# 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. Commonly used field techniques include passive warming, such as open-top chambers to increase temperatures, and active warming methods (forced air, soil cables,infra-red radiation), as well as precipitation manipulations, including drought, snow-removal, and supplemental precipitation treatments. Add citations.

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. Rollinson 2012, Pelini et al 2014, Jameison et al 2015). Field experiments can be performed in places when 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. 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 seem to be overwhelmed with what to do with these detailed data, as 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 (Clark et al 2014,Price and Wasser).

The focus on biological responses to mean shifts makes sense, atleast 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 for the forecasting potential of climate change experiments to be realized. We first use plot-level microclimate data from XX 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 then simple shifts in the mean. Finally, we use these data, as well as experience gained from XX years of combined experience on the part of the authors in field-installed in situ experimental warming, to make recommendations for future climate change experiments.

# 3 Complications in extrapolating experimental climate change

Climate change experiments often collect detailed microcliamte data, at the plot level. However, in our experience, biologists are generally interested primarly in the biological responses associated with each treatment (e.g. growth or abundance of a species), rather than the details of the climate manipulation. As such, 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 snowcover is present (e.g. Clark et al 2014, Austria,Norway) or becuase 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.
- 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, and this may hide huge variations in


Figure 1: Figure 1. Time series of soil temperature over one year, in treatments and controls at XX sites.

minimum and maximum temperautres.

- 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 subsitution. 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 (gradients in slope, aspect, etc) present at the scale at which the extrapolation is being made.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.

- 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 incuded 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. To account for differences in the type of warming and other unmeasured site/stufy 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.

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). In addition, soil moisture was lower in structural controls compared with ambient conditions (Figure 1S).

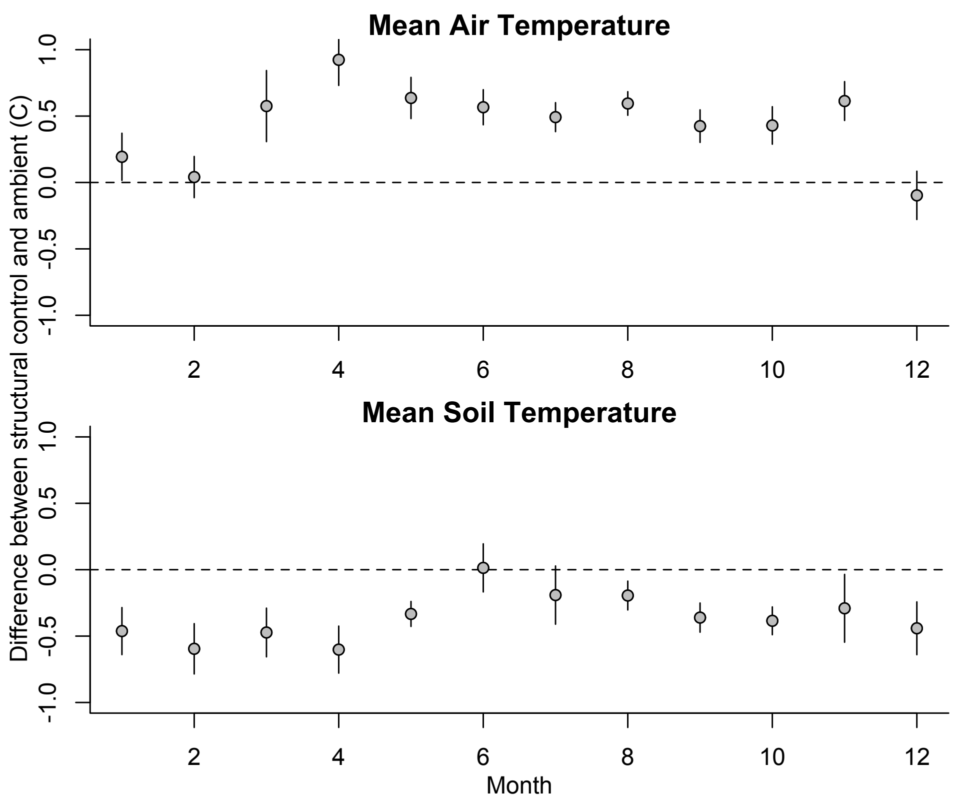


Figure 2: Difference between mean air and soil temperatures in structural controls compared with ambient controls, with no control chambers or warming infrastructure in place. Air temperatures were higher, whereas soil temperatures were lower in the structural controls compared with ambient conditions.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

Temperature interacts with many other climatic and nonclimatic factors to alter the abiotic environment. It is important that experimentally induced changes in other variables are realistic; for example, that experimental treatment does not increase moisture an an area projected to get much drier). Understanding the effect of an experimental treatment on the suite of interrelated variables becomes particularly important when one is trying to determine mechanistic explanations for observed responses to warming.

- 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, I mean if warming increase the abundance and composition of species it might change competition for resources...
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# 5 Biological Implications

We have highlighted a suite of factors that complicate simple 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/temperature, cite Wolkavich et al's earlier work finding discrepency 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.
- genetic component? GXE interactions?
- herbivory

# 6 Recommendations for future climate change experiments

The warming effects we describe are not meant to be criticisms or to imply that experimental warming studies are not worthwhile. On the contrary, we believe that climate change experiments provide invaluable information about biological responses to warming. We also 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.

- Include sham and ambient controls, and collect, use, and report data collectedwithin them. (carefully define what is a sham in the intro)
- Carefully consider and report the timing of warming treatment applied,including exact start and end dates within and across years.
- Collect climate data at least twice daily, and ideally hourly; report these data, in particular, variations in daytime and nighttime and season variations in climate variables. can use time-series modeling, not just monthly (or even daily) means. Get the ACF and PACF
- 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?
- Consider implementing and following community standards for reporting climate data (and phenology -Chuine et al. 2017)
- Construct regression designs to examine possible nonlinear responses to warming
- Publish data with good, useful metadata!
- Publish data with good, useful metadata! Recommend archives?
- Warming experiments should run for several seasons to account for the interannual variations that may interact with the warming treatment itself (especially when looking at non linear processes such as phenology)
- 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.
- Run experiment long enough to capture more than transient responses.

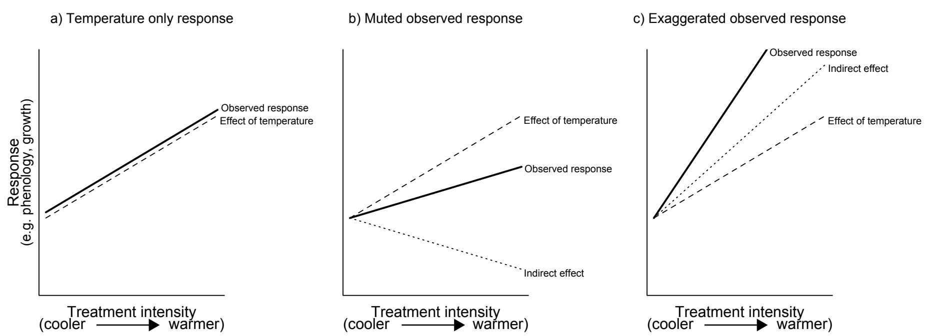


Figure 3: Figure 3. Experimental warming may cause biological responses to be muted or exaggerated, compared to direct responses to temperature alone, when indirect effects of experimental warming are also drivers of focal responses. For example, phenology may appear to be less sensitive to warming in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