ECOSYSTEMS

Tracking Soil Temperature and Moisture in a Multi-Factor Climate Experiment in Temperate Grassland: Do Climate Manipulation Methods Produce their Intended Effects?

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ABSTRACT

Passive open-top chambers (OTCs) and rainout shelters (RSs) have been used for over two decades to manipulate temperature and water availability in experiments on plant communities. These types of manipulations have been independently evaluated; however, as experiments become more complex and multiple factors are evaluated the potential for unknown or undesirable treatment effects increases. We present the effects of temperature manipulations (with OTCs), water manipulations (with RSs and water additions), and a clipping treatment, implemented in a fully factorial design, on soil moisture and temperature over 2 years in a temperate grassland. Temperature was increased 0.2°C by OTCs. Soil volumetric water content was reduced 3% by RSs and increased 2% by watering. However, clipping vegetation, treatment interactions, and weather conditions also affected soil temperature and moisture. For example,

in OTCs RSs increased the temperature an additional 0.4°C, watering lowered it 0.4°C, and clipping raised temperature 2°C. Similarly, changes in soil moisture due to the RSs decreased VWC by 3% and increased 1% by clipping whereas soil moisture due to watering was reduced 1% by the OTCs and clipping. We also found that OTCs are more effective at raising temperatures on cooler days when soil temperatures are below 16.3°C. Our results suggest that all treatment types generally affect soil variables in predicable ways, but use of such devices should be adopted with caution, as they do not act independently, or exclusively, on the target variables.

Key words: open-top chamber; rainout shelter; climate change; soil volumetric water content; clipping; disturbance.

INTRODUCTION

There is increasing evidence that global climate change is altering plant community composition and structure (Walther and others 2002; Parmesan and Yohe 2003; Root and others 2003; Walker and

others 2006; Hudson and Henry 2009). Ongoing greenhouse gas emissions caused by human activities will likely continue to contribute to global change in the future (IPCC 2007). Predictive climate models suggest an array of future climate conditions with the major drivers, temperature and precipitation, interacting in complex ways (IPCC 2007). To understand the consequences of climate change on plant communities, it is necessary to manipulate climatic factors in controlled field experiments. For the most part, climate manipulations have been implemented singularly (for example, Köchy and Wilson 2004; Gedan and Bertness 2009; but see Grime and others 2000), but manipulations also need to be implemented factorially to understand their interactions. Furthermore, plant communities experiencing climate change will be interacting with other processes, such as disturbance, which could also be incorporated into climate experiments to understand the complexity of climate change effects on plant communities.

Most climate change experiments have focused on temperature and precipitation because these are the factors most likely to be altered by global climate change. Different methods have been used to manipulate temperature and precipitation in small-scale experiments, but do these manipulations produce a desired result when used together? Temperature manipulations have been done using heating cables (for example, Grime 2001; Dunne and others 2004), heaters (for example, Norby and others 1997), infra-red lamps (for example, Shaw and others 2002), and open-top chambers (OTCs, for example, Marion and others 1997). We tested the performance of open-top chambers; they have been used to test the effects of warming on herbaceous plant communities in the Arctic (Henry and Molau 1997; Marion and others 1997; Wahren and others 2005; Rustad and others 2001), grassland steppe in Tibet (Klein and others 2004), in the alpine (Klanderud and Totland 2005), and in salt-marshes (Gedan and Bertness 2009). The design of OTCs usually consists of a translucent material walled around the experimental plot (Marion and others 1997). In general, OTCs are approximately 1 m in diameter and 30–40 cm high, but larger OTCs (4.7 m diameter, 3.5 m high) have been used on trees (Whitehead and others 1995). Marion and others (1997) report temperature effects for different OTC designs that range from slight reductions of soil temperature at some locations, but an average increase of 2.2°C under optimal conditions; this is typical of other studies in the Arctic (Coulson and others 1993) and Mongolian grasslands (Klein

and others 2005). Chambers also increased air temperature from less than 1°C in 4.7 m diameter chambers (Whitehead and others 1995) to increases as much as 6°C in chambers with reduced top-openings (Bremer and others 1996), but a typical OTC design increases air temperature 1–2°C (Coulson and others 1993; Klein and others 2005). Despite the relatively small size of OTCs, they have been shown to have similar effects to natural landscape scale warming patterns (Hollister and Webber 2000) and temperature increases of less than 1°C are sufficient to induce change in soil respiration, nitrogen mineralization, and above-ground plant biomass (Rustad and others 2001).

Soil moisture can be either increased by adding water, or reduced using a rainout shelter (RS). RSs have been used extensively in grassland ecosystems (Svejcar and others 1999; Fay and others 2000; Yahdjian and Sala 2002), but have been more variable in design than OTCs. Typically, a translucent material is used to intercept falling rain. These structures can either be fixed (Fay and others 2000; Köchy and Wilson 2004) or moveable. For example, Grime and others (2000) used a motorized design with precipitation sensors that deploy the shelter only when it is raining to minimize unwanted shading by the shelter. The amount of rain intercepted has also been modified using slat like structures that can vary in size (Yahdjian and Sala 2002). Regardless of design, they are effective at lowering soil moisture but have the unwanted effect of intercepting solar radiation. OTC and RS devices can be used in combination with other treatment types to understand the interactions between processes that alter plant communities.

Disturbance of vegetation is a globally significant process; it is estimated that half of the terrestrial land mass is grazed by domesticated livestock (Havstad and others 2008). Grazing can either increase (Bremer and others 1998) or decrease (Vare and others 1996) soil temperature depending on environment or season (Johnston and others 1971). Furthermore, live biomass or litter can also change soil temperature and moisture (Klein and others 2004). Thus, any disturbance that removes plant material may also alter soil temperature and moisture.

Effects of warming, water availability, and disturbance are likely to become complex when they interact. Changes in soil temperature can affect soil moisture and vice versa. Temperature increases will elevate evaporation rates, whereas moisture due to water's high heat capacity can increase the amount of energy required to raise temperature, but once heated will remain warmer for a longer period than

drier soils. By measuring how soil temperature and moisture are affected by climate and disturbance manipulations, the validity of such experiments can be confirmed.

We ran a 4-year experiment examining the interacting effects of OTCs, water availability, and the clipping of vegetation on the structure and species composition of semi-arid grasslands in the southern interior of British Columbia, Canada (Fraser and others 2009). In a subset of the experimental plots, at the same location, we monitored soil temperature and moisture through two growing seasons. Here, we report the performance of OTCs and RSs in the semi-arid grassland and examine if these two climate manipulations produced their intended effects, whether clipping affected soil temperature and moisture, whether interacting treatments create unintended effects and if weather conditions affected performance.

METHODS

Site Description

The study was done in Lac du Bois Grassland Provincial Park within the bunchgrass grasslands of the southern interior of British Columbia, 6 km north of Kamloops, Canada (UTM 10 E 0680737 N 5625980; elevation 731 m a.s.l., Figure 1A). The region is semi-arid with annual precipitation of 279 mm, 75.5 mm of which is snowfall. Average annual daily temperature for the region is 8.9°C, the warmest month is July (21.0°C), and the coldest is January (−4.2°C) (Environment Canada 2009). The grasslands are dominated by *Pseudoroegneria spicata* (Pursh) A. Love (Bluebunch wheatgrass) and the shrub *Artemisia tridentata* Nutt. (Big sagebrush) (van Ryswyk and others 1966). Other common species at the study site are *Koeleria macrantha* (Ledeb.) Shult. (June grass), *Achillea millefolium* L. (Yarrow), and *Astragalus collinus* (Hook.) Douglas ex G. Don (Hillside milkvetch). The soil is a brown Chernozem with a fine sandy loam texture (van Ryswyk and others 1966). Air temperature and precipitation were measured at the site from May through October of each year using a rain gauge and temperature logger (Model RG3-M, Onset Computer Corporation, Bourne, USA), each of which were placed 1 m above the ground.

Experimental Design

Thirty-six 1 m² experimental plots were located at a single south facing site with a slope of 13°. Although the surrounding grasslands were grazed by cattle, all of our plots were located within a fenced exclosure that had not been grazed for approximately 30 years. All plots were selected to exclude *A. tridentata* because the focus was on the herbaceous community. Each plot was at least 1 m away from other plots and from any *A. tridentata* shrubs. A fully factorial experiment included two warming treatments (plots were either warmed with an OTC or at ambient temperature), three precipitation treatments (plots with precipitation reduced using a RS, water increased by weekly hand watering, and natural ambient precipitation), and two clipping treatments (plots were clipped once annually in July to a height of 5 cm above the soil surface or left unclipped). The experiment was established in May 2005 and the first clipping occurred in July 2005. OTCs and RSs were in place from April to October in 2005 through 2007 and from April to August in 2008. The factorial experiment had 12 treatment combinations, each of which was replicated three times at the site, thus we are reporting data monitored in 36 experimental plots.

Open-Top Chambers

The OTCs (Figure 1B) we used were similar to the plastic tent design described in Marion and others (1997). Each OTC had a square base, 1.5 m a side. The plastic was secured to a wooden support driven into the ground. The stakes were angled so that the top-opening was square, 1 m on a side and 40 cm above the soil surface. The plastic (Tufflite IV™, 6 mil, 0.152 mm thick, Tyco Plastics and Agricultural Films, Monroe, LA, USA, 93% PAR transmission) has high transmission of photosynthetically active radiation, repels dust from its surface (important for maintaining light transmission especially in our dust-prone study region), and is durable and economical.

Water Manipulations

We constructed rainout shelters (Figure 1C) similar to the design of Köchy and Wilson (2004), which comprised a 1 m² plastic sheet, the same material used in the OTCs, attached to a pole 1 m high at one corner and anchored at the remaining three corners such that they were each 30 cm above the soil surface to allow airflow. The sheet was oriented to block rain from the dominant wind directions during the growing season. Some treatments had both a RS and an OTC; in this case, the RS was within the OTC but water off the RS would drain outside the border of the plot as it would in other RS plots (Figure 1C).

Water availability in the plots was increased by hand watering once a week from May through

Figure 1. Photos of **A** experimental site in Lac du Bois Provincial Park, Canada, **B** an open-top chamber (foreground), and **C** a rainout shelter and open-top chamber.

October of each year. Once per week each plot received enough water to increase the monthly 30 year rainfall average by 30%. The historical (1970–2000) rainfalls for the months May through September were 24.4, 35.2, 29.5, 29.1, and 28.0 mm (Environment Canada 2009), thus we added 1.8, 2.6, 2.2, 2.2, and 2.1 l each week in the respective months. Plots were hand-watered with care to ensure minimal runoff from the plot. We used rainwater that was collected locally and stored in a black plastic cistern to minimize algal growth.

Soil Measurements

Two response variables, soil temperature and soil moisture, were monitored in the center of each plot. A temperature probe (TMC50-HD, connected to a HOBO® U12 Data Logger, Onset Computer Corporation, Bourne, USA) was placed 5 cm deep into the soil. A soil moisture probe (10 cm long, Soil Moisture Smart Sensor, S-SMB-M005 using a

ECH$_2$0® Dielectric Aquameter probe, Decagon Devices, Inc., Pullman, USA, connected to a HOBO® Micro Station data logger, Onset Computer Corporation, Bourne, USA) was placed vertically so that the top was 1 cm below the soil surface. We installed the probes near the soil surface to measure the maximum effects of the treatments because treatment effects will dampen with depth (Marion and others 1997). The probes were installed in May of each year and programmed to record measurements every 30 min. Due to the sandy texture of the soil, data from the soil moisture probes were recalculated for the local soil type (Campbell 2002). Soil temperature and moisture were monitored from May to October in 2007 and from May to August in 2008.

Statistical Analyses

Multi-factor repeated measure analysis of variance (RMANOVA) was used to test for treatment effects

on mean daily temperature, data subsets based on the quartiles of the temperature in control plots, the daily minimum and maximum temperature, and daily temperature variance. The same procedure was also used to test for treatment effect on mean daily volumetric water content (VWC), mean daily maximum VWC, mean daily minimum VWC, and the daily variance of VWC. RMANOVAs that included TIME (hour, day, or month) were also run to test within-subject effects of time. In tests of month as the time factor, the response variables were mean daily temperature, daily temperature variance, mean daily VWC, and daily VWC variance. In the test of hour and day as a time factor, the response variable was mean daily temperature. A RMANOVA was run to test for differences of VWC in plots on the days after watering. A paired T test was used to compare the VWC within plots on days when rain fell to days when rain did not fall. All data were approximately normal. All analyses were done using R version 2.7.0 (R Development Core Team 2008).

RESULTS

Site

From May to October, the mean air temperature was 17.8°C in 2007 and 17.1°C in 2008 (Figure 2). The hottest recorded air temperature was 45.8°C at the end of June 2008. The coolest air temperature was −2.8°C in early May 2007. In 2007, 129 mm of rain fell; 34 mm more rain than 2008. Most rainfall events were less than 5 mm per day, the largest daily rainfall was 15 mm in July 2007 (Figure 2). The average standing biomass at the site was 29.2 g/0.25 m^2 and the average amount of litter was 33.4 g/0.25 m^2.

Soil Temperature

The mean soil temperature of control plots was 19.0°C (range 3.1–49.0°C), the mean daily maximum was 27.9°C and the mean daily minimum was 12.6°C (Figure 3A).

Treatment Effects on Temperature

Watering treatments and clipping altered soil temperature, but there was no significant effect of the OTC on mean temperature (Table 1; Figure 3A). The mean temperature in ambient water plots, water addition plots, and RS plots was 19.4, 18.8,

Figure 3. **A** Mean (±1 SE) soil temperature and **B** mean (±1 SE) soil moisture in all twelve treatment combinations. Precipitation in the plots was at ambient (Wc), increased with hand watering (W+) or reduced with rainout shelters (RS). Plots either had an open-top chamber (OTC) or not (No OTC). Plots were clipped (C+) or were not clipped (C−). ''Control'' indicates unmanipulated plots for all treatments. In **A** *triangles* indicate the mean daily maximum temperature and *inverted triangles* indicate mean daily minimum temperature. In **B** *circles* indicate mean daily soil moisture on days with rain (*closed circle*) and days without rain (*open circles*); *asterisk* above the bars indicate a significant difference of mean daily soil moisture between days with ($n = 67$) and without ($n = 153$) precipitation, *ns* not significant (Paired T test, $P < 0.05$).
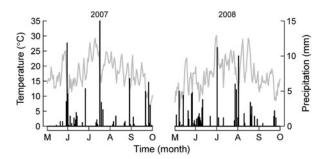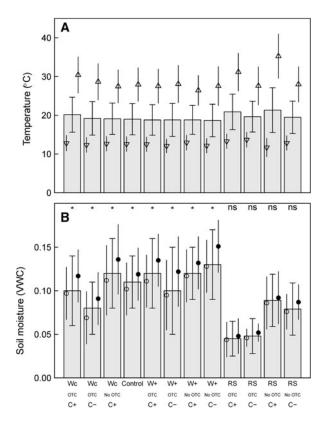

Figure 2. Mean daily air temperature (*gray lines*) and daily rainfall totals (*black bars*) at the site. Data were collected during the growing season from May to October in 2007 and 2008.

and 20.3°C, respectively. Clipping increased temperature, clipped plots had a mean temperature of 19.8°C and unclipped plots averaged 19.1°C. The hottest treatment was the combination of a RS and clipping (Figures 3A, 4) that was on average 2.3°C warmer than the control plot followed by the treatment that had an OTC and was clipped (1.9°C warmer than control). The coolest treatment was the water addition (1.3°C cooler than control plots). There was a WATER × CLIPPING interaction effect on soil temperature (Table 1) such that clipping increased temperature in ambient water and RS plots but had no effect on temperature in water addition plots.

The daily mean maximum, minimum, and variance of temperature were all affected by treatments (Table 1). The minimum temperature was affected by an OTC × WATER interaction where, in the RS plots, the OTC increased the mean minimum temperature from 12.3 to 13.5°C. The mean daily maximum temperature of the plots was different due to water treatments (ambient water = 28.6°C, water addition = 27.4°C, and water removal plots = 30.3°C). Clipping increased the maximum temperature from 27.9 to 29.5°C. There was an OTC × WATER interaction where OTCs increased the mean maximum daily temperature in the water addition and ambient water plots, but decreased maximum temperature in the RS plots. As well, there was a WATER × CLIP interaction where clipping raised the maximum temperature in the water removal plots over 5°C, from 27.7 to 33.1°C. The variance of temperature was increased by RS treatments (ambient water = 33.8, water addition = 30.3, and water removal plots = 42.8). In the RS plots there was a difference of temperature variance between the OTC treatments; ambient plots had a variance of 50.2, whereas OTC plots had a variance of 35.2. There was also a WATER × CLIP interaction where again, in the RS plots, clipping increased variance to 56.2 compared to 30.9 in the unclipped plots.

Temporal Effects on Temperature

The change in temperature varied hourly, daily, and monthly and there were significant TREATMENT × TIME interactions (Tables 2, 3), indicating that treatment effects were not consistent through time. The effect of the water treatments and clipping follows the same general pattern as the main effects and their interactions. On an hourly basis, there was an OTC × WATER × HOUR and a WATER × CLIP × HOUR interaction.

Table 1. Repeated Measure ANOVA Testing the Effect of Treatments on Mean Daily Temperature

	df	Temperature (all data)		Coolest days <11.3°C (11 days)		Cool days <16.3°C (54 days)		Warm days >22.2°C (56 days)		Warmest days >27.2°C (5 days)		Min		Max		Variance	
		F value	P	F value	P	F value	P	F value	P	F value	P	F value	P	F value	P	F value	P
OTC	1	1.19	0.286	8.56	0.007	4.99	0.035	0.001	0.997	0.44	0.511	1.14	0.296	0.13	0.725	0.06	0.811
WATER	2	16.85	<0.001	9.90	<0.001	22.34	<0.001	7.34	0.003	4.44	0.023	1.12	0.342	5.71	0.009	3.15	0.061
CLIP	1	12.02	0.002	4.12	0.054	11.47	0.002	4.22	0.051	3.38	0.079	0.05	0.819	5.29	0.030	2.9	0.143
OTC × WATER	2	1.03	0.371	0.097	0.908	0.21	0.808	2.24	0.128	3.17	0.060	2.67	0.090	2.73	0.086	3.01	0.068
OTC × CLIP	1	0.004	0.953	0.14	0.715	0.07	0.795	0.01	0.909	0.01	0.914	0.17	0.681	0.01	0.915	0.39	0.540
WATER × CLIP	2	4.68	0.019	0.21	0.816	0.87	0.429	3.79	0.037	2.58	0.097	2.28	0.123	6.77	0.004	5.39	0.012
OTC × WATER × CLIP	2	1.19	0.323	1.31	0.287	1.14	0.336	0.73	0.492	1.09	0.351	0.37	0.692	1.51	0.240	1.53	0.237
Residuals	24																

Data were analyzed separately for days of different temperatures separated on the basis of daily mean temperature in control plots (quartiles and quartiles plus 5°C). The minimum, maximum and variance of all data were also tested. Temperature was modified using OTCs, water was either added, reduced with a rainout shelter or at ambient, and plots were clipped or not clipped. Significant (P < 0.1) effects are in bold.
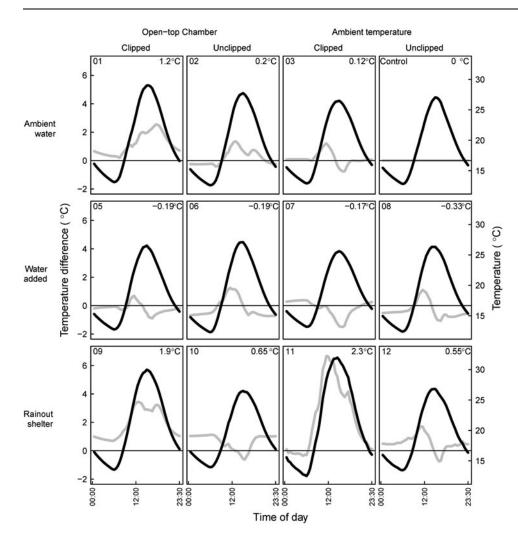
Figure 4. Mean hourly soil temperatures measured at 5 cm depth (averaged over days and replicates) in all treatments. The *top right plot* is soil temperature in the control plot (mean temperature 19.0°C). All other *panels* show the mean temperature (*black line, right axis*) of treatment plots. The *gray line* is difference between soil temperature of the treatment plot and the control plot (*left axis*). The *number* in the top right indicates the mean temperature change relative to the control and the *horizontal line* indicates zero change relative to the control.

Table 2. Repeated Measure ANOVA Testing Effects on Mean Hourly Temperature and Mean Daily Temperature with Time of the Day (Measured on the Hour and Half Hour) and Day as Factors

	df	Hour		Day	
		F value	P	F value	P
TIME (hour or day)	1	653.59	**<0.001**	25.7	**<0.001**
OTC × TIME	1	0.634	0.974	0.32	0.569
WATER × TIME	2	1.31	**0.029**	14.0	**<0.001**
CLIP × TIME	1	1.57	**0.009**	0.72	0.397
OTC × WATER × TIME	2	1.75	**<0.001**	1.93	0.146
OTC × CLIP × TIME	1	0.25	1	4.73	**0.030**
WATER × CLIP × TIME	2	3.55	**<0.001**	5.46	**0.004**
OTC × WATER × CLIP × TIME	2	0.50	1	0.16	0.852
Residuals	Hour = 1,128				
	Days = 7695				

Only the within-subject effects are shown. Temperature was modified using OTCs, water was either added, reduced with a rainout shelter or at ambient and plots were clipped or not clipped. Significant ($P < 0.1$) effects are in bold.

Similarly, there was an OTC × WATER × DAY and a WATER × CLIP × DAY interaction. These analyses reveal significant time interactions with the OTCs suggesting that OTCs have an effect during some times of the day and not others. Over a daily cycle (Figure 4) within a treatment temperatures

Table 3. Repeated Measure ANOVA of Effects on Soil Temperature and Moisture and Their Variance with Month as a Factor

	df	Temperature		Temperature variance		Moisture		Moisture variance	
		F value	P	F value	P	F value	P	F value	P
MONTH	3	1322.37	**<0.001**	12.78	**<0.001**	66.50	**<0.001**	44.65	**<0.001**
OTC × MONTH	3	0.17	0.913	0.40	0.752	3.62	**0.017**	1.49	0.225
WATER × MONTH	6	1.38	0.236	0.39	0.886	14.08	**<0.001**	8.44	**<0.001**
CLIP × MONTH	3	1.62	0.193	0.87	0.462	0.20	0.894	2.42	**0.073**
OTC × WATER × MONTH	6	0.84	0.542	0.40	0.874	3.54	**0.004**	2.32	**0.042**
OTC × CLIP × MONTH	3	0.34	0.795	0.05	0.982	0.48	0.700	0.29	0.836
WATER × CLIP × MONTH	6	2.11	**0.062**	1.64	0.148	6.73	**<0.001**	3.50	**0.004**
OTC × WATER × CLIP × MONTH	6	0.43	0.855	0.13	0.992	1.93	**0.088**	0.44	0.850
Residuals	72								

Only within-subject effects are shown. Temperature was modified using OTCs, water was either added, reduced with a rainout shelter or at ambient and plots were clipped or not clipped. Significant (P < 0.1) effects are in bold.

could decline below those of the control or increase above that of the control.

In the 4 months presented in Figure 5A–C, although temperature varied monthly there were no MONTH × main effect interactions (Table 3). There was a WATER × CLIP × MONTH interaction, where among RS plots, those that were clipped were warmer than the unclipped plots in June and July (Figure 5C). The variance of temperature varied by month, but not by treatments (Table 3; Figure 5E–G).

Weather Effects on Temperature

We separated the data based on the quartiles of the mean daily temperature in the control plots, and found that the OTCs, water and clipping treatments all affected soil temperature, but effects were dependent on the natural temperature (Table 1, Figure 6). On the cooler days (<16.3°C), the OTCs, water removal, and clipping caused an increase in temperature. On warm days (>22.2°C), OTCs had no effect, watering and clipping treatments responded and interacted with each other as described above. On the warmest days (>27.2°C, the quartile plus 5°C) OTCs did not change temperature and there was an additional OTC × WATER interaction where RS plots with an OTC were cooler than RS only plots, and the OTCs increased temperature in ambient water plots. Thus, OTCs significantly increased temperature on the coolest 54 days. Furthermore, on extremely cool days (<11.3°C, the quartile minus 5°C) the significance of the OTC effect on temperature increases, which suggests that the OTCs are more effective as ambient temperatures decline.

Soil Moisture

The mean soil moisture of control plots was 11% VWC, the range was 2–35% VWC, the mean daily maximum was 16%, and the mean daily minimum was 9% VWC (Figure 3B).
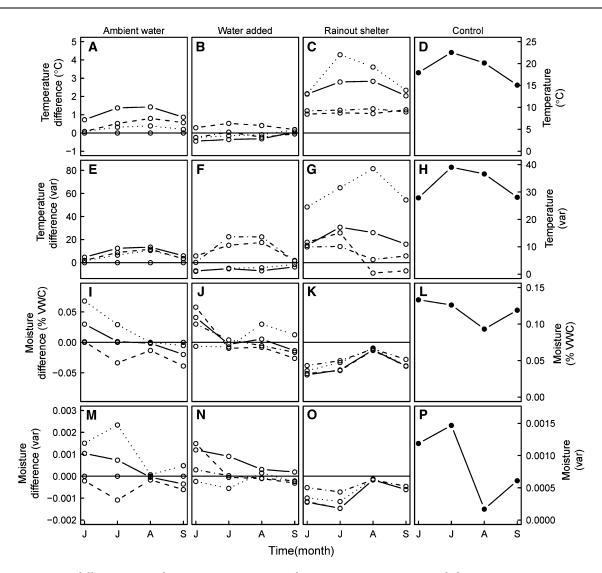
Treatment Effects on Moisture

OTCs and RSs decreased mean, maximum, and minimum soil moisture, whereas water addition tended to increase those three variables; clipping did not affect soil moisture (Table 4). There were no significant interactions between the water treatments and either OTCs or clipping. However, soil moisture levels in plots with both OTCs and RSs tended to be much lower than in any other plot (Figure 3B).

Temporal Effects on Moisture

No difference of mean daily soil moisture was observed in the water addition plots on the day water was added to the plots compared to the following days (Repeated Measure ANOVA, df = 6, F value = 1.29, P = 0.257, there were no significant interactions) indicating that soil moisture levels were consistently elevated between watering events (Figure 7).

In 2007, soil moisture in ambient water plots declined from June through August with a slight increase in September, which follows the same pattern as monthly rainfall that year. Rainout shelters kept soil moisture below control plot levels (Figure 5K), but the difference between these treatments and the control plots diminished from May to August. The addition of water raised the soil
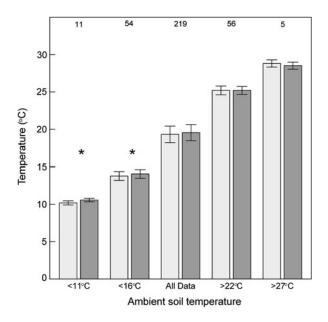
Figure 5. Mean difference in soil temperature (**A–C**) and moisture means (**I–K**) and their respective variances (**E–G**, **M–O**) in the different treatments compared to the control plots measured from June through September 2007. Also presented on the right axes are soil temperature means (**D**) and soil moisture means (**L**) and their variances (**H, P**) in the control plots. The treatment combinations are represented by different lines: OTC (Open-top chamber) and clipping (*solid line*), OTC without clipping (*dashed line*), no OTC with clipping (*dotted line*), no OTC without clipping (*dash and dot line*). In panels **L–R**, plots received ambient rainfall, had 30% of average monthly rainfall added weekly, or were covered with a rainout shelter. The *solid horizontal line* indicates zero difference from control plots.

moisture levels early in the season, but the effect tended to decrease through the summer (Figure 5J). By August there was little difference between the mean soil moisture of the three water treatments. There was an OTC × WATER × MONTH interaction and a WATER × CLIP × MONTH interaction as well as a full 4-way interaction. This pattern is likely due to the decrease in precipitation inputs; this trend is apparent in the control plots, where soil moisture decreased from June to August, but then increased in September

(Figure 5L). The mean daily variance of soil moisture showed similar variation by month (Figure 5M–O). The variance of the control plots declined in August, the driest month. The plots with the lowest variance were generally the RS plots.

Weather Effects on Moisture

There was a trend for precipitation events to increase soil moisture in all plot types, but the effect was not significant in the RS plots (Figure 3B).

Figure 6. Mean (±1 SE) soil temperature in plots with (*dark*) and without (*light*) OTCs in different ambient conditions. Ambient conditions were selected based on the quartiles of mean daily soil temperature in the control plots as well as extreme temperatures (quartiles ± 5°C). *Numbers* above the bars indicated the number of days within the range. *Asterisk* above the bar indicates a significant difference within the pair (Repeated measures analysis of variance, $P < 0.05$, Table 1).

DISCUSSION

We have shown that OTCs, RSs, and watering and clipping of vegetation all changed soil moisture and temperature. Interactions between treatments, temporal variation, and weather altered the effects of the treatments, confirming that multi-factor experiments can create complex effects within the manipulated environment.

Temperature

OTC Effects on Temperature

We found variable effects of OTCs on soil temperature. OTCs did not consistently increase temperature and their effect was at the lower end of reported ranges of increase. OTCs in other studies of herbaceous communities have sometimes reduced temperatures but more typically raise temperature from 2.2°C (Marion and others 1997) to as high as 5°C (Coulson and others 1993; Marion and others 1997). Plots with both OTCs and RSs had higher minimum temperatures than other plots, but also had lower maximum temperatures. It is possible that under the hottest conditions, the combination of an OTC and RS shaded the plot or prevented evaporating moisture from leaving the structure.
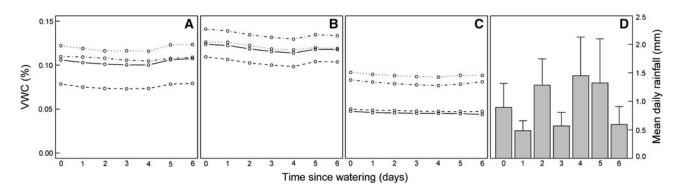
Unintended Effects on Temperature

Rainout shelters increased soil temperature. This is an unwanted effect but not unexpected and likely a realistic impact of future climate change because reduced precipitation will lead to declines in soil moisture that will lessen the amount of energy required to increase soil temperature. It is also possible that the warming is a direct effect of the RS, rather than due to a drop in soil water content. Large RSs used in the Konza prairie also induced a soil temperature increase, but no air temperature increase (Fay and others 2000). Our RSs were open to airflow so they likely did not increase air temperature. Slatted rainout shelters used in Argentina caused a reduction or an increase of soil temperature depending on natural climate

Table 4. Repeated Measure ANOVA Testing the Effect of Treatments on Mean Daily Soil Moisture, Daily Maximum Moisture, Daily Minimum Moisture and Variance of Moisture

	df	M_{avg}		M_{max}		M_{min}		M_{var}	
		F value	P	F value	P	F value	P	F value	P
OTC	1	4.98	**0.035**	5.47	**0.028**	4.82	**0.038**	0.70	0.411
WATER	2	9.10	**<0.001**	10.54	**<0.001**	8.13	**0.002**	22.36	**<0.001**
CLIP	1	0.31	0.582	0.36	0.551	0.28	0.604	0.44	0.513
OTC × WATER	2	0.40	0.675	0.47	0.632	0.36	0.702	6.20	**0.007**
OTC × CLIP	1	0.23	0.633	0.28	0.601	0.22	0.642	0.00	0.999
Water x CLIP	2	0.33	0.719	0.47	0.629	0.25	0.782	7.58	**0.003**
OTC × WATER × CLIP	2	0.29	0.752	0.22	0.797	0.32	0.727	2.68	**0.088**
Residuals	24								

Temperature was modified using OTCs, water was either added, reduced with a rainout shelter or at ambient and plots were clipped or not clipped. Significant ($P < 0.1$) effects are in bold.

Figure 7. Mean daily soil volumetric water content (% VWC), measured in the top 10 cm of each plot (**A–C**) and mean (+1 SE) daily rainfall for the same days (**D**). The treatment combinations are represented by different lines: OTC (Open-top chamber) and clipping (*Solid line*), OTC without clipping (*dashed line*), no OTC with clipping (*dotted line*), no OTC without clipping (*dash and dot line*). In the panel plots received ambient rainfall (**A**), had 30% of average monthly rainfall added weekly on day zero (**B**), or were covered with a rainout shelter (**C**).

conditions (Yahdjian and Sala 2002); this may be due to the design that allowed more rainfall and airflow on the plot. Conversely, adding water to our plots nullified the warming effect of the chamber and reduced mean temperature below that of the control plot; however, among watered plots those with an OTC were warmer than those without. Water addition has been reported to decrease soil temperature, but the effect diminishes with depth (Brown and Archer 1999).

Clipping vegetation increased soil temperature. This is likely due to an increased interception of solar radiation at the soil surface, as has been observed in other grasslands where clipping increased soil temperature up to 3°C in the Konza prairie (Bremer and others 1998) and 1–1.7°C in low-grazed shrubland in Mongolia (Klein and others 2005). The 1.6°C increase of soil temperature due to clipping that we report was likely less than that measured by Bremer and others (1998) because of the large amount of standing biomass at their tall-grass prairie sites (700 g/m^2) compared to our site (120 g/m^2). At our site, the vegetation is intercepting a smaller portion of the incoming solar radiation. In contrast, grazing by reindeer in the Arctic removed the insulating moss layer and decreased temperature (Vare and others 1996). In temperate grasslands, heavy grazing decreased wintertime soil temperatures, but increased summertime temperatures compared to lightly grazed sites (Johnston and others 1971). Researchers concerned about temperature effects due to vegetation removal should be aware that responses will vary across systems and season.

OTC Effectiveness Changes Over Time

Temperature differences between treatments varied on an hourly, daily, and monthly basis. This concurs with results from other studies that report a diurnal cycle in temperature increase due to OTCs, due to a strong relationship between solar radiation and heating (Whitehead and others 1995; Marion and others 1997). We also observed significant interactions across hours, days, and months in the treatment effects on temperature. This suggests that weather conditions may influence the effectiveness of OTCs in increasing temperature and the role the other treatments have influencing temperature.

Ambient Temperature alters OTC Warming Effects

Open-top chambers should be used with caution in studies trying to address warming effects on vegetation. OTCs have mostly been used in Arctic systems (Rustad and others 2001; Walker and others 2006) and were reported to be successful at increasing temperature (Marion and others 1997). We found that OTCs only significantly increased soil temperature when conditions were naturally cooler and the OTCs cause a slight cooling with some treatments when conditions were naturally warmer. This suggests that OTCs may not be the ideal method of creating artificial warming in warmer climates and are better suited to cooler climates. However, warming is expected to occur in most terrestrial systems and so investigations of warming effects should be undertaken in these systems. The use of OTCs as a warming tool should

be adopted with caution especially if the system is warmer (in our study, OTCs caused no temperature increase on days when average soil temperature of the control plot was >22°C).

Soil Moisture

Treatment Effects on Moisture

Open-top chambers caused a decline in soil moisture. This could be a result of natural processes, such as evaporation or increased biological water demand. However, a decline in soil moisture may be an unwanted effect of the OTC. Although the chambers are open on top, there is a 0.25 m border around each plot that is covered by the OTC, the chamber wall could intercept rainfall preventing water from penetrating the surrounding ground. Personal observation and the pattern of mean soil moisture in plots suggest that this was not the case. Only the heaviest of rainfall events wet the soil beyond a centimeter in this arid environment, indicating that water was trapped in the dry soil and did not travel far through the soil. The relative soil moisture in between water addition and ambient water plots was similar in the respective plots with and without an OTC. Had OTCs been intercepting enough rainfall to lower soil moisture, we might expect the soil moisture level in water addition plots with an OTC to be relatively higher than ambient water plots compared to plots without an OTC. On the Mongolian steppe, which receives monsoon rains, there was no observable effect on soil moisture due to the OTC (Klein and others 2005). However, it is not unreasonable to expect changes in soil moisture due to the presence of an OTC and this variable should be monitored as a potential covariate.

Rainout shelters significantly reduced soil moisture, whereas water addition only slightly increased soil moisture levels. Arid and semi-arid grasslands are likely most susceptible to declines in water availability because water is most likely to be a limiting resource. Consequently, rainout shelters have been used extensively in grasslands to test the effect of water reduction on plant communities (Yahdjian and Sala 2002; Fay and others 2000; Köchy and Wilson 2004; Svejcar and others 1999) and have all been successful at reducing soil moisture levels. Due to the variety of designs and sizes of RSs, it is difficult to directly compare different methods.

We added 30% more water to plots, and although there was a measureable increase in soil moisture it was not significant. Early in the season when temperatures are cooler, added water likely

has the ability to penetrate deeper into the soil. Later in the season, however, as temperature rises and natural precipitation decreases, added water does not penetrate deeply into the soil and will be subject to rapid evaporation. Brown and Archer (1999) found that heavy watering increased soil moisture to a depth of 150 cm by more than 10% VMC in savanna parkland. However, they added substantially more water than in our experiment— 100 mm of water every 2 weeks compared to the 1.8–2.6 mm range we added weekly. Again, lack of treatment significance does not translate into a lack of biological significance as we did observe a positive response of vegetation to the water additions (C.N. Carlyle, unpublished data).

Water Pulsing

Temporal variability of resources (pulsing) can alter the outcome of plant–plant interactions (Novoplansky and Goldberg 2001) and plant community diversity (Knapp and others 2002). For this reason, we were concerned that adding water may pulse soil moisture, increasing its variability, or that RSs may intercept precipitation in a way that lowers soil moisture variability. We found no difference in mean daily soil moisture averaged over the duration of the experiment following hand watering of the plots. We did find that the daily variance of soil moisture was different among the watering treatments overall and in different months. Soil moisture variance in the RS plots was always lower than in the control plots, this is likely due to the prevention of precipitation increasing soil moisture. This pattern raises the possibility that any observed responses in the plant community are due to temporal variance rather than resource availability. A dedicated experiment would be required to determine the cause of vegetation change because declines in resource availability, in high stress environments (Grime 2001), and declines in resource variance (Knapp and others 2002) both predict a decline in species diversity.

Experimental Design Recommendations

In this study, we showed that OTCs and RSs were able to warm or reduce soil moisture in small scale plots in temperate grasslands. However, the devices interacted with each other and other treatments, their effects were altered by weather, and they did not act exclusively on their target variables—OTCs altered soil moisture and RS altered soil temperature. Other treatments modified the effects of the OTC, RSs increased the temperature 0.4°C, watering decreased the temperature 0.4°C, and clipping

raised temperature 2°C. Similarly, changes in soil moisture due to the RSs decreased VWC by 3.1% and increased 1% by clipping; and soil moisture due to watering was reduced 1% by the OTC and clipping.

These observations raise a number of experimental design issues. The warming caused by OTCs may be limited to naturally cooler ambient conditions. OTCs are passive devices, experiments requiring consistent warming or occurring in warmer climates may require other types of devices (for example, heating cables or infra-red lamps). Advanced testing of both OTCs and RSs in new regions and ecosystems is encouraged. Rainout shelters were effective at reducing soil moisture but they also reduced the variability of soil moisture levels; the experiment can be designed to remove these effects. For example, Köchy and Wilson (2004) placed RSs over all experimental plots to control for the effects of the RS and then added different amounts of water to each plot. This approach would also control for light intercepted by the RS. Water additions lowered soil temperature, whereas clipping increased temperature and lowered moisture. These effects are unavoidable without more elaborate devices, but should be considered when interpreting results even though it may be difficult to separate the intentional and unintentional treatment effects. As final recommendations, some monitoring of soil moisture and temperature is necessary in climate manipulation experiments even if one is not the target variable. Although experiments with multiple factors are necessary to understand the complex interactions that alter plant communities, we urge caution when using these devices because of unintended effects.

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