# 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

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## 1 Aim

The aim is to write a Concept/Synthesis Paper about maximizing benefits of field-based climate change experiments by improved understanding of how climate is altered by these experiments. Experiments need to report what climate variables are modified by their experiment and how. This is particularly valuable for improving our understanding of biological impacts of climate change.

build up a discussion of studies that report only mean shifts in temperature in the intro.

## 2 Introduction

Experimental in situ climate manipulations offer several advantages to understanding biological impacts of climate change: (controlled, relative speed- i.e. multiple manipulations can be conducted simultaneously, can hit higher temps such as those forecasted, can do them in places where other data collection is hard, are less artificial than ex situ controlled experiments such as chambers

These advantages come at a cost, however. Experimental in situ climate manipulations are logistically challenging, expensive, and more important: other climatic variables than the target ones are affected with possible interactions (often overlooked), And it is dfficult to design replicated experiments that actually do the interactions well, and even moderately realistically.

Problem: People often want to extrapolate the results of warming experiments to real life to understand (and forecast) biological impacts of climate change. Even in cases when this is not the explicit goal, 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, as well as on differences in responses among provenances/genotypes/species. However, our ability to make this application is limited because a detailed assessment of exactly how experimental warming treatments alter climate, and the extent to which these manipulations accurately model the real world, is lacking. Furthermore, especially given the high number of warming methods applied, rising another question: are they comparable?

# 3 Experimental climate change vs. real climate: how do they compare?

## 3.1 Infrastructure

The experimental structures themselves alter temperature and other important biotic and abiotic variables (see note below), in ways that are not generally examined or reported in experimental warming studies. Compare sham and ambient data on temperature (mixed effects models). we should also make explicit what a sham is and how a control plot should be

- Soil temperature is LOWER in the shams, compared with the ambient air (Figure 1). Define exp methods included in this analyses, and other details.
- Air temperature is HIGHER in the shams, compared with the ambient air (Figure 1).
- The pattern was consistent for min and max air and soil temperatures, as well (Figure 2).
- From anne-marie: It seems as though it may be interesting (and important) to focus on other variables that shams may affect than temperature, as the net effect of the sham plus the intended temperature treatment is often what is measured/reported. We should think about discussing the facts that infrastructure may shade the plots and intercept precipitation. Thus, if covariates of soil moisture and solar radiation are not measured/considered, there could be erroneous conclusions about cause and effect. Perhaps even more importantly, there have been a number of good studies now that show that there are important interactions between warming and herbivory. Thus, if shams affect access of herbivores to the plots (like open-top chambers may do), they may give results that are not realistic. (This discussion should likely go in the biotic interactions section, but should be mentioned here in the infrastructure section. I am happy to provide some good references.) I am not convinced by section 3.1 (as it stands now) hat this is important, as long as all of the temperature, moisture, humidity data from the treatment and control plots are reported. Why go through all the extra cost (and space)? If we are to make this argument, I think it needs more supporting evidence/ discussion in section 3.1 (please see my notes on initial ideas on how to do so)

## 3.2 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.

- 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 Time

In addition, there is often temporal variation in 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.

- Seasonal variations in experimental warming effects (plots over time; Christy is working on this?).
- Daily variations in experimental warming effects (Tmin vs Tmax). This is often neglected (common to report only the daily mean temperature that may hide huge variations in min and max) and recently there are several papers showing the importance of diurnal over nocturnal temperature on phenology.
- Compare these seasonal and daily variations to observational data (i.e. plot seasonal and daily variations for warmest vs coldest years)
- Treatments are not applied consistently over the year- IR heaters can't apply consistent warming throughout the year, and some warming experiments turn off warming during some seasons (e.g. Clark et al, this is very common in the heating cable exp, like the ones in Austria, Norway, it is likely that this would yield different effects than if heating were turned on during winter (because then you change soil nutrient mineralization which might be important in winter and so change nutrient availability and moisture for the growing season).
- Include a 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. Site recent Global Change Biology paper by Harte et al. Ideally, we want to run studies long enough to capture population-level responses to warming.

# 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.

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.