

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

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## Details of Statistical Analyses and Results

### 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 S4). 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 S5). 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 vary among sites and years, random effects were site and year nested within site, modeled with a random slopes and random intercept 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 S6, S7, S8), as well as

summaries from models fit to each month of data, as is shown in Figure 4 in the main text (Tables S9, S10, S11).

## 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 a fixed, continuous effect of target warming level (this ranged from 1.0 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 day of year 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 structure, to allow the effect of target warming to vary among sites (Table S12).

Since our previous analyses revealed that there can be reduced soil moisture due to the experimental structures themselves, we wanted to compare the effect of the structures themselves (i.e. in structural controls) to ambient levels, as well as to the warmed plots. We therefore fit a model with categorical fixed effects of “ambient,” “structural control,” and “warmed.” We again included site as a random effect, with day of year 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 S13).

## 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. To do this, we fit 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 (day of year of budburst). We first fit a model of target warming only to these data, accounting for non-independence by including species, site, and study year nested within site as intercept-only random effects (Table S14). We compared this to a model with measured above-ground temperature, mean winter soil moisture, and their interaction as explanatory variables (with the same random effects structure). 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 S15), so we discuss and interpret that model in the main text, summarize it in Table S14, and present its coefficients in Figure 7.

## References

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## Suppelemental 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.

study id	location	source	data years	warming type
exp01	Waltham, MA, USA	Hoeppe 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: **Climate measurement details for sites included in the C3E database.** We give the target warming treatment(s) ( $^{\circ}\text{C}$ ), precipitation treatment(s) (percent of ambient), method of above-ground temperature measurement (with height of measurement, in cm, for air), depth(s) of soil temperature measurement (cm), and depth(s) of soil moisture measurement (cm) used in each study.

study	warming treatment(s)	precipitation treatment(s)	above-ground temperature	soil temperature depth(s)	soil moisture depth(s)
exp01	1	50, 100, 150	canopy	2, 10	30
exp02	1.5	70, 100			15, 30
exp03	3		air (30)	10	30
exp04	3		air (30)	10	30
exp05	1.5	100, 150		15	15
exp06	1.5			12, 25	12, 25
exp07	1.5-5.5		air (22)	2, 6	30
exp08	5			5	
exp09	2	100, 120	surface	3	8
exp10	1.5-5.5		air (22)	2, 6	30
exp11	1			12	
exp12	4	100, 200	air (14)	7.5, 22.5	15

Table S3: extbfSummary of linear mixed-effects models of how target warming treatment affects daily temperature range (DTR) for above-ground temperatures, and for minimum and maximum above-ground temperatures in climate change experiments. We excluded data from plots with precipitation treatments from these analyses. Estimates (est.) are the intercept and coefficient for target warming from the model; se is the standard error for these estimates. The effect of target warming on observed warming was significant based on Type II Wald  $\chi^2$  tests of fixed effects for minimum above-ground temperature ( $\chi^2=40.95$ ,  $df=1$ ,  $p<0.001$ ) and maximum above-ground temperature ( $\chi^2=4.63$ ,  $df=1$ ,  $p=0.03$ ), but not for DTR ( $\chi^2=1.18$ ,  $df=1$ ,  $p=0.28$ ). Random effects were site ( $n=7$ ) and year nested within site ( $n=29$  year-site combinations), with a random slope and intercept structure. Total number of observations=135,943, and units are degrees Celsius for all three models.

predictor	DTR		min above-ground temp.		max above-ground temp.	
	est.	se	est.	se	est.	se
intercept	14.01	1.61	5.97	0.91	20.12	1.78
target warming effect	-0.38	0.35	0.84	0.13	0.50	0.23

Table S4: extbfAnalysis of variance table for temporal linear mixed-effects models of daily mean soil temperature, minimum above-ground temperature, and maximum above-ground temperature, fit by maximum likelihood. See Figure 3 in the main text. We list degrees of freedom (which are identical across response variables), test statistics, and p-values for Type III Wald  $\chi^2$  tests of fixed effects in the models. For all models, random effects were site ( $n=4$  for soil temperature model,  $n=3$  for above-ground temperature models) and block nested within site (intercept-only structure;  $n=18$  for soil,  $n=12$  for above-ground); total number of observations=36,813 for soil and 28,875 for above-ground; units are degrees Celsius.

predictor	df	mean soil temp.		min above-ground temp.		max above-ground temp.	
		$\chi^2$	p	$\chi^2$	p	$\chi^2$	p
intercept	1	126.02	<0.001	24.07	<0.001	233.1	<0.001
temp. treatment	4	634.87	<0.001	248.69	<0.001	28.95	<0.001
year	4	325.55	<0.001	327.74	<0.001	318.75	<0.001
temp. treatment:year	12	196.77	<0.001	126.41	<0.001	188.95	<0.001

Table S5: extbfAnalysis of variance table for spatial linear mixed-effects models of daily mean soil temperature, minimum above-ground temperature, and maximum above-ground temperature, fit by maximum likelihood. See Figure 3 in the main text. We list degrees of freedom (which are identical for all models), test statistics, and p-values for Type III Wald  $\chi^2$  tests of fixed effects in the models. For all models, random effects were site (n=6) and year nested within site (intercept-only structure; n=6); total number of observations=17,177.

predictor	df	mean soil temp.		min above-ground temp.		max above-ground temp.	
		$\chi^2$	p	$\chi^2$	p	$\chi^2$	p
intercept	1	334.9	<0.001	48.23	<0.001	419.45	<0.001
temp. treatment	4	382.31	<0.001	215.06	<0.001	83.03	<0.001
block	5	17.43	0.004	60.13	<0.001	44.45	<0.001
temp. treatment:block	14	149.27	<0.001	75.16	<0.001	173.88	<0.001

Table S6: extbfSummaries of linear mixed-effects models comparing effects of ambient versus structural controls on daily mean, minimum, and maximum soil temperature in climate change experiments across the year. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For these annual models, differences between control types were significant based on Type II Wald  $\chi^2$  tests of fixed effects for mean soil temperature ( $\chi^2=5.53$ ,  $df=1$ ,  $p=0.02$ ) and minimum soil temperature ( $\chi^2=3.87$ ,  $df=1$ ,  $p=0.05$ ), but not for maximum soil temperature ( $\chi^2=2.07$ ,  $df=1$ ,  $p=0.15$ ). For all models, random effects of site ( $n=5$  for mean model,  $n=4$  for min and max models) and year nested within site ( $n=21$  for mean model,  $n=20$  for min and max models) were fit with a random slope and intercept structure; total number of observations= 48,860 for the mean model and 44,530 for the min and max models; units are degrees Celsius.

	mean soil temp.		min soil temp.		max soil temp.	
predictor	est.	se	est.	se	est.	se
intercept	11.89	1.42	10.81	1.48	13.92	1.61
structure effect	-0.57	0.24	-0.63	0.32	-0.54	0.38

Table S7: extbfSummaries of linear mixed-effects models comparing effects of ambient versus structural controls on daily minimum and maximum air temperature in climate change experiments, across the year. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For these annual models, differences between control types were not significant based on Type II Wald  $\chi^2$  tests of fixed effects for minimum air temperature ( $\chi^2=1.07$ ,  $df=1$ ,  $p=0.30$ ), nor for maximum air temperature ( $\chi^2=0.01$ ,  $df=1$ ,  $p=0.91$ ). For both models, random effects of site ( $n=4$ ) and year nested within site ( $n=20$ ) were fit with a random slope and intercept structure; total number of observations= 44,085; units are degrees Celsius.

	min air temp.		max air temp.	
predictor	est.	se	est.	se
intercept	6.29	1.51	17.74	1.81
structure effect	0.36	0.35	0.02	0.21



Table S8: extbfSummary of a linear mixed-effects model comparing effects of ambient versus structural controls on daily soil moisture (percent volumetric water content, VWC) in climate change experiments across the year. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For this annual model, the difference between control types was significant based on Type II Wald  $\chi^2$  tests of fixed effects ( $\chi^2=89.95$ ,  $df=1$ ,  $p<0.001$ ). Random effects of site ( $n=5$ ) and year nested within site ( $n=21$  year-site combinations) were fit with a random slope and intercept structure; total number of observations= 44,468.

predictor	soil moisture (vwc)	
	est.	se
intercept	21.20	1.86
structure effect	-2.43	0.26

Table S9: extbfSummaries of linear mixed-effects models, fit to each month of data, comparing effects of ambient versus structural controls on daily mean, minimum, and maximum soil temperature, fit to each month separately, consistent with Figure 4 in the main text. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, and p-values for Type II Wald  $\chi^2$  tests of fixed effects (df=1 for all tests). Random effects of site (n=5 for all mean soil temperature models; n=4 for all min and max soil temperature models) and year nested within site (n=19 or 20 year-site combinations for all mean soil temperature models; n=18 or 19 for all min and max soil temperature models) were fit with a random slope and intercept structure; total number of observations ranged from 3,814 to 4,186; units are degrees Celsius.

mon	predictor	mean soil temp.				min soil temp.				max soil temp.			
		est.	se	$\chi^2$	p	est.	se	$\chi^2$	p	est.	se	$\chi^2$	p
01	intercept	2.66	1.25	3.63	0.057	2.34	1.21	2.09	0.149	3.92	1.65	13.71	<0.001
	structure effect	-0.45	0.23			-0.72	0.50			-0.35	0.09		
02	intercept	2.86	1.44	13.06	<0.001	2.58	1.26	3.24	0.072	4.66	1.92	1.99	0.158
	structure effect	-0.44	0.12			-0.67	0.37			-0.41	0.29		
03	intercept	5.24	1.78	6.44	0.011	4.66	1.58	3.64	0.056	7.75	2.04	0.92	0.337
	structure effect	-0.44	0.17			-0.44	0.23			-0.50	0.52		
04	intercept	9.98	1.85	8.53	0.003	8.93	1.98	10.52	0.001	13.24	1.80	0.96	0.327
	structure effect	-0.67	0.23			-0.65	0.20			-0.63	0.65		
05	intercept	14.92	1.37	3.85	0.05	13.74	1.54	4.91	0.027	17.54	1.41	0.59	0.441
	structure effect	-0.31	0.16			-0.27	0.12			-0.32	0.42		
06	intercept	18.29	1.58	0	0.972	17.43	1.57	0.76	0.383	20.98	1.78	0.04	0.844
	structure effect	-0.01	0.20			-0.14	0.16			0.09	0.47		
07	intercept	21.07	1.33	0.06	0.815	19.97	1.34	0.45	0.501	23.76	1.46	0.01	0.914
	structure effect	-0.07	0.28			-0.12	0.18			-0.07	0.61		
08	intercept	20.93	1.20	2.56	0.11	19.59	1.29	1.35	0.244	23.23	1.42	1.58	0.209
	structure effect	-0.26	0.16			-0.20	0.17			-0.37	0.30		
09	intercept	18.23	1.24	10.15	0.001	16.94	1.36	0.58	0.445	20.54	1.43	1.74	0.188
	structure effect	-0.36	0.11			-0.21	0.27			-0.40	0.31		
10	intercept	13.03	1.22	10.48	0.001	12.26	1.24	1.39	0.239	15.42	1.39	10.02	0.002
	structure effect	-0.42	0.13			-0.56	0.48			-0.50	0.16		
11	intercept	8.27	1.13	1.87	0.172	7.34	1.23	0.83	0.363	10.11	1.43	3.16	0.075
	structure effect	-0.33	0.24			-0.52	0.57			-0.28	0.16		
12	intercept	5.03	1.21	2.8	0.094	4.38	1.24	1.53	0.215	6.40	1.53	4.83	0.028
	structure effect	-0.40	0.24			-0.61	0.49			-0.26	0.12		

Table S10: extbfSummaries of linear mixed-effects models, fit to each month comparing effects of ambient versus structural controls on daily minimum and maximum above-ground temperature, fit to each month separately, consistent with Figure 4 in the main text. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, and p-values for Type II Wald  $\chi^2$  tests of fixed effects (df=1 for all tests). Random effects of site (n=4 for both models) and year nested within site (n=18 year-site combinations for both models) were fit with a random slope and intercept structure; total number of observations was 3,726; units are degrees Celsius.

mon	predictor	min air temp.				max air temp.			
		est.	se	$\chi^2$	p	est.	se	$\chi^2$	p
01	intercept	-5.49	1.78	5.27	0.022	5.09	2.60	0.01	0.927
	structure effect	0.61	0.26			-0.03	0.29		
02	intercept	-3.92	1.83	1.41	0.235	7.10	3.03	2.93	0.087
	structure effect	0.55	0.46			0.36	0.21		
03	intercept	-0.08	1.55	8.59	0.003	12.60	2.41	2.75	0.097
	structure effect	0.50	0.17			0.52	0.31		
04	intercept	5.28	1.80	9.33	0.002	19.27	1.92	18.31	<0.001
	structure effect	0.55	0.18			1.26	0.29		
05	intercept	11.62	1.46	6.56	0.01	23.49	1.03	7.75	0.005
	structure effect	0.48	0.19			0.77	0.28		
06	intercept	15.45	1.47	10.13	0.001	26.32	1.82	4.4	0.036
	structure effect	0.43	0.14			0.59	0.28		
07	intercept	17.90	1.26	4.47	0.035	28.94	1.25	3.58	0.059
	structure effect	0.85	0.40			0.61	0.32		
08	intercept	17.07	1.43	2.07	0.15	27.39	1.15	0.87	0.35
	structure effect	0.65	0.45			0.33	0.35		
09	intercept	13.34	1.39	4.71	0.03	23.72	1.47	2.66	0.103
	structure effect	0.88	0.41			0.38	0.23		
10	intercept	7.26	1.26	4.27	0.039	17.29	1.70	1.89	0.169
	structure effect	0.79	0.38			0.30	0.22		
11	intercept	1.21	1.25	4.23	0.04	12.79	1.83	2.76	0.097
	structure effect	0.88	0.43			0.26	0.15		
12	intercept	-2.83	1.48	5.29	0.021	7.56	2.38	0.26	0.61
	structure effect	0.43	0.19			-0.11	0.23		

Table S11: extbfSummaries of linear mixed-effects models, fit to each month comparing effects of ambient versus structural controls on soil moisture (VWC), fit to each month separately, consistent with Figure 4 in the main text. Estimates (est.) are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, and p-values for Type II Wald  $\chi^2$  tests of fixed effects; df=1 for all models. Random effects of site (n=4) and year nested within site (n=18 year-site combinations) were fit with a random slope and intercept structure; total number of observations was 3,829.

mon	predictor	est.	se	$\chi^2$	p
01	intercept	22.58	3.23	59.24	<0.001
	structure effect	-2.77	0.36		
02	intercept	22.10	3.24	16.78	<0.001
	structure effect	-2.54	0.62		
03	intercept	23.58	2.43	8.3	0.004
	structure effect	-2.48	0.86		
04	intercept	22.54	2.15	9.24	0.0024
	structure effect	-2.06	0.68		
05	intercept	21.08	2.31	40.17	<0.001
	structure effect	-2.20	0.35		
06	intercept	18.44	1.37	30.78	<0.001
	structure effect	-2.12	0.38		
07	intercept	17.60	2.18	20.22	<0.001
	structure effect	-2.38	0.53		
08	intercept	16.59	1.90	12.95	<0.001
	structure effect	-2.09	0.58		
09	intercept	15.99	1.54	13.2	<0.001
	structure effect	-1.79	0.49		
10	intercept	20.15	1.93	20.9	<0.001
	structure effect	-2.27	0.50		
11	intercept	21.18	1.77	21.9	<0.001
	structure effect	-2.70	0.58		
12	intercept	22.74	2.83	15.64	<0.001
	structure effect	-2.88	0.73		

Table S12: extbfSummary of a linear mixed-effects model of how target warming treatment affects soil moisture (percent VWC) in climate change experiments. We excluded data from plots with precipitation treatments from this analysis. Estimates (est.) are the intercept and coefficient for target warming from the model; se is the standard error for these estimates. The effect of target warming was significant, based on Type II Wald  $\chi^2$  tests of the fixed effect ( $\chi^2=3.49$ ,  $df=2$ ,  $p=0.06$ ). Random effects were site ( $n=10$ ), year of study, and day of year nested within year ( $n=2434$  day of year-site combinations), with a random slope and intercept structure. Total number of observations was 72,730

	est.	se
intercept	20.85	1.28
target	-0.36	0.01

Table S13: extbfSummary of a linear mixed-effects model comparing soil moisture (percent VWC) in experimentally warmed plots to two different control types, structural and ambient controls. We excluded data from plots with precipitation treatments from this analysis. Estimates (est.) are the intercept (representing mean moisture in ambient controls) and coefficients from the from the model (i.e. differences between the ambient) for structural controls and warmed plots (pooled across all target warming levels); se is the standard error for these estimates. There were significant differences among warming types based on Type II Wald  $\chi^2$  tests of the fixed effect ( $\chi^2=7229.01$ ,  $df=2$ ,  $p<0.001$ ). Random effects were site ( $n=10$ ), year nested within site ( $n=35$  site-year combinations), and day of year nested within year (7,979 day of year-year-site combinations) with a random intercept structure. Total number of observations was 72,730

	est.	se
intercept	22.31	1.31
structure effect	-1.93	0.04
warmed effect	-2.85	0.03

Table S14: extbfComparison of linear mixed-effects models for budburst day of year that contain either target warming treatment only as a fixed effect or measured mean annual minimum temperature (degrees C), mean soil moisture (in percent VWC), and their interaction as fixed effects. Estimates (est.) are the intercept and coefficients from the models; se is the standard error for these estimates. Both models include random effects of site (n=5), year of study nested within site (n=13 day year-site combinations), and plant species (n=54), each with a random intercept structure. Total number of observations was 12839

fixed effect	est.	se
(Intercept)	110.06	6.95
target	-2.01	0.08
(Intercept)	146.42	5.14
agtmin_rel	-6.22	0.41
soilmois_janmar	-135.11	11.5
agtmin_rel:soilmois_janmar	16.14	1.86

Table S15: Comparison of model fits from four models with different fixed effects: 1) target warming only, 2) measured mean annual minimum temperature (tmin) only, tmin and soil moisture (soilmois), and tmin, soilmois, and their interaction. We additionally compared models with mean annual maximum temperature, and seasonal temperature variables; we present only tmin here because this variable provided the best model fit (i.e. lowest AIC).

model	df	aic	deltaaic
tmin*soilmois	8.00	104752.16	0.00
tmin+soilmois	7.00	104825.61	73.50
target	6.00	104889.13	137.00
tmin	6.00	104903.49	151.30

## Supplemenetal Figures

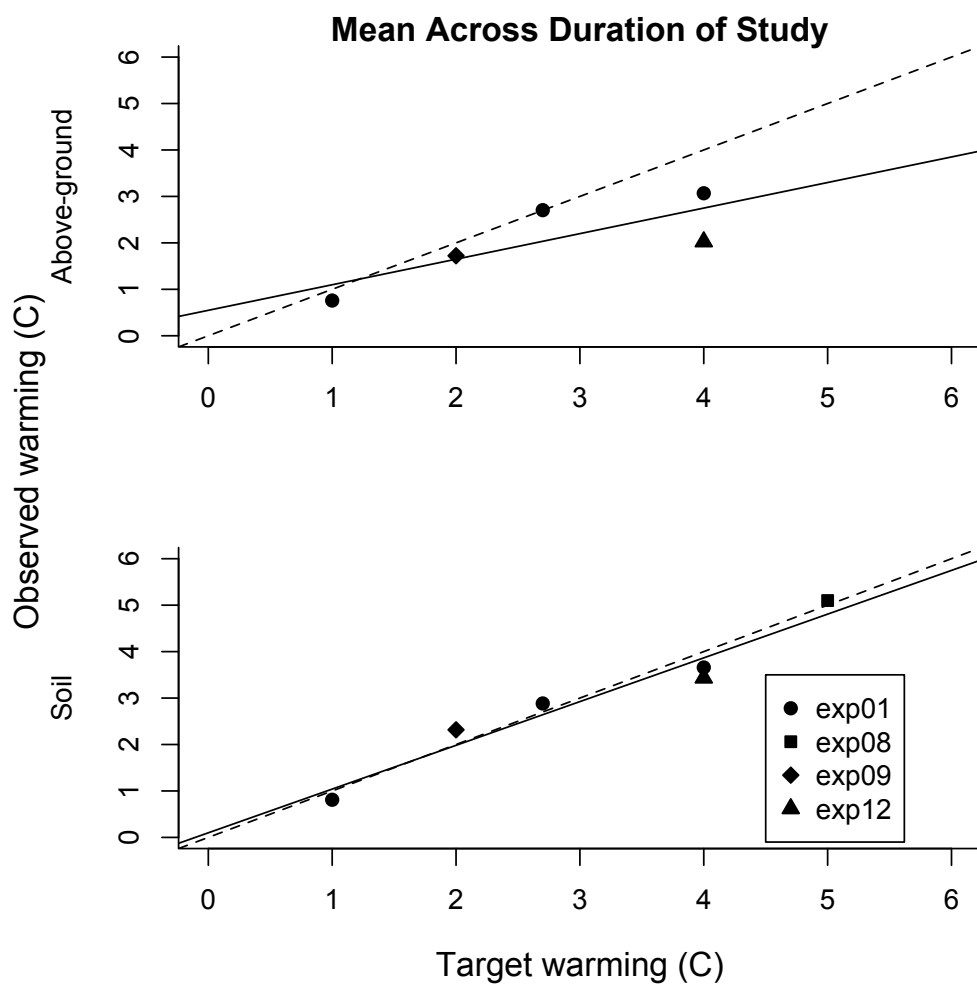


Figure S1: **Mean warming across the study duration.** Reporting only the mean temperature difference across the duration of the study, as is commonly done in publications of climate change experiments, hides potentially important variations in daily, seasonal, and annual temperatures among treatments. Compare to Figure 3 in the main text.