

How do climate change experiments actually change climate?

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1 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 understand biological impacts of climate change.

2 Introduction

Future climate change is expected to cause dramatic changes 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 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. Over the past 25 years much focus has been on manipulations to replicated expected higher temperatures. Commonly used field techniques for this include passive warming, such as open-top chambers to increase temperatures, and active warming methods (forced air, soil cables, infrared radiation). Active warming methods are the most controlled, consistent, and "true to climate change predictions," (Aronson & McNulty, 2009; Wolkovich *et al.*, 2012) and we therefore focus on these methods here. In the past XX years, 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 offer several advantages for understanding biological impacts of climate change. Experiments allow temperature and precipitation to be modified in a relatively controlled and rapid way, for example to compare species' performance under current climate conditions versus those forecasted at some future, warmer time (e.g. Pelini *et al.*, 2014; Rollinson & Kaye, 2012; Jamieson *et al.*, 2015). Field experiments can be performed in places where no historic data exist, so that scientists can understand how a range of climatic conditions affect focal organisms and communities, and are less artificial than ex situ controlled experiments such as greenhouses and laboratory warming chambers.

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, and multiple climatic variables may be affected by these manipulations, beyond the target ones. Furthermore, these manipulations often include detailed monitoring of climate variables, yielding large amounts of data, such as daily, or even hourly temperature and other climate variables, over the course of the experiment. Scientists, however, rarely present the results of these detailed data—most publications 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 focus on biological responses to mean shifts makes sense, at least as a first pass at understanding how species respond to warming or other climatic changes. However, as we seek to prepare for future, altered conditions in our biological environment, scientists and others often wish to extrapolate the results of these in situ climate change experiments to forecast how organisms and ecosystems will respond to particular climate change scenarios. Even in cases when 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 mean differences, and the extent to which these manipulations accurately model the real world, both present and future, are 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 10 climate change experiments that manipulate temperature (and precipitation, in some cases) to demonstrate the complex ways that climate is altered by active warming treatments, both directly and indirectly. We then discuss the challenges of interpreting biological implications of experimental shifts in climate, when these climate manipulations are more complex than simple shifts in the mean. Finally, we make recommendations for future climate change experiments.

3 Complications in extrapolating experimental climate change

Climate change experiments often collect detailed microclimate data, at the plot level. However, biologists are generally interested primarily in the biological responses associated with each treatment (e.g. growth or abundance of a species). Not surprisingly then, authors typically report the mean change in temperature, humidity, or other climatic factor achieved under different treatments, and provide more detailed information on the observed biological responses. The imposed climate manipulations result in much more than a simple shift in the mean, however.

3.1 Treatments Vary Over Time

There is often temporal variation in applications of experimental warming, and this variation may be divergent from real (i.e. non-experimental) temperature patterns so it should carefully be considered in extrapolating experimental warming to future climate change impacts. Add details and examples of why this occurs, since warming experiments are tied to ambient conditions.

- 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) (Austria, Norway studies) 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). Furthermore, seasonal precipitation patterns can alter the effectiveness of warming treatments.

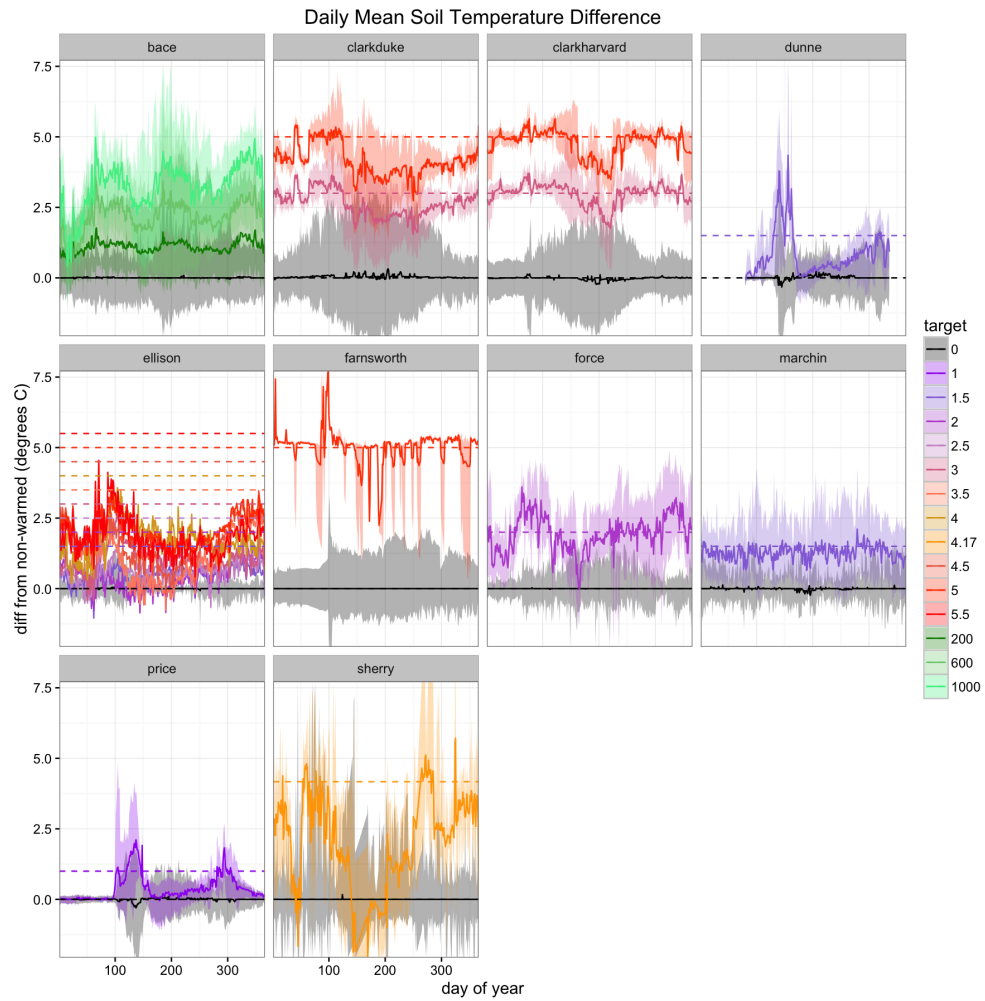


Figure 1: Time series of deviations from mean soil temperature over one year, in control (black line) and warming treatments with various target warming levels at 10 study sites.

- In addition to seasonal patterns, experimental warming effects can vary on a daily timescale. It is common to report only the daily mean temperature, however, this may hide huge variations in minimum and maximum temperatures.
- Anne Marie- please add 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."

3.2 Treatments Vary in Space

There is 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. Presumably there will also be spatial variation in climate change effects. Accurate extrapolation 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. From Aaron: "most space-for-time substitutions turn out to be inaccurate. I think because we make assumptions about state of assemblages and temporal stationarity that are unrealistic." (Add citations about this?)

- Analysis of plot vs. block level variation vs. treatment effects. Lizzie is working on this.
- Documented variation in warming within plots (i.e. edge effects)? (This is known for open-top chambers)

3.3 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 many studies include "shams" or "disturbance controls" to account for them. However, the magnitude of structural effects on climate are rarely discussed, accounted for, 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, Clark et al, Ellison et al, Marchin). These studies 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 Supplement for detailed methods).

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 1). This was consistent across the different temperature models we fit (monthly mean, minimum, and maximum), and the sign of the effects was consistent across study-sites and months, although the magnitude varied among sites (Table 1) and across the year (Figure 1). 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.

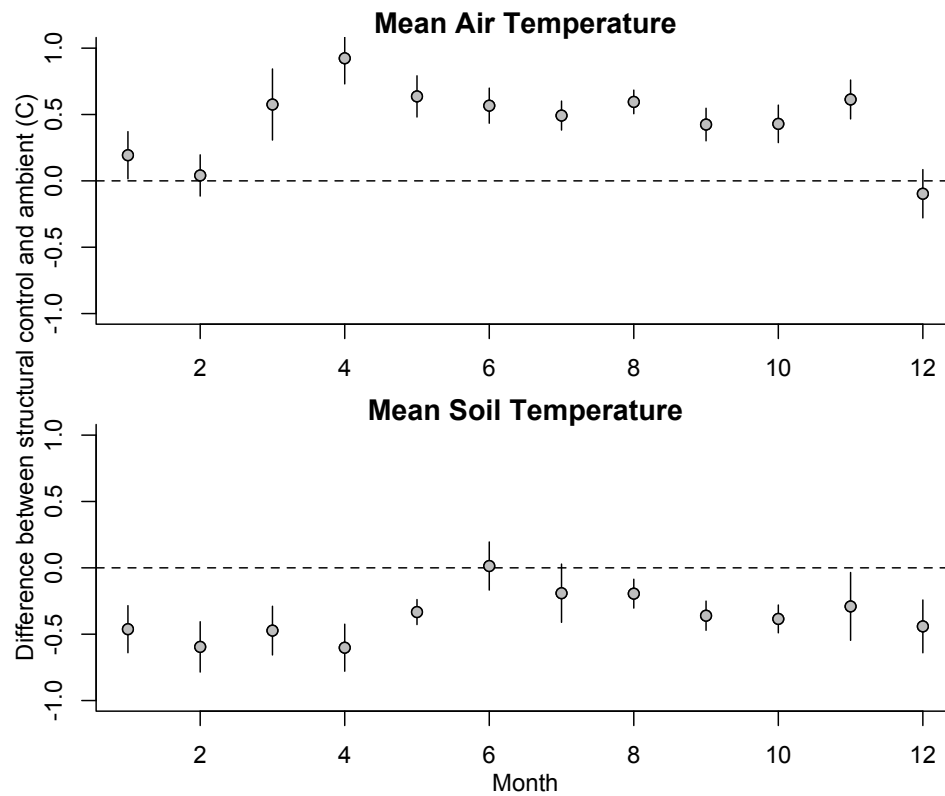


Figure 2: Difference between mean air and soil temperatures in structural controls compared with ambient controls, with no control chambers or warming infrastructure in place. Air temperatures were higher, whereas soil temperatures were lower in the structural controls compared with ambient conditions. 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 `shamvambient.R` for details).

4 Secondary Effects of climate change manipulations

Climate change experiments often manipulate one or two 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 increase moisture in an area projected to get much drier. At the very least, it is important to quantify the secondary effects of applied manipulations. Understanding the effects of an experimental treatment on the suite of interrelated variables is critical when one is trying to determine mechanistic explanations for observed responses to warming.

- Effects of precipitation on temp (BACE, Rollinson)
- Effects of experimental warming on air humidity (use Isabelle's data?). This affects VPD with potential impact for stomata closure (paper out on this response (sapflow, vpd) from Pam Templer's group using Harvard Forest ant warming chambers effects on oak trees)
- Change in biotic interactions: if warming increase the abundance and composition of species it might change competition for resources...

5 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 3).

Examples:

- Plant phenology: likely to be altered in opposing ways by the increased air temperatures and decrease soil moisture, cite Wolkovich et al's earlier work finding discrepancy between observation and experimental phenology responses to warming. (Aaron: plants also respond to variability, perhaps more than mean, as we saw in W Mass this year with fruit tree flowering)
- Soil respiration or other microbe studies? (tight link between microbial activity and plant growth under warming. net mineralization should be accounted for)
- Plant growth- photosynthesis and transpiration are likely to be altered in opposing ways by the increased air temperatures and decrease soil moisture/temperature
- change in biotic interactions (see previous comment): both plant-plant and microbes/fungi-plants
- intraspecific variation? All plants, ants, microbes, etc. of a single species not equivalently responsive.
- herbivory

6 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 ate 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)

7 Supplemental Information

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.

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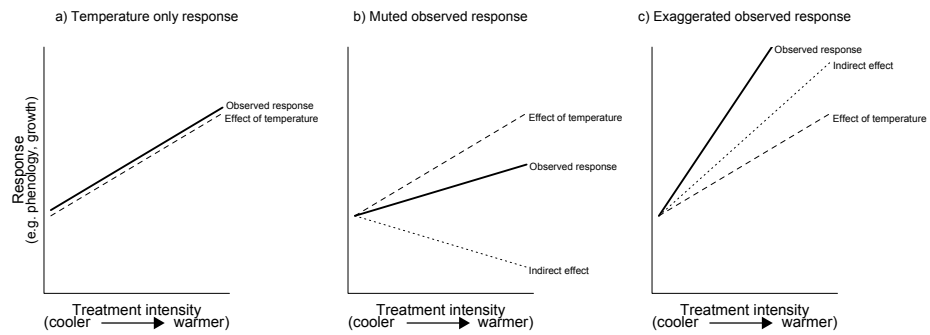


Figure 3: Experimental warming may cause biological responses to be muted or exaggerated, compared to direct responses to temperature alone, when indirect effects of experimental warming are also drivers of focal responses. For example, phenology may appear to be less sensitive to warming in experiments versus observational studies (Wolkovich *et al.*, 2012) because experimental warming reduces soil moisture, perhaps more than natural warming.