How do climate change experiments actually change climate?

A. K. Ettinger,I. Chuine, B. Cook, J. Dukes, A. Ellison, M. Johnston, A.M. Panetta, C. Rollinson, Y. Vitasse, E. Wolkovich

September 21, 2016

Aim

The aim is to write a Concept/Synthesis Paper, for Nature Climate Change, about maximizing benefits of field-based climate change experiments. We argue that there is a need to improve our understanding of how climate is actually altered by these experiments, particularly if we wish to use these experiments to forecast biological impacts of climate change.

Introduction

Future climate change is expected to cause dramatic alterations to Earth's biota. The physiology, distribution, and abundance of organisms will shift, and likely cause cascading community and ecosystem effects (Thomas *et al.*, 2004; Parmesan, 2006; Sheldon *et al.*, 2011; Urban *et al.*, 2012). Much uncertainty remains,however, about how particular individuals, populations, communities, and ecosystems will respond, making predicting organism responses to the climate change one of the most significant challenges facing biology today.

One way that people have sought to understand and forecast future biological conditions is through in situ experimental climate manipulations. Many studies have focused on manipulations to replicate expected higher temperatures. Commonly used field techniques for this include passive warming, such as open-top chambers, and active warming methods, including forced air, soil cables,infra-red radiation. Active warming methods are the most controlled, consistent, and "true to climate change predictions" (Kimball, 2005; Kimball *et al.*, 2008; Aronson & McNulty, 2009; Wolkovich *et al.*, 2012), and we therefore focus on these methods here. Recently, interest has also expanded to understand changing precipitation. Today, many active warming methods are frequently combined with precipitation manipulations, including drought, snow-removal, and supplemental precipitation treatments, in an effort to create climatic conditions such as those forecasted under future climate change scenarios (Price & Waser, 1998; Cleland *et al.*, 2006; Sherry *et al.*, 2007; Rollinson & Kaye, 2012).

Experimental in situ climate manipulations with active warming offer several advantages over other approaches, such as long-term observational data and growth chamber studies for understanding biological impacts of climate change. These experiments allow effects of temperature and precipitation to be isolated from other environmental changes. In addition, a range of warming and/or precipitation treatments can be applied, such that potential non-linear relationships of climate responses can be evaluated. These advantages come at a cost, however. Experimental in situ climate manipulations are logistically challenging and expensive (Aronson & McNulty, 2009). It is difficult to design, implement, and monitor replicated experiments that consistently apply the intended climate manipulations.

As we seek to prepare for future, altered conditions in our biological environment, scientists and others often

wish to extrapolate the results of in situ climate change experiments to forecast how organisms and ecosystems will respond to particular climate change scenarios. Even in cases where this is not the explicit goal of warming and other climate change experiments, it would be incredibly useful to be able to apply knowledge gained from these experiments to improve our understanding and forecasting of how anthropogenic warming will affect species' performance (growth, survival) and distributions. Our ability to make this application is currently limited because a detailed assessment of exactly how experimental warming treatments alter climate, beyond the typically reported mean differences, and the extent to which these manipulations accurately model the real world, both present and future, is lacking.

Here, we suggest that a more nuanced understanding of how climate change experiments actually change climate is critical if we wish to realize the forecasting potential of climate change experiments. We first use plot-level microclimate data from 12 climate change experiments that manipulate temperature (and precipitation, in some cases), while monitoring daily temperature and other climate vairables, to demonstrate the complex ways that climate is altered by active warming treatments, both directly and indirectly. The data we use are from experiments in North America and Europe that were collected between 1991 and 2014, and have been merged into a new, publicly available database (see Supplemental Materials for details). We then discuss the challenges of interpreting biological implications of experimental shifts in climate, when these climate manipulations are more complex then simple shifts in the mean. Finally, we make recommendations for future climate change experiments.

Complications in extrapolating 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 the experiment. However, biologists are generally interested primarily in the biological responses associated with each treatment (e.g. growth, abundance, or phenology of a species). Not surprisingly, then, 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 or not that mean change matched their target level of change (Price & Waser, 1998; Clark *et al.*, 2014a,b; Rollinson & Kaye, 2012). The imposed climate manipulations result in much more than a simple shift in the mean, however. The magnitude of change experienced by organisms in these manipulations is likely to vary in time and space, and the equipment required to conduct these manipulations can also alter climate at the plot level.

Treatments vary over time

The common practice of reporting only the mean temperature difference, across the duration of the study, may hide variations in annual, seasonal, and daily minimum and maximum temperatures.There are frequently strong seasonal variations in experimental warming effects (Figure 1). This can occur because treatments are not applied consistently over the year, either because heat applications are frequently shut off during some seasons such as when snow cover is present (e.g. Clark *et al.*, 2014a,b) (Yann and Isabelle- could you recomend some studies from Europe that also use this methodology) or because some heating methods, even if left on throughout the year, are not capable of applying consistent warming year-round (e.g. infrared radiation, CITATION- Christy, Yann, and/or Jeff could you suggest 1 or 2?). Furthermore, seasonal precipitation patterns can alter the effectiveness of warming treatments (CITATION- Christy, Yann, and/or Jeff could you suggest 1 or 2?).

In addition to seasonal patterns, experimental warming effects can vary widely across longer timescales, such as among years (Figure 2). This is probably due to interactive effects of warming treatments and other aspects of weather that may vary annually. For example, Hoepner and Dukes (2012) found that infrared heaters failed to achieve the target temperatures during rainstorms.

Warming treatments can also vary on shorter timescales, such as within a day. This often leads to a decrease in the diurnal temperature range within experimental plots, compared with ambient conditions (Hoeppner & Dukes, 2012). This may be similar to what is projected for parts of world (Stocker *et al.*, 2013). However, this will likely vary spatially, as some regions have experienced higher daytime warming than nighttime warming, whereas others have experienced the opposite(Stocker *et al.*, 2013).

A detailed comparison of projections versus observations in climate change experiments is lacking. Thus, it is unknown how divergent these annual, seasonal, and daily variations may be from real (i.e. non-experimental) climate patterns.

Anne Marie- please write a paragraph on your suggested discussion "that 3-5 year studies may not capture ultimate, long-term responses that may actually be in the opposite direction to short-term responses. Cite recent Global Change Biology paper by Harte et al. Ideally, we want to run studies long enough to capture population-level responses to warming." I would love to work this in and I think you are the one to write it!

Treatments vary in space

In addition to temporal variation, there can be spatial variation in experimental warming effects, such that extrapolation of experimental warming to forecast climate change impacts may not be a straightforward space-for-time substitution. For example, we used three studies that used a blocked design to examine spatial variation in the amount of warming (i.e. the difference between treatment and control plots within a block). We found that the amount of warming may vary by more than one degree among blocks (Figure 2, Table 1).

Presumably, there will be spatial variation in future climate change effects, given that warming to date has varied spatially (Stocker *et al.*, 2013)). Accurate extrapolation of climate change experiments may therefore depend on the extent to which experiments encompass a representative amount of existing natural variation (e.g. gradients in slope, aspect, etc) present at the scale at which the extrapolation is being made. An added complication is that inferences made from space-for-time substitutions are frequently invalidated, when they have been tested with empirical evidence (Johnson & Miyanishi, 2008). When experimental manipulations aimed at understanding future responses are imposed in a spatially varying environment, we need to be explicit about what assumptions are made in this modified space-for-time substution, think critically about whether these assumptions are realistic, and then carefully interpret results in light of these assumptions. (Aaron- do you think we need more here about space-for-time substition and its problems? If so, what? or do you have citations we should add?). There is also documented small-scale variation in the amount of warming, within experimental plots, atleast from passive warming studies (Marion *et al.*, 1997).

Experimental infrastructure alters climate

The experimental structures themselves alter temperature and other important biotic and abiotic variables, in ways that are not generally examined or reported in experimental warming studies. The possible existence of these effects are widely acknowledged, and some studies include "shams" or "disturbance controls" to account for them. However, the magnitude of structural effects on climate are rarely discussed or interpreted in climate change studies.

To investigate the magnitude of these effects, we compared temperature and soil moisture data from four active warming studies at two sites: Duke Forest and Harvard Forest(Farnsworth *et al.*, 1995; Clark *et al.*, 2014a; **?**; Pelini *et al.*, 2011). These were the only studies in our database that included two types of control plots: structural controls (i.e. "shams" or "disturbance controls," which contained all the warming infrastructure, such as soil cables or infrared heating units but with no heat applied) and ambient controls with no infrastructure added (see Supplemental Materials for details).

We were surprised to find that experimental structures altered air and soil temperatures in opposing ways: air temperatures were higher in the structural controls, compared with the ambient air with no structures installed, whereas soil temperatures were lower in the structural controls compared with ambient soil (Figure 3). This was consistent across the different temperature models we fit (mean, minimum, and maximum), and the sign of the effects was consistent across study-sites and months, although the magnitude varied among sites (Table 3) and across seasons (Figure 3). Soil moisture was lower in structural controls compared with ambient conditions (Figure 1S). In addition to these documented effects, experimental structures may alter conditions by creating shade, intercepting precipitation, and altering herbivory and other biotic interactions. Further documentation and analysis of the effects of these experimental structures on abiotic and biotic factors, as well as in depth interpretation of how these effects may alter focal variables, is an important next step for climate change experimentation, particularly if we wish to apply results to forecasting.

Secondary effects of climate change manipulations

Climate change experiments often manipulate one or two climate variables, such as temperature and precipitation. However, as scientists who have conducted these experiments have likely experienced, climatic variables are nearly impossible to completely isolate from one another. Temperature, for example, interacts with precipitation to alter the abiotic environment; Rollinson et al (2012) observed that a twenty percent increase in precipitation reduced mean hourly temperatures by 0.3 degrees Celsius over the course of their two-year experiment. Ideally, experimentally induced changes in other variables would be realistic; for example, the experimental treatment should not decrease moisture in an area projected to get wetter. At the very least, it is important to quantify the secondary effects of applied manipulations.

Precipitation treatments typically reduce temperatures in climate change manipulations, as described above (e.g. Sherry *et al.*, 2007; Rollinson & Kaye, 2012), but the magnitude of this effect can vary in space and time (Figure 2S). Experimental warming reduces vapor pressure deficit and soil water content (e.g. Figure 3S Sherry *et al.*, 2007; Morin *et al.*, 2010; Templer *et al.*, 2016). The magnitude of these effects are also likely to vary in space and time.

Warming and precipitation treatments can also alter community composition, which is likely to have additional secondary effects. For example, tree composition shifted after three years of warming and modified precipitation treatments (Rollinson & Kaye, 2012). These shifts in composition may change competitive dynamics and, in turn, affect resource levels. It can be difficult to tease out limiting resources and abiotic and biotic drivers of biological responses, but understanding the effects of an experimental treatment on these interrelated variables is critical when trying to determine mechanistic explanations for observed responses to warming.

Biological implications

We have highlighted a suite of factors that complicate interpretation of warming experiments. We argue that these largely unintended alterations are important for scientists to fully understand and report in their research because they are likely to have biological implications (Figure 4).

Climate change experiments may affect phenology in complicated ways, for example. Plant phenology is likely to be altered in opposing ways by the increased air temperatures and decreased soil moisture characterized by warming treatments. Indeed, these opposing driers may be responseible for the observed discrepancy between observational and experimental phenology responses to warming(Wolkovich *et al.*, 2012). Plant phenology responds to minimum temperatures, as well as mean and maximuma, and this may also play a role in the discrepency between observational and experimental studies (Shen *et al.*, 2016; Matthews & Mazer, 2016).

Lizzie, Aaron, Yann, Isabelle-Please recommend other citations for this!

Plant growth is also likely to be altered in opposing ways by the increased air temperatures and decreased soil moisture levels in experimentally warmed plots. With warming and decreased VPD, stomata closure may reduce sapflow and growth (Templer *et al.*, 2016). Even small shifts in temperature may have a big effect, since the response is nonlinear.

Direct and indirect effects of climate change experiments are also likely to affect soil respiration in ways that may alter net mineralization and therefore have other cascading effects. Yann: please add a few sentences and citations here!

change in biotic interactions (see previous comment): both plant-plant and microbes/fungi-plants herbivory

Recommendations for future climate change experiments

The complications of climate change experiments that we describe are not meant to be criticisms or to imply that experimental climate change studies are not worthwhile. On the contrary, we believe that climate change experiments provide invaluable information about biological responses to climate change. We believe that we need to more fully explore the ways in which these warming experiments are altering climate, as it is clearly not simply shifting the mean. Here we describe a few recommendations to improve implementation, interpretation, and communication of future climate change experiments.

- Prior to experimental setup, consult climate change projections for the study region. Pick a warming/precipitation treatment method that most accurately mimics anticipated changes. Or at the minimum, report how your study compares to projected changes.
- Include structural and ambient controls, and collect, use, and report data collected within them in.
- Run experiments for as long as possible. Climate change experiments should run for several seasons to account for the inter-annual variations that may interact with the warming treatment itself (especially when looking at non linear processes such as phenology), and to capture more than transient responses.
- Collect climate data at least twice daily, and ideally hourly.
- Carefully consider and report the timing of warming treatment applied.
- Publish high quality, usable data and metadata. In the metadata, report the number and cause of missing data points for climate, especially those collected in warming treatments. (For example, are data missing because the heaters went out, or because rodents at the sensors?) Also report the timing of applied warming treatments (i.e. exact start and end dates, within and across years), as well as variations in daytime and nighttime and season variations in climate variables.
- Consider implementing and following community standards for reporting climate data (and phenology -Chuine et al. 2017)

References

Thomas, C. D. *et al.* Extinction risk from climate change. *Nature* **427**, 145–148 (2004). PT: J.

Parmesan, C. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics* **37**, 637–669 (2006). PT: J.

Sheldon, K. S., Yang, S. & Tewksbury, J. J. Climate change and community disassembly: impacts of warming on tropical and temperate montane community structure. *Ecology Letters* **14**, 1191–1200 (2011).

Urban, M. C., Tewksbury, J. J. & Sheldon, K. S. On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B-Biological Sciences* **279**, 2072–2080 (2012). PT: J; NR: 38; TC: 1; J9: P ROY SOC B-BIOL SCI; PG: 9; GA: 925RT; UT: WOS:000302779600025.

Kimball, B. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* **11**, 2041–2056 (2005).

Kimball, B. A. *et al.* Infrared heater arrays for warming ecosystem field plots. *Global Change Biology* **14**, 309–320 (2008).

Aronson, E. L. & McNulty, S. G. Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality. *Agricultural and Forest Meteorology* **149**, 1791–1799 (2009).

Wolkovich, E. M. *et al.* Warming experiments underpredict plant phenological responses to climate change. *Nature* **485**, 494–497 (2012). PT: J; UT: WOS:000304344500041.

Price, M. V. & Waser, N. M. Effects of experimental warming on plant reproductive phenology in a subalpine meadow. *Ecology* **79**, 1261–1271 (1998).

Cleland, E. E., Chiariello, N. R., Loarie, S. R., Mooney, H. A. & Field, C. B. Diverse responses of phenology to global changes in a grassland ecosystem. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 13740–13744 (2006). LR: 20140908; JID: 7505876; 0 (Soil); 142M471B3J (Carbon Dioxide); N762921K75 (Nitrogen); OID: NLM: PMC1560087; 2006/09/05 [aheadofprint]; ppublish.

Sherry, R. A. *et al.* Divergence of reproductive phenology under climate warming. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 198–202 (2007). LR: 20140907; JID: 7505876; OID: NLM: PMC1713188; 2006/12/20 [aheadofprint]; ppublish.

Rollinson, C. R. & Kaye, M. W. Experimental warming alters spring phenology of certain plant functional groups in an early successional forest community. *Global Change Biology* **18**, 1108–1116 (2012).

Clark, J. S., Salk, C., Melillo, J. & Mohan, J. Tree phenology responses to winter chilling, spring warming, at north and south range limits. *Functional Ecology* **28**, 1344–1355 (2014a).

Clark, J. S., Melillo, J., Mohan, J. & Salk, C. The seasonal timing of warming that controls onset of the growing season. *Global Change Biology* **20**, 1136–1145 (2014b).

Hoeppner, S. S. & Dukes, J. S. Interactive responses of old-field plant growth and composition to warming and precipitation. *Global Change Biology* **18**, 1754–1768 (2012).

Stocker, T. *et al.* IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change (2013).

Johnson, E. A. & Miyanishi, K. Testing the assumptions of chronosequences in succession. *Ecology Letters* **11**, 419–431 (2008).

Marion, G. *et al.* Open-top designs for manipulating field temperature in high-latitude ecosystems. *Global Change Biology* **3**, 20–32 (1997).

Farnsworth, E., Nunez-Farfan, J., Careaga, S. & Bazzaz, F. Phenology and growth of three temperate forest life forms in response to artificial soil warming. *Journal of Ecology* 967–977 (1995).

Pelini, S. L. *et al.* Heating up the forest: openâĂŘtop chamber warming manipulation of arthropod communities at Harvard and Duke Forests. *Methods in Ecology and Evolution* **2**, 534–540 (2011).

Morin, X., Roy, J., Sonié, L. & Chuine, I. Changes in leaf phenology of three European oak species in response to experimental climate change. *New Phytologist* **186**, 900–910 (2010).

Templer, P. H., Phillips, N. G., Ellison, A. M. & Pelini, S. L. Ecosystem warming increases sap flow rates of northern red oak trees. *Ecosphere* **7** (2016).

Shen, M. *et al.* Strong impacts of daily minimum temperature on the green-up date and summer greenness of the Tibetan Plateau. *Global change biology* (2016).

Matthews, E. R. & Mazer, S. J. Historical changes in flowering phenology are governed by temperature× precipitation interactions in a widespread perennial herb in western North America. *New Phytologist* **210**, 157–167 (2016).

Tables

	Chisq	Df	Pr(>Chisq)
(Intercept)	861.834	1.000	0.000
temptreat	431.799	3.000	0.000
block	5.795	2.000	0.055
temptreat:block	43.094	6.000	0.000

Table 1: Effects of warming vary by block, as summarized by a linear mixed effects model of mean soil temperatures, with year and site as nested random effects

	Chisq	Df	Pr(>Chisq)
(Intercept)	1455.294	1.000	0.000
temptreat	126.093	3.000	0.000
year	16.676	1.000	0.000
temptreat:year	61.646	3.000	0.000

Table 2: Effects of warming vary by year, as summarized by a linear mixed effects model of mean soil temperatures, with year and site as nested random effect

Figures

Supplemental Materials

Supplemental Methods

To account for differences in the type of warming and other unmeasured site/study differences (e.g. forced air for Ellison and Marchin; heating cables for Farnsworth and ??), we fit linear mixed effects models with random effect of study-site. Response variables were daily soil or air temperature (models with daily mean, minimum, and maximum were all fit) and , and the explanatory variable was control type (infrastructure or ambient). We used a random slopes and random intercepts structure, so that the effect of control type, as well as the mean temperature, were allowed to vary across study-sites. We fit models across the entire year, as well as separate models for each month to examine if effects varied seasonally.

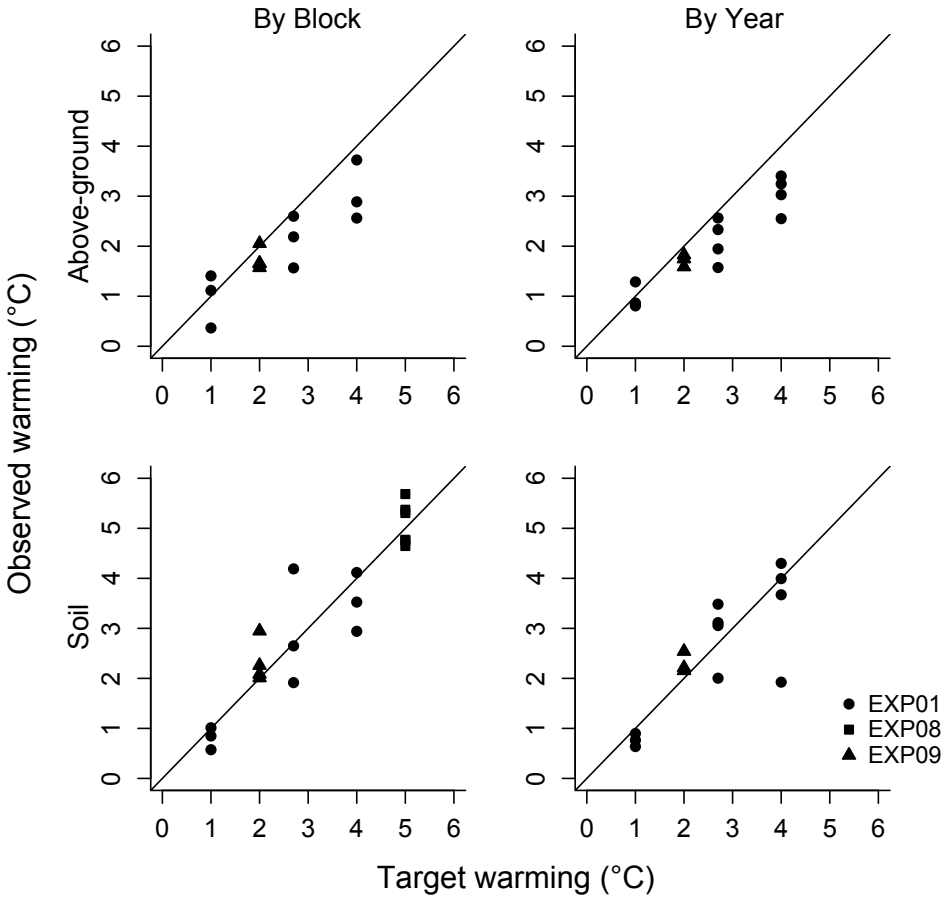

Figure 1: The amount of warming (i.e. the difference between treatment and control plots, within each block) varies among blocks (left panels), as well as among years (right panels). See Tables 1 and 2 for statistical differences.

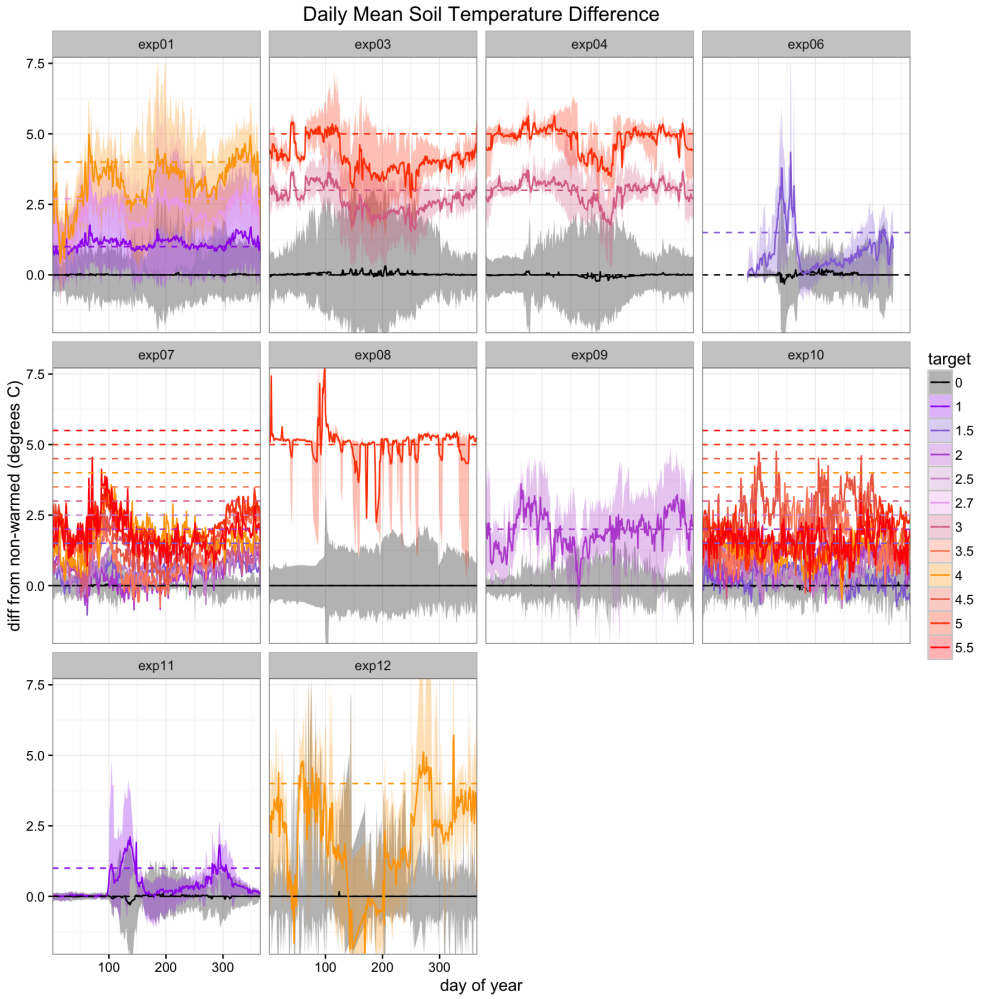

Figure 2: Time series of deviations from mean soil temperature over one year, in control (black line) and warming treatments with various target warming levels at 10 study sites.

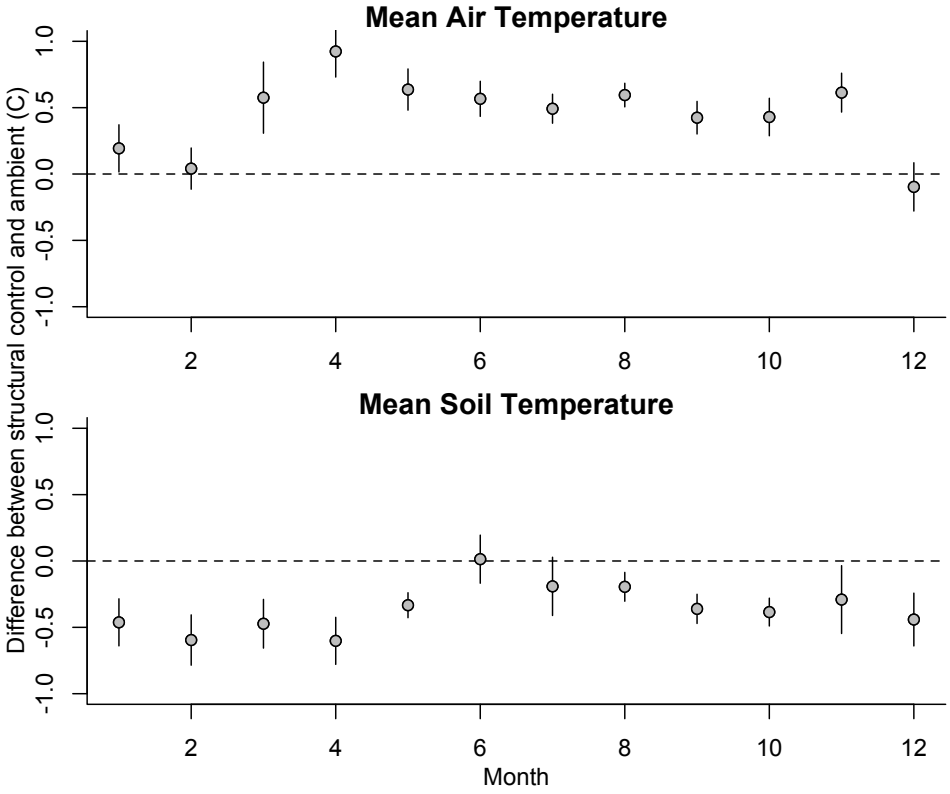

Figure 3: Difference between mean air and soil temperatures in structural controls compared with ambient controls, with no control chambers or warming infrastructure in place. Air temperatures were higher, whereas soil temperatures were lower in the structural controls compared with ambient conditions. We show fixed effects from a mixed effects model that accounts for differences in experimental design and other factors among sites by including site as an intercept-only random effect (see Supplemental Materials for details).

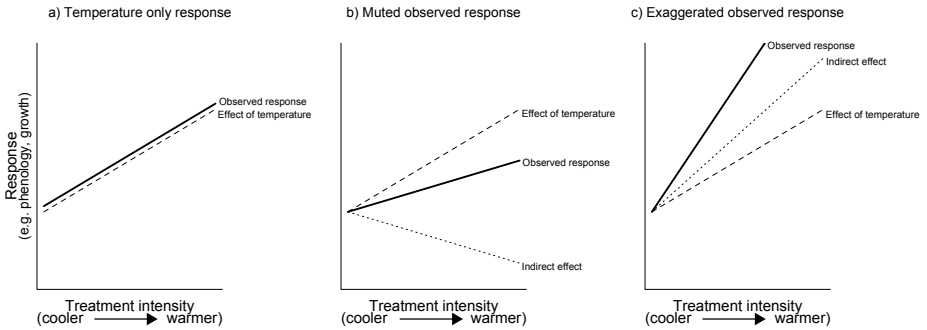

Figure 4: Experimental warming may cause biological responses to be muted or exaggerated, compared to direct responses to temperature alone, when indirect effects of experimental warming are also drivers of focal responses. For example, phenology may appear to be less sensitive to warming in experiments versus observational studies (Wolkovich *et al.*, 2012) because experimental warming reduces soil moisture, perhaps more than natural warming.