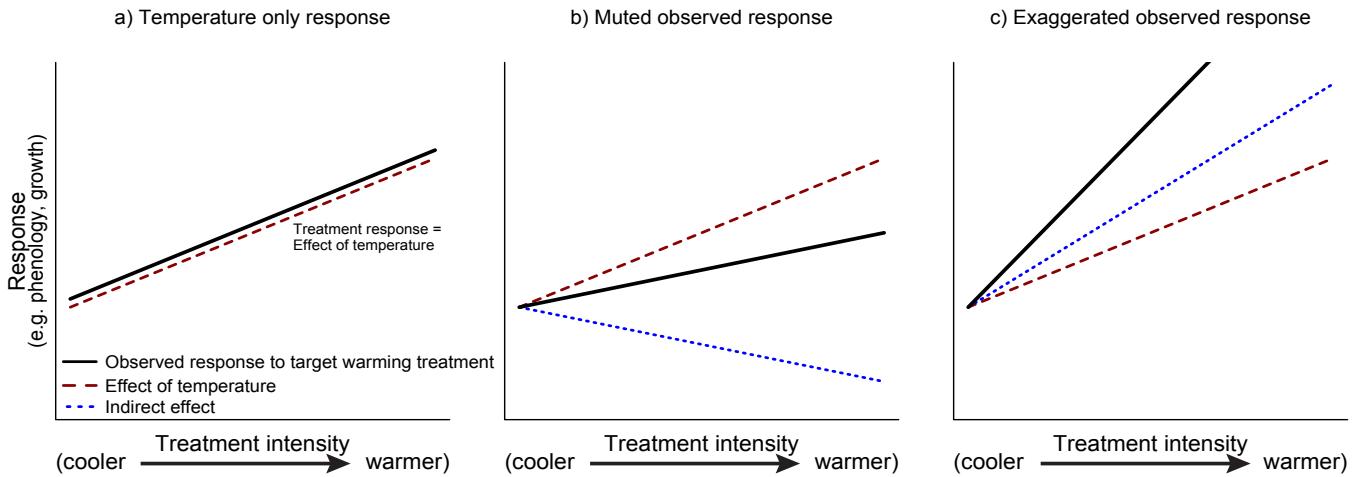


Figure 6: Theoretical biological responses to experimental warming and their interpretation. Direct responses to temperature alone (a) can be easily understood. Complications arise when biological responses are a mix of the direct temperature and indirect non-temperature effects of experimental warming. Then experimental warming may cause biological responses to be muted (b) or exaggerated (c). Quantifying, interpreting, and reporting these non-temperature effects in experiments is critical, and their presence is both a strength and a challenge of climate change experiments. They may represent ecologically realistic effects that might not have been predicted without the *in situ* field experiment. Alternatively, they may represent artifacts that are unlikely to occur outside of an experimental context. Slopes of these example lines assume a linear response with additive direct and indirect effects. The relationship between these effects could be more complex (e.g., nonlinear; antagonistic, multiplicative, or otherwise interactive).

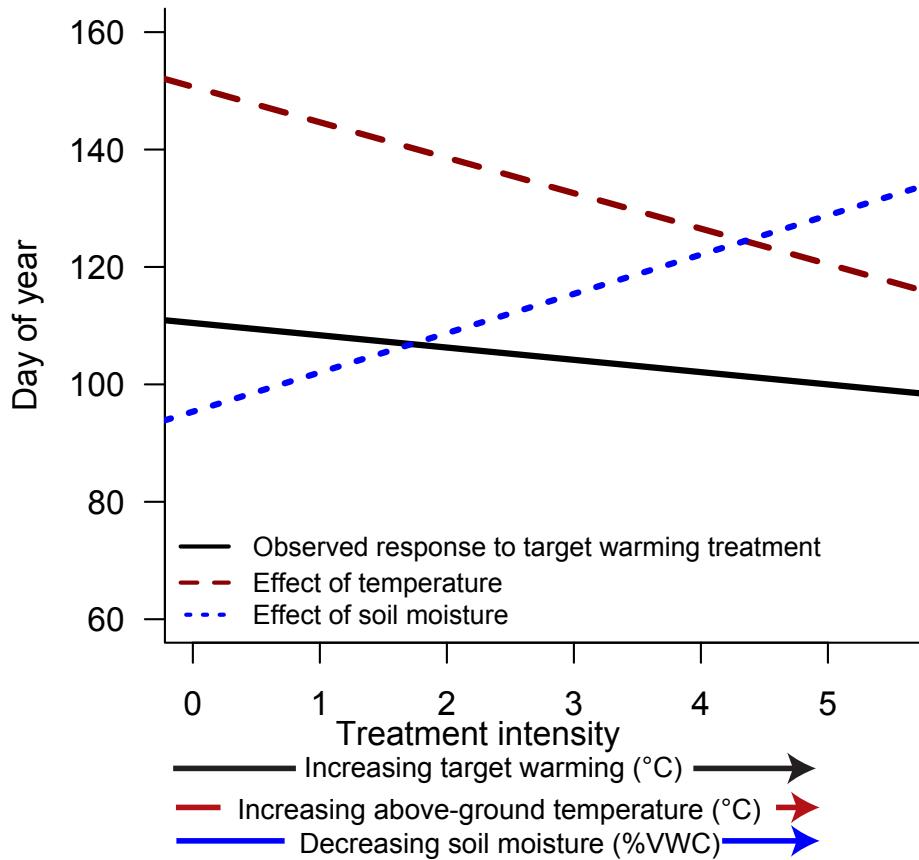


Figure 7: Observed response of budburst day of year to experimental climate change is an example of a muted response: the observed response to increasing treatment intensity (i.e., the coefficient of a model fit with only target [or reported, if there was no explicit target] temperature as the explanatory variable, black line; units for x-axis are °C of target warming) suggests a weaker temperature sensitivity than the effect of temperature in a more biologically accurate (and better-fitting) model that includes both measured above-ground temperature (dashed red line, for which x-axis units are °C of measured temperature) and soil moisture (dotted blue line, for which x-axis units are % VWC, decreasing from left to right in conjunction with warming intensity), as well as their interaction. Analysis includes all studies that monitored budburst and measured soil moisture and above-ground temperature (exp01, exp03, exp04, exp07, exp10); structural control data were used for this analysis (ambient controls were excluded from those studies that contained both). See Supplemental Materials, especially Tables S17 & S18, for additional details.

623 Box 1: Different methods for achieving warming.

624 Active-warming experiments may differ both in the way that they achieve warming (“warming type” in Table
625 S1), and the way that warming is controlled (“warming control” in Table S1). There are three warming types
626 used by studies in the MC3E database (Figure 2). These are infrared (n=9), an open-air method in which
627 infrared heaters are mounted above the ground; forced air (n=3), in which air is heated and then pumped
628 through an airflow system into a chamber; and soil warming (n=1), a chamber-less method in which soil is
629 heated with buried electric resistance cable. Two additional studies in the database used combined forced
630 air in chambers and soil warming. Warming is controlled by either constant wattage, in which an unvarying
631 energy output is used, or by feedback control, in which energy outputs are linked to a thermometer and
632 varied depending on the measured temperature in plots, in order to maintain consistent warming levels.

633 In this paper, we describe complications and non-temperature effects associated with active warming experi-
634 ments, across these divergent warming methodologies. Some of the non-temperature effects described may be
635 more likely to occur with particular methods than others. Alterations to airflow, for example, may be most
636 dramatic with methods employing chambers. Plot shading and precipitation interference are likely to occur in
637 chamber and infrared techniques, which both involve above-ground infrastructure, and less likely in methods
638 that only warm from the soil. Soil warming methods, however, may be less representative of climate change,
639 which will be driven by above-ground rather than below-ground warming, and disturb the soil with their
640 infrastructure, which may alter conductivity, water flow, and other soil properties. The biological impacts of
641 such effects may be further enhanced or muted based on site characteristics (e.g., if a site is already heavily
642 shaded, impacts from above-ground infrastructure shading may be lower).

643 Table 1 highlights that there may be differences in non-temperature effects across these different warming
644 methodologies. In the MC3E database, sample sizes within each warming and control type were quite low, so
645 we were unable to statistically distinguish differences in non-temperature effects across the different methods
646 in all analyses. For example, the constant wattage control studies have greater average variation (2.2 °C
647 variation on average for constant versus 1.1 °C variation for feedback), but this difference is not significant
648 ($p=0.21$). We note that the studies showing both the greatest and least variation employed constant wattage
649 (greatest: plots in exp12, with target warming of 4.0 °C, varied by as much as 4.87 °C on average; least:
650 plots in exp13 with 1.5 °C of target warming, varied by 0.03 °C per °C of target warming). These results are
651 not conclusive, because our sample size is quite low (n=3 studies for constant and n=2 studies for feedback

652 studies with blocked designs).

653 We expect that the list of non-temperature effects in Table 1 is not exhaustive, but represents what we can
654 document here or has been documented previously. We recommend additional detailed studies of these, and
655 other, effects across warming designs. This will allow future researchers to more fully evaluate the challenges
656 and opportunities of each method, and select an experimental approach well-suited to their particularly
657 research focus.

658 **Box 2: Recommendations for future climate change experiments**

659 1. *Collect and analyze plot-level climate data.* This includes analyzing and interpreting minimum and
660 maximum values, as well as variance and critical thresholds (e.g., the number and duration of freeze-thaw
661 events and accumulated chilling hours, McDaniel *et al.*, 2014b; Vasseur *et al.*, 2014). We suggest saving
662 the raw data from data loggers (often collected at hourly or higher resolution) to allow quantification
663 of variance (and other summaries) at different temporal resolutions. In assessing which frequency of
664 measurements is most appropriate for analyses (e.g., hourly, twice daily), it is critical to consider the
665 chronobiology of the event and organisms of interest. For ants, this might mean that temperatures be
666 monitored every minute (Helm & Shavit, 2017); for bacteria, even more frequently.

667 2. *Analyze measured climate variables rather than targets.* There can be substantial variation in the effects
668 of warming and precipitation treatments among plots and across time (Figure 3). Analyzing measured
669 climate will allow much more in-depth understanding of the drivers and biological effects of variation
670 in temperature and moisture.

671 3. *Publish high quality, usable data and metadata.* Given that climate manipulations are logistically
672 challenging and expensive (Aronson & McNulty, 2009), and that they often produce a large volume of
673 fine-scale climate data, good curation and data sharing will ensure wider use and deeper understanding
674 of these valuable data. When studying biological implications of a global challenge as large as climate
675 change, progress will come from designing and reporting experiments in ways that facilitate an eventual
676 global data set. Researchers should also be explicit in their warming design (e.g., infrared heating with
677 feedback control or forced air heating with constant wattage) to aid future analyses of the performance
678 of different designs, across sites and over time (Box 1, Table 1).

- 679 4. *Include both structural and ambient controls* and collect, use, and report microclimate and biological
680 data within them. Fewer than half of the studies in our MC3E database reported microclimate data
681 from these two control types (6 out of 15 studies); however, all experiments that did include both
682 control types showed significant effects of infrastructure (Figure 4).
- 683 5. *Design relevant manipulations* by consulting observational records and forecasts, including seasonal
684 and annual variation in projected warming. When it is not possible or desirable to match anticipated
685 changes in climate, studies should report how imposed treatments compare to projected changes and
686 past observations (e.g., Hoover *et al.*, 2014; Zhu *et al.*, 2016). In addition, if continuous treatments are
687 not applied throughout the study, we recommend reporting the seasonality and timing of treatments
688 and monitoring the climate throughout the year.
- 689 6. *Maximize the duration of climate change experiments* by running some experiments for as long as
690 possible, since the magnitude of climate change treatments can vary considerably among years (Figure
691 3). In addition, long-term responses of individuals and populations can differ from transient responses
692 (Saleska *et al.*, 2002; Franklin, 1989; Giasson *et al.*, 2013; Harte *et al.*, 2015). We were able to acquire
693 data extending for ≥ 5 years for only one study in the MC3E database (exp01), restricting our ability
694 to investigate the effect of study length on experimental climate change.
- 695 7. *Conduct syntheses across studies.* As more detailed data are published from experimental climate
696 change studies in divergent ecosystems and warming types, meta-analyses will advance our under-
697 standing of the ways that warming affects microclimate and biotic interactions. For example, it would
698 be useful to compare microclimate data among studies using infrared warming applied with constant
699 wattage versus infrared warming that varies energy inputs based on measured temperatures (Box 1).