Supplemental Materials for: How do climate change experiments actually change climate?

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

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Additional methods for database development

For our literature review, we searched Web of Science (ISI) for Topic=(warm* OR temperature*) AND Topic=(plant* AND phenolog*) AND Topic=(experiment* OR manip*). We restricted dates to the time period after the STONE database (i.e. January 2011 through March 2015). This yielded 277 new studies. We removed all passive warming studies from the list, and contacted authors for daily data. The resulting database contains daily climate data collected between 1991 and 2014 from North American and European climate change experiments (Table S1, Figure S1).

We were unable to include the following studies because authors declined to share their data or did not respond: (Schwartzberg et al., 2014; Moser et al., 2011; Carón et al., 2015; Ellebjerg et al., 2008)

Details of statistical analyses and results

For all analyses, we use mixed-effects models implemented using the lme4 package in R, version 3.2.4 (Bates et al., 2015; Team, 2016). Mixed-effects models, also called multi-level or hierarchical models, can account for structured data that violate the independence assumption of traditional linear regression (Gelman and Hill, 2007). In our analyses, we use levels/groupings of experimental site, year, and day of year (doy) to account for this mutual dependence among data points. To test for significance of fixed effects in our models, we use Type II tests for models including only main effects and Type III tests for models including interactions, as well as main effects.

Analysis of effects of time and space on local experimental climate

To test how treatment effects vary spatially (i.e., among blocks within a study) and temporally (i.e., among years within a study), we used data from the four studies in the C3E database that used blocked designs. We fit linear mixed-effect models with mean daily soil temperature, minimum daily air temperature, and maximum daily air temperature as response predictors (Figure 3 in the main text). For temporal models, we included fixed effects of temperature treatment, year, and their interaction; random effects were site and block nested within site (intercept-only structure, Table **??**). For spatial models, we included fixed effects of temperature treatment, block, and their interaction; random effects were site and year nested within site (intercept-only structure, Table **??**). Both of these models excluded data from plots with precipitation treatments.

Analysis of effects of infrastructure on local experimental climate

To test how infrastructure affects local climate, we compared temperature and soil moisture data from the studies in the C3E database that monitored climate in 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. These five studies occurred at two sites: Duke Forest and Harvard Forest (Farnsworth et al., 1995; Clark et al., 2014; Marchin et al., 2015; Pelini et al., 2011). We fit linear mixed effects models by month with mean daily soil temperature, minimum and maximum daily air and soil temperature (Farnsworth et al. (1995) did not measure these predictors so there are only four different studies in these models), and soil moisture as response predictors. The fixed explanatory predictor was control type (sham or ambient). To allow for both mean differences in temperature and the effect of control to to vary among sites and years, random effects were site and year nested within site, modeled with a random slopes and random intercepts structure. We found that experimental structures altered above-ground and soil temperatures in opposing ways: above-ground temperatures were higher in the structural controls, compared with ambient conditions with no structures installed, whereas soil temperatures were lower in the structural controls compared with ambient soil (Figure 4 in the main text). In addition, soil moisture was lower in structural controls compared with ambient conditions. These general patterns were consistent across the different temperature models we fit (mean, minimum, and maximum soil and air temperatures), although the magnitude varied across months, as well as among studies. We show summaries from models fit to the entire year (Tables **??**, **??**, **??**), as well as summaries from models fit to each month of data, as is shown in Figure 4 in the main text (Tables **??**, **??**, **??**).

Analysis of effects of precipitation treatments on above-ground temperature

Of the twelve experiments in the C3E database, four manipulated precipitation and measured above-ground temperature. To examine the effects of precipitation treatment on above-ground temperature, we fit linear mixed effect models to data from these four sites with above-ground temperature (daily minimum and maximum) as the response variables. Predictors were precipitation treatment (a continuous fixed effect, which ranged from 50 to 200 % of ambient for these four studies), target warming (a continuous fixed effect, which ranged from 0 to 4 °C for these four studies), and their interaction. To account for methodological and other differences among site, we included site as a random effect, with year and doy nested within site to account for the non-independent nature of measurements taken on the same day within sites. We used a random intercept model structure, (Table **??**).

Analysis of effects of experimental warming on soil moisture

Of the twelve experiments in the C3E database, ten measured and reported soil moisture. To examine the effects of target warming treatment on soil moisture, we fit linear mixed effects models to data from these ten sites, excluding plots with precipitation treatments. We first fit a model with soil moisture as the response and a predictor of target warming (this was a continuous fixed effect, which ranged from 0 to 5.2 °C for these 10 studies). To account for methodological and other differences among site, we included site as a random effect, with year and doy nested within site to account for the non-independent nature of measurements taken on the same day within sites. We used a random slope and intercept model structure, to allow the effect of target warming to vary among sites (Table **??**).

In addition to testing how experimental warming influenced soil moisture, we also tested how experimental structures influenced soil moisture. We compared the soil moisture measured in structural controls to both ambient controls and warmed plots by fitting a model with categorical fixed effects of "ambient," "structural control," and "warmed." We again included site as a random effect, with doy nested within site to account for the non-independent nature of measurements taken on the same day within sites, and used a random intercept structure (Table ??).

Analysis of budburst phenology

We wanted to investigate how using measured plot-level climate variables, as opposed to target warming, alters estimates of temperature sensitivity in ecology. To do this, we fit two different types of models to data from the five study sites in the C3E database that recorded above-ground temperature and soil moisture, as well as phenology data (doy of budburst). We focus on budburst, as this phenological phase was reported most commonly among studies in the C3E database. For all models, we accounted for non-independence by including species, site, and year nested within site as intercept-only random effects (Table ??). The target warming model included only one explanatory variables (the target amount of warming). We compared this to models with mean annual measured above-ground temperature (offset by subtracting the minimum temperature across all studies and plots, to make model intercepts more similar), mean winter (January-March) soil moisture, and their interaction as explanatory variables. The slope for temperature in the measured climate model can be directly compared to the slope for target warming in the target warming model because the units are the same (change in budburst, in days/°C).

To determine which specific above-ground temperature variable to include, we compared AICs of models for with four different temperature variables (mean annual minimum and maximum temperatures, mean January-March minimum and maximum temperatures). The model with mean annual minimum temperature, mean January-March soil moisture, and their interaction provided the best model fit (lowest AIC, highest explained variation, Table ??), so we discuss and interpret that model in the main text, summarize it in Table ??, and present its coefficients in Figure 7.

References

Bates, D., M. Maechler, B. M. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67:1–48.

Carón, M., P. De Frenne, J. Brunet, O. Chabrerie, S. A. Cousins, L. De Backer, G. Decocq, M. Diekmann, T. Heinken, A. Kolb, et al. 2015. Interacting effects of warming and drought on regeneration and early growth of acer pseudoplatanus and a. platanoides. Plant Biology 17:52–62.

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

Cleland, E. E., I. Chuine, A. Menzel, H. A. Mooney, and M. D. Schwartz. 2007. Shifting plant phenology in response to global change. Trends in Ecology and Evolution 22:357–365.

Dunne, J. A., J. Harte, and K. J. Taylor. 2003. Subalpine meadow flowering phenology responses to climate change: integrating experimental and gradient methods. Ecological Monographs 73:69–86.

Ellebjerg, S. M., M. P. Tamstorf, L. Illeris, A. Michelsen, and B. U. Hansen. 2008. Inter-annual variability and controls of plant phenology and productivity at zackenberg. Advances in Ecological Research 40:249–273.

Farnsworth, E., J. Nunez-Farfan, S. Careaga, and F. Bazzaz. 1995. Phenology and growth of three temperate forest life forms in response to artificial soil warming. Journal of Ecology 83:967–977.

Gelman, A., and J. Hill. 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press, New York, NY, USA.

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

Marchin, R. M., C. F. Salk, W. A. Hoffmann, and R. R. Dunn. 2015. Temperature alone does not explain phenological variation of diverse temperate plants under experimental warming. Global Change Biology 21:3138–3151.

Morin, X., J. Roy, L. Sonié, and I. Chuine. 2010. Changes in leaf phenology of three european oak species in response to experimental climate change. New Phytologist 186:900–910.

Moser, B., J. D. Fridley, A. P. Askew, and J. P. Grime. 2011. Simulated migration in a long-term climate change experiment: invasions impeded by dispersal limitation, not biotic resistance. Journal of Ecology 99:1229–1236.

Pelini, S. L., F. P. Bowles, A. M. Ellison, N. J. Gotelli, N. J. Sanders, and R. R. Dunn. 2011. Heating up the forest: open-top chamber warming manipulation of arthropod communities at Harvard and Duke Forests. Methods in Ecology and Evolution 2:534–540.

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

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

Schwartzberg, E. G., M. A. Jamieson, K. F. Raffa, P. B. Reich, R. A. Montgomery, and R. L. Lindroth. 2014. Simulated climate warming alters phenological synchrony between an outbreak insect herbivore and host trees. Oecologia 175:1041–1049.

Sherry, R. A., X. Zhou, S. Gu, J. A. A. 3rd, D. S. Schimel, P. S. Verburg, L. L. Wallace, and Y. Luo. 2007. Divergence of reproductive phenology under climate warming. Proceedings of the National Academy of Sciences of the United States of America 104:198–202.

Team, R. C. 2016. R: A language and environment for statistical computing.

Supplemental Tables

Table S1: **Sites included in the C3E database**. Experimental sites correspond to the map (Figure 1, main text). We give the study ID, location, source, years of data included, and warming type used in the study. Note that some sites may have multiple sources; however, we list only one here. Note that we were unable to include the following studies because authors declined to share their data or did not respond: (Schwartzberg et al., 2014; Moser et al., 2011; Carón et al., 2015; Ellebjerg et al., 2008).

study id	location	source	data years	warming type
exp01	Waltham, MA, USA	Hoeppner and Dukes (2012)	2009-2011	infrared
exp02	Montpelier, France	Morin et al. (2010)	2004	infrared
exp03	Duke Forest, NC, USA	Clark et al. (2014)	2009-2014	forced air and soil warming
exp04	Harvard Forest, MA, USA	Clark et al. (2014)	2009-2012	forced air and soil warming
exp05	Jasper Ridge Biological Preserve, CA, USA	Cleland et al. (2007)	1998-2002	infrared
exp06	Rocky Mountain Biological Lab, CO, USA	Dunne et al. (2003)	1995-1998	infrared
exp07	Harvard Forest, MA, USA	Pelini et al. (2011)	2010-2015	forced air
exp08	Harvard Forest, MA, USA	Farnsworth et al. (1995)	1993	soil warming
exp09	Stone Valley Forest, PA, USA	Rollinson and Kaye (2012)	2009-2010	infrared
exp10	Duke Forest, NC, USA	Marchin et al. (2015)	2010-2013	forced air
exp11	Rocky Mountain Biological Lab, CO, USA	Price and Waser (1998)	1991-1994	infrared
exp12	Kessler Farm Field Laboratory, OK, USA	Sherry et al. (2007)	2003	infrared

Table S2: **Experimental sites included in the C3E database**. Experimental sites correspond to the map (Figure 1, main text). We give the study ID, location, source, years of data included, warming type,target warming treatment (°C), precipitation treatment (percent of ambient), method of above-ground temperature measurement (with height of measurement, in cm, for air), depth of soil temperature measurement (cm), and depth of soil moisture measurement (cm) used in each study. Note that some sites may have multiple sources; however, we list only one here.

study	location	data years	warming type	warming treatment	precip treatment	above-ground temperature	soil temperature depth	soil moisture depth
exp01	Waltham, MA, USA	2009-2011	infrared	1, 2.7, 4	50, 100, 150	canopy	2, 10	30
exp02	Montpelier, France	2004	infrared	1.5, 3	70, 100			15, 30
exp03	Duke Forest, NC, USA	2009-2014	forced air and soil warming	3, 5		air (30)	10	30
exp04	Harvard Forest, MA, USA	2009-2012	forced air and soil warming	3, 5		air (30)	10	30
exp05	Jasper Ridge Biological Preserve, CA, USA	1998-2002	infrared	1.5	100, 150		15	15
exp06	Rocky Mountain Biological Lab, CO, USA	1995-1998	infrared	1.5			12, 25	12, 25
exp07	Harvard Forest, MA, USA	2010-2015	forced air	1.5-5.5		air (22)	2, 6	30
exp08	Harvard Forest, MA, USA	1993	soil warming	5			5	
exp09	Stone Valley Forest, PA, USA	2009-2010	infrared	2	100, 120	surface	3	8
exp10	Duke Forest, NC, USA	2010-2013	forced air	1.5-5.5		air (22)	2, 6	30
exp11	Rocky Mountain Biological Lab, CO, USA	1991-1994	infrared	1			12	
exp12	Kessler Farm Field Laboratory, OK, USA	2003	infrared	4	100, 200	air (14)	7.5, 22.5	15