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Assessment of Open Top Chambers to Simulate Effects of Climate Change on Soil Temperature and Cover Crop Response in Agricultural Systems

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Abstract

Climate change is expected to yield warmer winters that have the potential to place additional stress on our already stressed agricultural systems. Understanding how agricultural systems may respond to these changes is essential to creating crop and land management plans that ensure food security for future generations. To better understand how warming winters can/will affect air and soil temperatures and cover crop performance, open top chambers (OTCs) were deployed post cover crop seeding in a field experiment at the UNH Kingman Research Farm in Madbury, NH. The experiment consisted of four cover crop treatments sown into or after corn: an interseeded mixture of clover, tillage radish, and annual ryegrass; interseeded winter rye; winter rye seeded post corn harvest; and a weedy control. Only the two interseeded treatments and the control were included in the present study. Cover crops were replicated across four blocks, and each replicate was split into two subplots. OTCs were randomly assigned to one subplot within each replicate and the other subplot served as an ambient control (no OTC). Temperature sensors were placed at three depths within the OTCs and outside the OTCs– aboveground, 3 cm belowground, and 10 cm belowground. Temperature data were recorded hourly from November 2023 to April 2024 while percent ground cover was measured twice in March and once in April 2024. A literature review examining the relationship between OTC height to top-diameter ratio and warming effect was also conducted to understand the viability of OTCs as a passive warming device in climate warming experiments. On average OTCs were found to cause a soil and air warming effect of 1ºC, with a max warming effect of 2ºC. OTCs were also associated with a higher percent ground cover across all three cover crop treatments. The literature review revealed a positive correlation between OTC height to top-diameter ratio and the magnitude of the reported warming effect. These results suggest that OTCs are an effective method for passively generating air and soil warming in climate change experiments, as

the OTCs used in this experiment caused a significant winter warming effect that was correlated with enhanced plant cover.

Introduction

The ability of our agricultural systems to reliably provide food for the growing population is more concerning now than ever in the face of climate change. With unpredictable temperature swings and more frequent severe storms, the challenge of food production will only grow in difficulty in the future. Understanding how increased temperatures associated with climate change will affect our agricultural systems is essential in creating plans for land management and crop production to ensure sustainable food production for future generations.

Warming Winters

In the Northeast US, winters are warming more dramatically than any other season (Whitehead et al., 2023). Warming winters translate to reduced snowpack and variable freeze/thaw cycles which have major negative consequences for agriculture (Kreyling, 2010). Stable freeze/thaw cycles are important for soil microbial health and plant nutrient uptake, as variable freezing and thawing of the soil can result in microbial cell lysis and plant root injury, resulting in reduced nutrient uptake by the plant during the winter and a reduction in beneficial soil microorganisms (Kreyling, 2010). Additionally, reduced snowpack and the consequent extensive cycle of soil freeze and thaw has negative implications for nutrient cycling and nutrient loss, as in the case of nitrogen losses as N_2O and NO_3 (Green et al., 2022). As winters continue to warm, it is essential that farmers and climate scientists alike work together to understand how increasing temperatures will affect crop production.

Cover Crops

Between 2017 and 2022, cover crop adoption increased 17% in the US and continues to rise in 2024 (*2022 Census of Agriculture*, n.d.). Cover crops provide non-monetary benefits to growers that range from weed suppression to soil erosion prevention, and thus are an important component of our agricultural system. The extent that cover crops are able to provide these benefits may be under threat due to earlier snowmelt caused by warming winters (Graybill, 2023). The effects of warmer winters due to climate change are expected to vary, where some cover crops are predicted to benefit from an extended growing season in the form of increased biomass, whereas others will likely experience more harm from warming temperatures (Graybill, 2023; Jørgensen et al., 2010). Understanding how a variety of cover crops will respond to climate change will be necessary for farmers to create management plans that optimize benefits during the winter months.

Open Top Chambers

One method for predicting how agricultural systems will respond to increased temperatures is the open top chamber. Open top chambers, commonly referred to as OTCs, have been used as passive warming devices to simulate warming climate scenarios in systems ranging from agricultural to forested to the arctic. OTCs are structures that are most often constructed of six to eight plexiglass panels attached to metal or wooden frames (Hannah, 2021). These structures can be anywhere from tens of centimeters to numerous meters in height and basal diameters. As the name implies, these chambers are not sealed off, allowing for air flow and rainfall to reach the soil surface. These structures passively warm the air inside them in a similar way that greenhouses do, where the plexiglass walls trap heat and slow the dissipation of the heated air (Chabbi & Loescher, 2017; Hannah, 2021). The use of OTCs in agricultural systems is important now more than ever, as predicting how major crops like wheat and corn will respond to warming temperatures will be essential to reducing potential crop losses. High-latitude ecosystems, such as those in the temperate regions of the world, are suspected to be impacted more by winter warming than other regions of the world (Kreyling, 2010). As a result, OTCs have been promoted as a useful tool in understanding the response of high-latitude ecosystems to warming (Marion et al., 1997). This study evaluated the use of OTCs to simulate effects of climate change on air and soil temperatures and cover crop response in agricultural systems.

Literature Review

Trends and Major Findings

OTCs have been used in climate change studies since the 1980's and have taken on many forms since then. Of the OTC literature published, the majority deals with forest and arctic systems and how soil, flora, and fauna in these systems respond to rising temperatures. More recent literature, however, investigates OTCs as a warming model in agricultural systems. Welshofer et al (2018) used polycarbonate OTCs to simulate warming in taller plant dominated systems by constructing 1.5 m tall structures. Researchers found that OTCs had no significant effect on soil temperature or moisture, but a strong effect on air temperature within the OTC (Welshofer et al., 2018). Although soil moisture was largely unaffected, freeze and thaw cycles were disrupted by the warming treatments due to reduced snowpack under the OTC treatment. These findings highlight the importance of snowpack in regulating freeze/thaw cycles and the potential impact a warming climate may have on future freeze/thaw cycles, notably in temperate regions of the world. Earlier research also supports this conclusion, as snowmelt earlier in the spring and soil exposed to cooler spring temperatures were found among OTC treatments compared to ambient treatments (Dabros et al., 2010).

Other belowground processes, such as microbial activity, have been found to be disrupted by increased temperatures and decreased soil moisture– a side effect of increased temperatures. Outcomes of OTC warming experiments that observe microbial biomass and activity are context dependent and vary in results across latitudes. As a result of increased soil temperatures, induced by OTCs, soil water content decreased leading to a reduction in soil microbial metabolic rates (Fang et al., 2020). Other literature indicates that soil inside OTCs increase certain bacterial and fungal biomass compared to soil outside OTCs, where increased temperatures elevate microbial degradation of soil organic matter (SOM), leading to increased growth of microorganisms in OTC soils (Kim et al., 2018).

OTC Height to Diameter Ratio x Warming Effect

An infinite number of OTC height to diameter options are possible and varying combinations have been tested across many different studies. Differently sized and shaped OTCs have been tested and evaluated for degree of warming compared to controls as in the case of Marion et al, (1997). OTCs were found to have the greatest warming effect when they were more conical in shape and had a higher height to diameter ratio (Marion et al., 1997). OTC height to top diameter ratio has been found to have a major impact on the extent that the chamber will cause warmer temperatures (Aronson & McNulty, 2009). In general, designs with a larger height to diameter ratio are expected to have a greater warming effect in a given experiment (Aronson & McNulty, 2009).

Other OTC Applications

In addition to being used in passively warmed experiments, OTCs have been modified and fitted with active warming apparatuses and fans to modify the environment within the chamber as another means of simulating climate change induced warming on forest and agricultural systems. OTCs fitted with active warming apparatuses are used to control the degree of warming in temperature dependent experiments (Nayak et al., 2023; Sun et al., 2013) and have been found to warm the environment within the chamber to a higher degree than passive-warming OTCs, but come with an energy-use tradeoff (Frei et al., 2020; Norby et al., 1997). Because of this tradeoff, passive warming OTCs have been found to be an effective low-cost method for measuring warming effects on herbaceous plant communities (Godfree et al., 2011).

Methods

Site Description

This research took place at UNH Kingman Research Farm in Madbury New Hampshire (43.17ºN, 70.93ºW). Madbury has an average annual temperature of 9ºC and an average of 1,300 mm of rain per year (US Department of Commerce, n.d.). The main soil types at this location are Charlton fine sandy loams. The 360 acre agricultural experiment station includes farmland used for horticultural and agronomic research, as well as forests primarily used for recreation and wildlife management research (*Kingman Research Farm*, n.d.). The experiment took place in a field that has been historically used for annual vegetable and row crops.

Experimental Design

The Warming Effect on Cover Crops experiment was started with the planting of glyphosate resistant corn on May 30th, 2023. The corn was replanted on June 21st after the initial corn suffered crow damage. Glyphosate was applied to the emerged seedlings on July 14th, and again to areas that were missed by the initial application on July 19th to give the corn a competitive advantage against weeds. Four cover crop treatments were then established into the standing corn plots on July 21st. These treatments were replicated four times across four blocks. The four cover crop treatments were an interseeded mixture comprised of annual ryegrass (50% mixture weight), red clover (30%), crimson clover (10%), and tillage radish (10%); interseeded winter rye; winter rye sown one week after corn harvest; and a weedy, no cover crop control. On November 1st, 2023, half of each treatment plot was randomly assigned an open top chamber

(OTC) to examine the effects of warming on the cover crop treatments (Image 1). The other half of the treatment plots were left alone to serve as an ambient control. The OTCs were constructed of fiberglass sheets, reinforced with strips of punched flat bar and high-density polyethylene plastic. They had a basal diameter of 2.65 m, top-opening diameter of 1.75 m, and a height of 0.8 m. Prior to the deployment of the OTCs, temperature and soil moisture loggers were installed in each of the subplots, both OTC and ambient, to continuously monitor soil temperature and moisture.

Image 1. Open top chambers in block 1 interseeded rye and weedy control plots, November 3rd, 2023.

Data Collection

A literature review of open top chambers as climate warming models was conducted to assess the effectiveness of OTCs to simulate warming conditions. Twenty studies, with study sites in various biomes and ecosystems, were used in the literature review. Study sites ranged from agricultural fields to arctic experimental stations. OTC height and top-opening diameter from each study were recorded in an excel sheet. Height to diameter ratio of each OTC was then calculated. Warming effect of each study's OTC was found by subtracting the control aboveground temperature from the OTC aboveground temperature. Daytime temperature differences were the focus of this investigation, so nighttime temperatures from each study were not used in warming effect calculations. Height to diameter ratios were then plotted against warming effect to evaluate the relationship between height to diameter ratio and warming effect.

HOBO temperature logger pendants were used to measure soil temperature in each of the plots containing OTCs. Pendants were placed 3 cm and 10 cm below the soil, as well as above the soil, suspended in solar radiation shields. Temperature pendants were placed at each of the three soil depths in each of the OTCs as well as outside of the OTCs so that there were 18 pendants in each of the four blocks for a total of

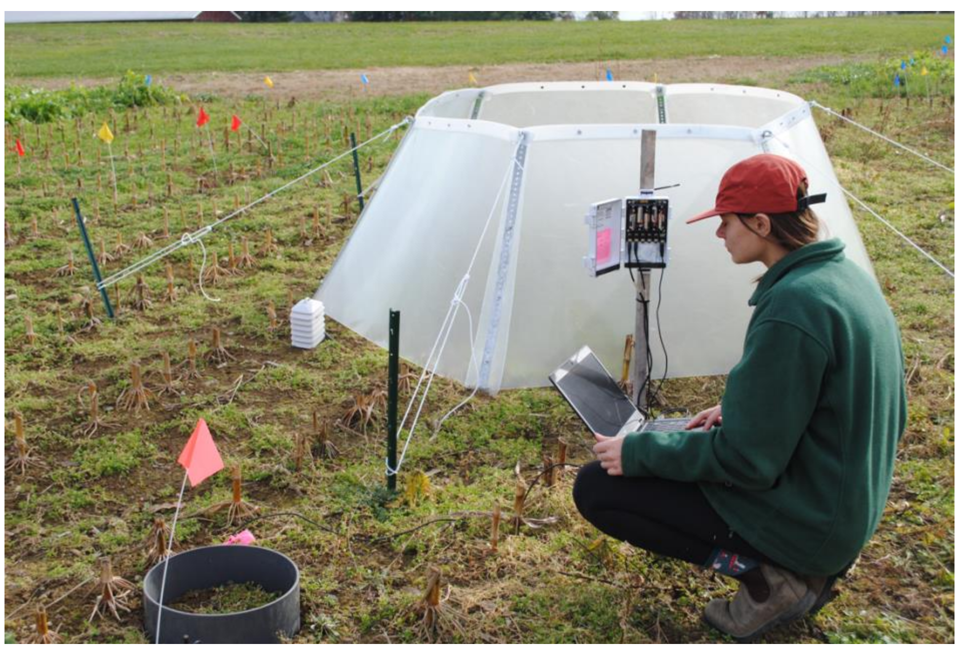

Image 2. Downloading of data from ECH2O temperature and moisture monitor.

54 pendants. Each Friday from November to March, data from the soil temperature pendants was collected via Bluetooth, where data from the pendants could be downloaded to a mobile device. In addition to the pendant temperature data, data from the HOBO and ECH2O soil temperature and moisture loggers was downloaded and recorded every Friday from November to March (Image 2). Note: there was a break in soil temperature and moisture data collection from late December to late January. Because loggers were running continuously, data collected were not "snapshot data", and as a result, daytime and nighttime temperature and moisture trends could be observed. The contiuously running loggers also allowed for data from late December to late January to be retrieved.

Starting in early March, once the snowpack had melted, approximate percent ground cover was recorded using the smart device application Canopeo. Images were taken of a small square of land– roughly 0.5 m x 0.5 m– both inside and outside of the OTCs for each cover crop treatment in each of the four blocks. Images then were processed through the application to estimate percent plant cover in each of the cover crop treatments (Image 3). Percent cover data was recorded three times from early March to early April as temperatures slowly increased.

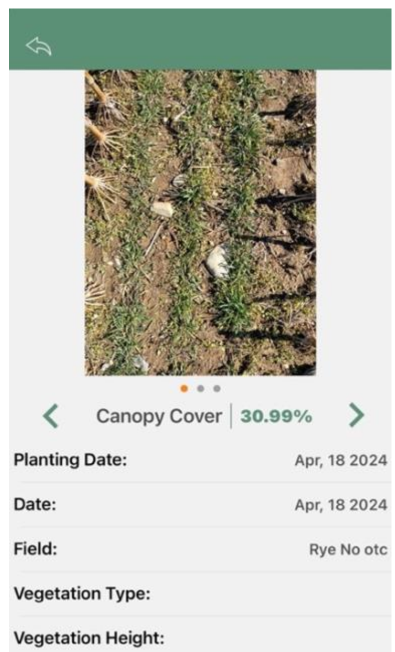

Image 3. Percent cover output (Canopeo)

Data Analysis

Canopeo data were expressed as a percentage and individually inputted into JMP where they were then analyzed. These data were evaluated across cover crop treatments, date of measurement, and warming treatments. One-way ANOVAs were used to determine impact of

OTCs on all treatments and to compare percent cover of individual treatments (e.g. interseeded mix OTC vs interseeded mix ambient).

Soil moisture and temperature data were sorted in Microsoft Excel. Data from HOBO temperature pendant loggers were retrieved via Bluetooth connection to a smart device and eventually uploaded to excel. The data were sorted in excel and then placed in JMP to plot average temperature over 24 hours at the three different depths (aboveground, 3 cm belowground and 10 cm belowground). Soil temperature data from HOBO and ECH2O loggers were examined visually but were not used for analysis, as this study sought to understand temperature dynamics at different soil depths inside OTCs and in an ambient control. Soil moisture data were collected but also were not analyzed for this study, as the results of the soil moisture data were not within the scope of this study.

Results

Literature Review

OTC height to top-opening diameter ratio was moderately correlated with warming effect as indicated by the 0.210 R^2 value (Figure 1). Generally, as height to diameter ratio increased, warming effect increased. Based on the regression line outputted by the regression plot, every 0.1 increase in height to diameter ratio, results in a 0.25ºC increase in temperature expressed as warming effect (Figure 1). Though OTC warming effect (ºC) was positively correlated with OTC height to top-diameter ratio, there was a considerable amount of variance in effect of height to diameter ratio on warming effect (Figure 1). When the two outliers that resulted in the least amount of warming were eliminated from the data, the strength of the correlation increased, and resulted in an R^2 value of 0.648.

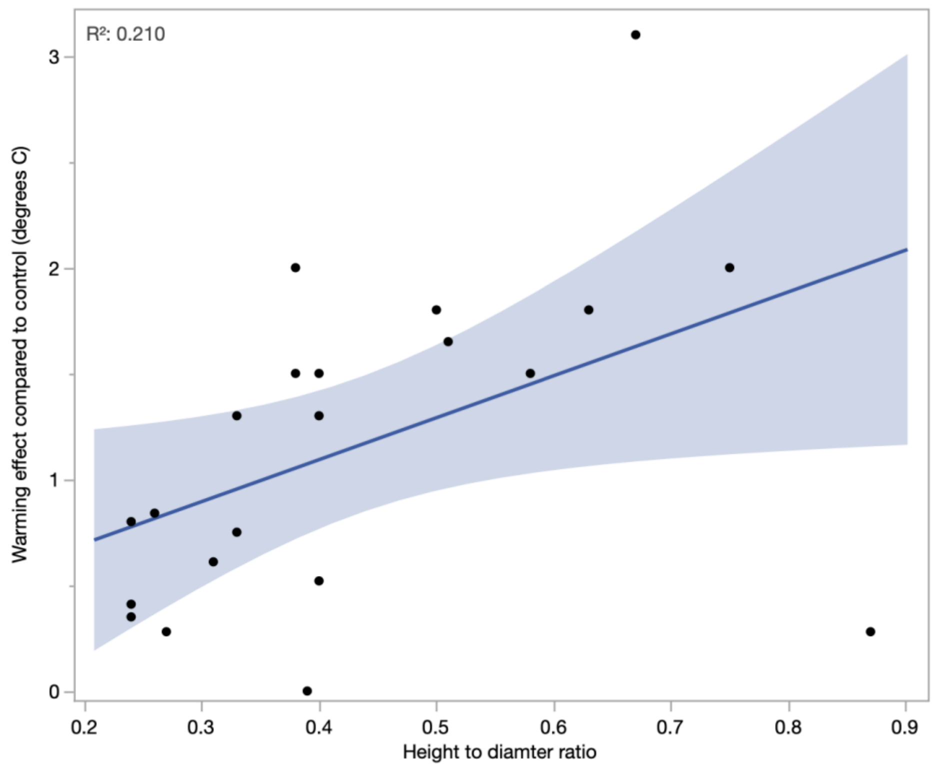

Figure 1. Data from literature review showing the relationship between OTC warming effect (ºC) and OTC height to diameter ratio.

Soil Temperature

Data at from the aboveground sensors were collected only from block 4, whereas data from belowground sensors (-3 cm and -10 cm) were collected from all four blocks. Average hourly temperature collected from HOBO pendant loggers from November 28th, 2023, to April 9th, 2024, differed between the OTC treated plots and the ambient plots. Average aboveground temperature during peak sunlight hours, between 11am and 2pm, was roughly 2ºC warmer under the OTC treatment than under the ambient control treatment (Figure 2). Aboveground temperatures were more similar between the OTC and ambient treatments from 7am to 10am and 3pm to 5pm. At all other times of day, midnight to 7am and 5pm to midnight, OTC treated plots experienced a warming effect of 0.5ºC to 1ºC (Figure 2). Temperature loggers 3 cm belowground recorded less severe warming from the OTC treatment compared to the ambient control, where the biggest warming effect was 0.5ºC (Figure 2). Average temperature 10 cm belowground was steadier throughout the 24-hour period from November 2023 to April 2024, with few fluctuations in temperature. On average, OTCs warmed the soil 1ºC 10 cm below the surface (Figure 2).

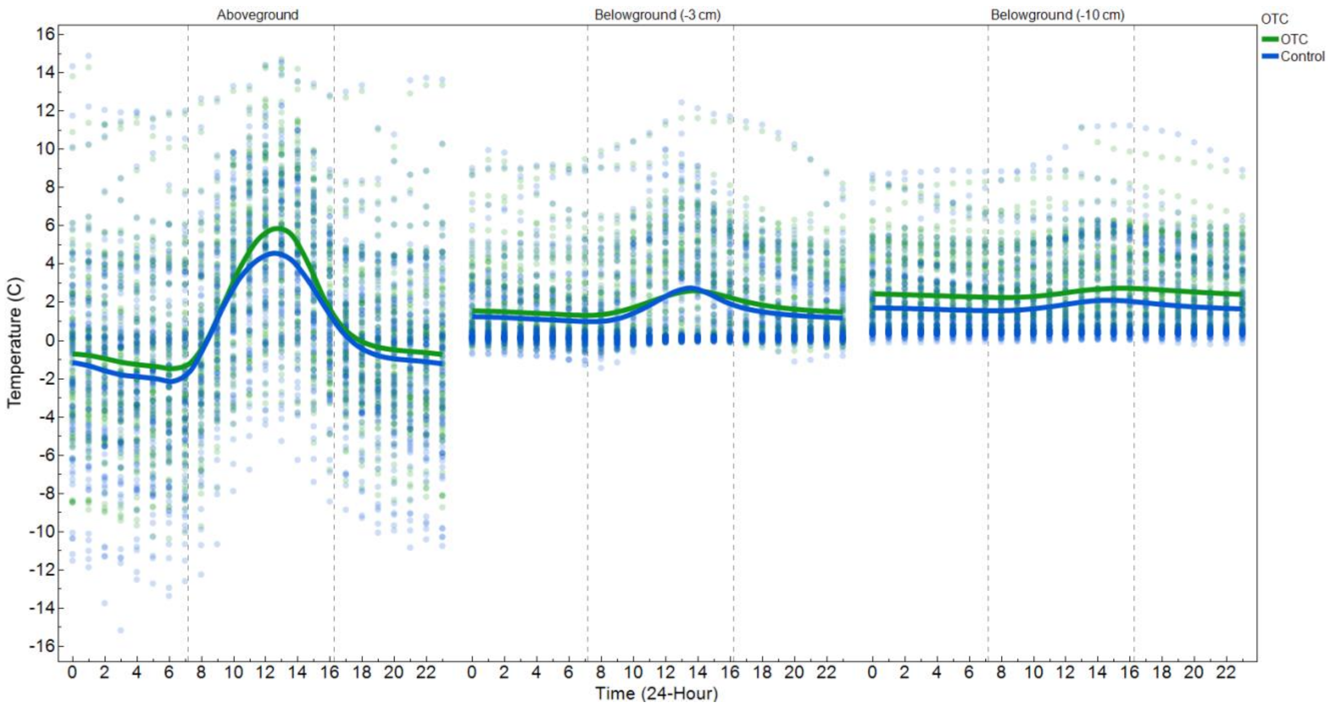

Figure 2. Average temperature over a 24-hour period from November 2023 to April 2024 at three sensor positions: aboveground, 3 cm belowground, and 10 cm belowground

Percent Cover

OTC and cover crop treatment both affected percent cover; there were significant differences between OTC and ambient treatments as well as between the different cover crop treatments (Figures 3 & 4). OTC treated plots experienced greater ground cover by vegetation (cover crops and/or weeds) than ambient plots (Figure 3), where ambient plots had an average ground cover of 27.65% and OTC plots had an average ground cover of 35.63% (Appendix A). On average, the interseeded mixture OTC plots had the greatest percent cover compared to all other treatments with an average cover of 40.82%, whereas the weedy control ambient plots had the lowest percent ground cover with an average cover of 23.57% (Figure 4; Appendix B). It should be noted that percent cover did not always accurately represent the amount of ground covered by each cover crop treatment; weedy growth made up a portion of ground cover in non-control treatments, increasing the ground cover percentage in some cover crop treatments. The ambient rye treatment performed the best out of all the ambient treatments and had the third highest percent ground cover of all treatments (OTC x cover crop) with an average cover of 35.14% (Figure 4; Appendix B).

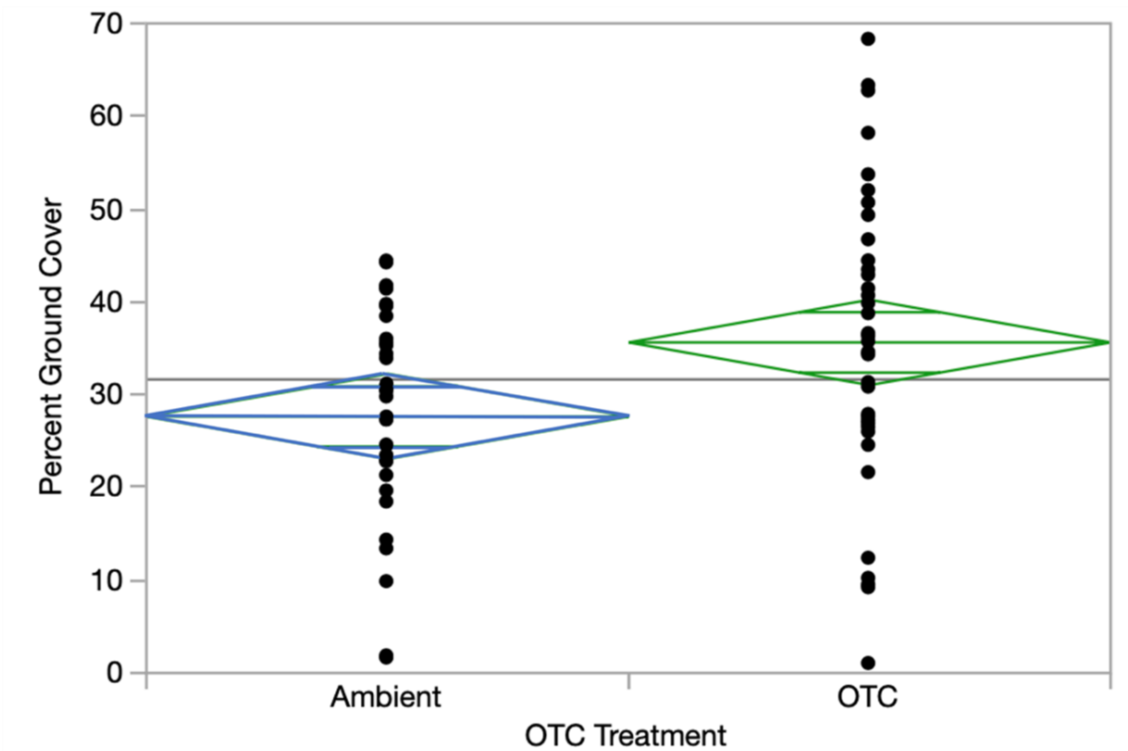

Figure 3. Percent ground cover in ambient and OTC plots across all cover crop treatments and sampling dates.

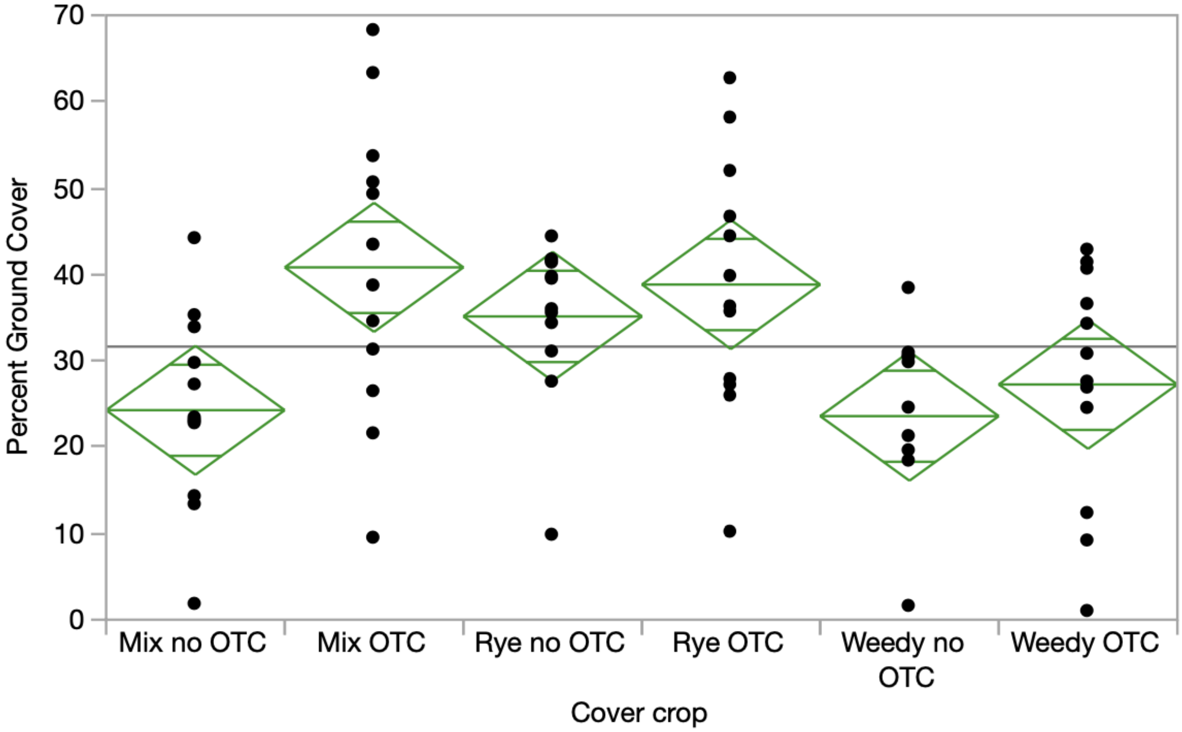

Figure 4. Percent ground cover in all cover crop x warming (ambient vs OTC) treatments across all sampling dates.

Discussion

Literature Review

In general, a higher height to diameter ratio resulted in a greater warming effect, and the relationship derived from the literature review suggests that with every 0.1 increase in height to top-diameter ratio, the warming effect will increase 0.25ºC until height to diameter ratio is maxed out. Hence, OTC height to top-diameter ratio appears to be a relatively accurate predictor of an OTC's warming effect. It should be noted that warming effect can and often is affected by other site- and context-specific variables such as moisture content and plant matter present, highlighting the fact that warming effect cannot be determined solely by height to top-diameter ratio. While the literature review focused on differences in daytime temperatures inside and outside OTCs, data from those studies as well as our own field experiment suggest that nighttime temperature differences between OTCs and control plots can also vary, and generally, OTCs result in warmer nighttime soil and air temperatures. The expected warming of nighttime air and soils aligns with what was observed in this experiment.

The study that reported no soil warming and used an OTC with a height to top-diameter ratio of roughly 0.4 attributed the lack of soil warming to increased vegetation cover which would intercept solar radiation, and thereby decrease warming (Kudo & Suzuki, 2003). Despite the lack of warming found at the soil surface, there was significant warming of aboveground air temperatures within the OTCs (1.5-2.3ºC) (Kudo & Suzuki, 2003). Kudo and Suzuki's (2003) results align with the results of our study, as soil 3 cm below the soil did not warm to the extent that the air warmed within the OTCs. The other study that had a relatively small warming effect (+0.28ºC) compared to height to top-diameter ratio (0.87) also attributed the small warming effect by the OTCs to canopy cover, as this study was conducted in a forest system (De Frenne et al., 2010). OTCs with large height to top-diameter ratios and small warming effects were not the only studies reporting unexpected results. Sullivan & Welker (2005) had a relatively small height to top-diameter ratio (0.26) and reported a surprising warming effect of 0.84ºC with a maximum warming effect of 1.5ºC. The researchers attributed this large warming effect, despite their small height to top-diameter ratio, to the timing of the experiment, as OTCs were deployed immediately after snowmelt had occurred (Sullivan & Welker, 2005). These results, though fitting on the regression plot, further illustrate that warming under OTC experiments is a product of many variables in addition to the height to top-diameter ratio of the OTC used in this study.

The findings of this review suggest that researchers may be able to control the amount of warming that results from using OTCs as passive warming devices by manipulating the height to top-diameter ratio. The results suggest that if a greater warming effect is desired, then OTCs should be constructed with a larger height to top-diameter ratio, making the device more conical in shape. If researchers desire a more conservative warming model, then OTCs should be constructed using a smaller height to top-diameter ratio.

This literature review included 20 studies that used OTCs as a warming model in a variety of ecosystems and across different biomes. This review primarily included studies that used OTCs in systems other than agricultural, as there is little available research that uses OTCs as passive warming devices in agricultural systems. The lack of literature exploring how agricultural systems will respond to predicted future warming indicates that further research exploring the use of OTCs as warming models in agricultural systems is needed, as OTCs have proven to be an effective, low-cost tool for predicting plant and soil response to warming.

Soil Temperature

In the field experiment, air and soil temperature, both at 3 cm and 10 cm below the soil surface, were strongly affected by the open top chamber treatment. In general OTCs were associated with an average warming effect of 1ºC and a maximum warming effect of 2ºC, indicating that the OTCs were capable of producing substantial warming both above and belowground. Air within the OTCs experienced the most dramatic increase in temperature, which aligns with what was expected based on previous research, as aboveground there is nothing to buffer the change in temperature (Welshofer et al., 2018). The maximum difference in temperature between the OTC treatment and the ambient treatment occurred between 11am and 2pm, which would encompass midday or peak sunlight hours from November to April. The similar air temperature between the OTC and ambient treatments between the hours of 7am and 10am as well as between 2pm and 5pm is speculated to be a result of the control plots being warmed more quickly than the OTC plots, where the air within the OTCs may have lagged behind in warming. The similar temperature during these hours inside the OTCs and out could also be a result of the angle of the sun, as during these hours the sun is lower in the sky and can be expected to produce a smaller warming effect. During these hours the angle of the sun may be low enough that it produces a negligible warming effect especially given the shadows that the OTCs cast, thus yielding similar temperatures within the OTCs and outside of them (Lindwall et al., 2016). The OTCs interference with photosynthetically active radiation (PAR) via shading has been observed before, and serves as the best hypothesis for why there was a no difference in temperature inside the OTCs and out before and after peak PAR hours (Bokhorst et al., 2007; Lindwall et al., 2016). Inversely, at the -3 cm depth during the peak sunlight hours, temperature inside the OTCs and outside in the ambient plots were the most similar. It is unclear why soil temperature at this depth was similar both inside and outside the OTCs between the hours of 11am and 2pm. It was expected that they would follow a similar trend to the air temperature. This phenomenon could be a result of the warm air and UV radiation taking longer to infiltrate and warm the soil.

Belowground, the -3 cm soil depth experienced the least amount of warming out of the three sensor depths. This phenomenon was surprising, as it was expected that the -10 cm depth would experience the least drastic warming effect out of the three depths due to its distance from the warmed air, the longer time frame that it takes for deeper layers of soil to thaw, and previous literature that has observed warmer soil closer to the surface (Bokhorst et al., 2007; Godfree et al., 2011). This result was not unprecedented however, as other studies have reported a significantly smaller increase in temperature in soil closer to the surface than in soil 5+ cm below the soil surface (De Frenne et al., 2010). The lack of diurnal fluctuations in temperature at the -10 cm depth was however expected, as soil was predicted to buffer any changes in temperature throughout the day. The difference in average soil temperature at the -10 cm depth and the -3 cm depth, where soil was warmer 10 cm below the soil surface than soil 3 cm below the soil surface, was likely a result of fewer disturbances occurring to the soil at -10 cm, and therefore fewer opportunities for heat to leave the system.

Percent Cover

Overall, percent ground cover was higher within the OTCs than in the ambient plots. The interseeded mix OTC treatment had the highest average and maximum percent ground cover out of all of the treatments observed. Each cover crop treatment that utilized an OTC had a higher average percent cover than its ambient counterpart, indicating that OTCs enhanced plant growth. It is likely that OTC warming created an earlier frost-free period and more optimal temperature conditions that allowed for earlier and more prolific plant growth (Sherwood et al., 2017). There is little literature supporting or refuting this hypothesis, however some studies suggest that a warming climate scenario will result in more prolific weed and even cash and cover crop growth (Hollister et al., 2005; Peters & Gerowitt, 2014), while other studies suggest that warming winters will negatively impact winter crops (Wu et al., 2017). This was seemingly the case for the interseeded mixed plots, where the ambient treatment had among the lowest average percent cover of any of the treatments, while the interseeded mix OTC treatment had the highest. Not all cover crops in the interseeded mix are winter hardy, as in the case of tillage radish, indicating that the warmer temperatures in the OTCs potentially extended the growth of tillage radish, and resulting in greater percent cover, more so than the cooler temperatures in the ambient treatments. In this case, the excess growth of tillage radish likely would have occurred during the beginning of the experiment, in November, before temperatures would have dipped low enough to halt the growth and ultimately kill the tillage radish. The increased ground cover inside the interseeded mix OTCs could have also been a result of increased annual ryegrass and clover growth compared to the ambient control. It should be noted again that weedy growth made up a portion of ground cover in the cover cropped treatments, and in some of these plots, made up the majority of the percent ground cover, as in the case of some interseeded mix plots. This could indicate that warmer winter temperatures favor weedy growth. This could also indicate that warmer winter temperatures allow for weeds to establish before cover crops, giving weeds an opportunity to become the dominant vegetation. It was expected that the weedy control OTC plots would have a higher percent cover than they did because of the positive effect increased temperatures can have on weed growth and development (Hannah, 2011). The performance of the winter rye in the ambient treatment was not surprising as winter rye is a popular cold weather cover crop that is chosen for its cold hardiness and fast growth that allows for quick establishment of aboveground biomass. Unlike some of the interseeded mix treatments, the percent ground cover for winter rye, both inside and outside the OTCs was indicative of its growth solely.

Relevance

This research has importance that goes beyond Kingman Research Farm's fields, as it validates the use of OTCs as warming models in agricultural experiments. Evaluating OTCs as a climate change simulating tool is useful because effective models of climate change will be necessary for farmers to create plans for future land management and crop production. Understanding how cover crops react to these climate warming scenarios is important for predicting how cover crops and other important cash crops and weeds might respond in the future if winters continue to warm. Ultimately, continued winter warming of air and soil temperatures due to climate change will lead to challenges, but also opportunities for agriculture, and research utilizing OTCs in a variety of agricultural systems will be necessary to understand the scope of these effects more fully. The research reported here contributes to that understanding.

Future Work

This research examined the effect of OTCs on soil and air temperature as well as potential winter warming to impact growth of cover crops. Future work examining the relationship between percent ground cover of varying cover crops and air and soil temperature could provide insights into how ground cover affects soil temperature in a warming climate. Another avenue for future work could assess the effect of warming air and soil temperatures on a greater diversity of cover crop species to understand how popular cover crops can be expected to perform in the face of climate change. Understanding how cover crop establishment and growth may change in the presence of warming conditions, notably over the winter months, can help farmers develop plans to mitigate potential negative effects of warming and take advantage of cover crop species that may respond positively to warming conditions. Research examining photosynthetically active radiation (PAR) throughout the day inside and outside OTCs would be helpful in determining if shading caused by the shape and structure of OTC walls could account for the similar air and soil temperatures inside and outside of the OTCs during the hours before and after peak PAR.

Conclusions

This experiment sought to determine the efficacy of open top chambers as a passive warming model in agricultural systems as well as to determine the effect they have on cover crop vegetation. Based on the literature review, and the results of this experiment, open top chambers are a viable model for simulating climate warming scenarios in agricultural systems. Height to top-diameter ratio is a moderately accurate predictor of the magnitude of the warming effect and can be manipulated to produce the desired level of warming. Based on the results of the field experiment with OTCs, in the Northeast US, a warming winter climate is likely to enhance both cover crop and weed growth in early spring.

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Appendix A- Percent cover by treatment type, cover crop, and date with Ambient and OTC total averages

Date	Cover Crop	Ambient Treatment	Percent Cover	OTC Treatment	Percent Cover
3/1/24	Mix no OTC	Ambient	1.75	OTC	9.41
3/1/24	Weedy no OTC	Ambient	1.52	OTC	0.93
3/1/24	Rye no OTC	Ambient	9.75	OTC	10.1
3/1/24	Mix no OTC	Ambient	14.22	OTC	21.49
3/1/24	Weedy no OTC	Ambient	19.63	OTC	26.78
3/1/24	Rye no OTC	Ambient	27.5	OTC	39.73
3/1/24	Mix no OTC	Ambient	22.66	OTC	43.36
3/1/24	Weedy no OTC	Ambient	18.33	OTC	27.51
3/1/24	Rye no OTC	Ambient	41.65	OTC	51.89
3/1/24	Mix no OTC	Ambient	13.28	OTC	31.22
3/1/24	Weedy no OTC	Ambient	30.3	OTC	24.43
3/1/24	Rye no OTC	Ambient	35.89	OTC	25.86
3/8/24	Mix no OTC	Ambient	27.16	OTC	38.64
3/8/24	Weedy no OTC	Ambient	19.52	OTC	9.09
3/8/24	Rye no OTC	Ambient	30.99	OTC	27.79
3/8/24	Mix no OTC	Ambient	23.05	OTC	26.38
3/8/24	Weedy no OTC	Ambient	30.48	OTC	40.57
3/8/24	Rye no OTC	Ambient	39.41	OTC	44.33
3/8/24	Mix no OTC	Ambient	29.67	OTC	53.6
3/8/24	Weedy no OTC	Ambient	21.18	OTC	34.2
3/8/24	Rye no OTC	Ambient	34.28	OTC	58.07
3/8/24	Mix no OTC	Ambient	22.87	OTC	49.22
3/8/24	Weedy no OTC	Ambient	30.85	OTC	30.73
3/8/24	Rye no OTC	Ambient	41.28	OTC	35.62
4/1/24	Mix no OTC	Ambient	23.33	OTC	50.57
4/1/24	Weedy no OTC	Ambient	18.44	OTC	12.27
4/1/24	Rye no OTC	Ambient	35.47	OTC	27.11
4/1/24	Mix no OTC	Ambient	35.19	OTC	34.48
4/1/24	Weedy no OTC	Ambient	38.34	OTC	42.78
4/1/24	Rye no OTC	Ambient	39.64	OTC	46.6
4/1/24	Mix no OTC	Ambient	44.11	OTC	68.19
4/1/24	Weedy no OTC	Ambient	24.47	OTC	41.32
4/1/24	Rye no OTC	Ambient	41.46	OTC	62.62
4/1/24	Mix no OTC	Ambient	33.8	OTC	63.22
4/1/24	Weedy no OTC	Ambient	29.75	OTC	36.49
4/1/24	Rye no OTC	Ambient	44.31	OTC	36.21
Average			**27.65361111**		**35.63361111**

Appendix B- Percent cover by block, treatment type, and date of measurement with treatment total averages

Cover crop	Block	Date	Percent Cover	Cover crop	Block	Date	Percent Cover
Mix no OTC	1	3/1/24	1.75	Mix OTC	1	3/1/24	9.41
Mix no OTC	2	3/1/24	14.22	Mix OTC	2	3/1/24	21.49
Mix no OTC	3	3/1/24	22.66	Mix OTC	3	3/1/24	43.36
Mix no OTC	4	3/1/24	13.28	Mix OTC	4	3/1/24	31.22
Mix no OTC	1	3/8/24	27.16	Mix OTC	1	3/8/24	38.64
Mix no OTC	2	3/8/24	23.05	Mix OTC	2	3/8/24	26.38
Mix no OTC	3	3/8/24	29.67	Mix OTC	3	3/8/24	53.6
Mix no OTC	4	3/8/24	22.87	Mix OTC	4	3/8/24	49.22
Mix no OTC	1	4/1/24	23.33	Mix OTC	1	4/1/24	50.57
Mix no OTC	2	4/1/24	35.19	Mix OTC	2	4/1/24	34.48
Mix no OTC	3	4/1/24	44.11	Mix OTC	3	4/1/24	68.19
Mix no OTC	4	4/1/24	33.8	Mix OTC	4	4/1/24	63.22
			24.2575				**40.815**
Rye no OTC	1	3/1/24	9.75	Rye OTC	1	3/1/24	10.1
Rye no OTC	2	3/1/24	27.5	Rye OTC	2	3/1/24	39.73
Rye no OTC	3	3/1/24	41.65	Rye OTC	3	3/1/24	51.89
Rye no OTC	4	3/1/24	35.89	Rye OTC	4	3/1/24	25.86
Rye no OTC	1	3/8/24	30.99	Rye OTC	1	3/8/24	27.79
Rye no OTC	2	3/8/24	39.41	Rye OTC	2	3/8/24	44.33
Rye no OTC	3	3/8/24	34.28	Rye OTC	3	3/8/24	58.07
Rye no OTC	4	3/8/24	41.28	Rye OTC	4	3/8/24	35.62
Rye no OTC	1	4/1/24	35.47	Rye OTC	1	4/1/24	27.11
Rye no OTC	2	4/1/24	39.64	Rye OTC	2	4/1/24	46.6
Rye no OTC	3	4/1/24	41.46	Rye OTC	3	4/1/24	62.62
Rye no OTC	4	4/1/24	44.31	Rye OTC	4	4/1/24	36.21
			35.13583333				**38.8275**
Weedy no OTC	1	3/1/24	1.52	Weedy OTC	1	3/1/24	0.93
Weedy no OTC	2	3/1/24	19.63	Weedy OTC	2	3/1/24	26.78
Weedy no OTC	3	3/1/24	18.33	Weedy OTC	3	3/1/24	27.51
Weedy no OTC	4	3/1/24	30.3	Weedy OTC	4	3/1/24	24.43
Weedy no OTC	1	3/8/24	19.52	Weedy OTC	1	3/8/24	9.09
Weedy no OTC	2	3/8/24	30.48	Weedy OTC	2	3/8/24	40.57
Weedy no OTC	3	3/8/24	21.18	Weedy OTC	3	3/8/24	34.2
Weedy no OTC	4	3/8/24	30.85	Weedy OTC	4	3/8/24	30.73

Weedy no OTC	1	4/1/24	18.44	Weedy OTC	1	4/1/24	12.27
Weedy no OTC	2	4/1/24	38.34	Weedy OTC	2	4/1/24	42.78
Weedy no OTC	3	4/1/24	24.47	Weedy OTC	3	4/1/24	41.32
Weedy no OTC	4	4/1/24	29.75	Weedy OTC	4	4/1/24	36.49
			23.5675				**27.25833333**