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Integrating Row Covers and Hydronic Heating for High Tunnel Season Extension Vegetable Production

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INTEGRATING ROW COVERS AND HYDRONIC HEATING FOR HIGH TUNNEL SEASON EXTENSION VEGETABLE PRODUCTION

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ABSTRACT

Combining bottom heating of soil with inexpensive fabric row covers improves yields and prevents cold damage with lettuce and arugula. Two experiments were conducted to determining an ideal heating tube placement and row cover thickness to allow growers to optimize heating systems. Temperature sensors in the first experiment were 30 cm from heating tubes with and without medium thickness (28 g m^{-2}) row covers. A second experiment compared temperatures under medium and thick (62 g m^{-2}) row covers when sensors were placed directly above the heating tubes. Hydronic heat alone increased average minimum nighttime temperature 0.4 °C 30 cm from the hydronic tubes. When combined with row covers, average minimum temperatures were 1.1 °C warmer 30 cm from hydronic tubes than row covers alone. With lettuce plants grown 15 cm from the heating tubes, plant weight increased 17% more than no heat. Lettuce grown under row covers weighed 70% more than plants without row covers. When row covers and hydronic heat were combined, lettuce 15 cm from tubing weighed 88% more than from the control. Temperature sensors placed 10 cm directly above hydronic tubes under row covers averaged nighttime minimums 3.3 °C more than covers alone. Planting arugula directly under hydronic heating tubes increased weight 33% under medium row covers and 60% under thick row covers compared to row covers alone. However, arugula weighed 10% more under medium row covers when compared to thick row covers.

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INTRODUCTION

For centuries, farmers have endeavored to improve the environment for vegetable production. The simplest techniques were windbreaks and south facing slopes to raise temperatures during winter (Hodges et al., 2004). Other early techniques for cold protection used simple glass cloches, cold frames, and glass houses to trap solar energy and extend the growing season. With season extension techniques, farmers can access new markets and reduce risks to crops from exposure to cold temperatures.

Since the introduction of plastic films to agriculture in the 1950s, a wide variety of season extension products have been fashioned using plastics or polymers such as polyester (Lamont, 2005). Currently, plastic film greenhouses, high tunnels, low tunnels, row covers, plastic mulches, and windbreaks are common products used to protect plants from cold and extend the growing season (Lamont, 2005). For plastic covered greenhouses, air is commonly blown between two layers of plastic to provide insulation. Shortwave radiation from the sun passes through the greenhouse film and heats the soil, plants, and internal greenhouse structure. The warmed objects radiate longwave infrared (IR) heat energy and the greenhouse film traps some of the radiated heat and IR light to warm the interior space (Sanford, 2011). Greenhouses may utilize supplemental heat and electrical ventilation or passive heat and passive ventilation to maintain precise temperature thresholds inside the greenhouse structure (Sanford, 2011). An unheated double layer plastic greenhouse provides 4.3 °C of frost protection 2 cm above soil level. (Ward and Bomford, 2013).

High tunnels are portable greenhouse-like structures covered with a single layer of plastic film. In crop production, plants are usually grown in the ground without permanent fossil fuel or electric powered heating or ventilation (Wells, 1993). High tunnels retain heat and humidity, mitigate the effects of wind, and disperse sunlight (Bumgarner et al., 2011). High tunnels allow for season extension. For example, high tunnels permit planting tomatoes three to four weeks earlier than field planted tomatoes (Wells, 1991). A high tunnel with a single layer of plastic increased nighttime minimum temperatures an average of 2 °C at a height of 1.2 m above the ground (Retamal-Selgado et al., 2015). The same authors showed an increase in blueberry yields of 44 % and allowed for blueberries to be harvested 14 days earlier. Temperature variation within high tunnels may occur. For example, temperatures on the edge of a 10 m wide tunnel were 1 to 2 °C cooler than the center (Wein, 2009). Temperatures may also fall below outside temperatures based on the transparency of the greenhouse material to IR radiation (Wien, 2009).

The economics related to use of high tunnels may vary by crop and location. In Western Washington where high tunnels were compared to field grown plants, tomatoes were more profitable grown in high tunnels but lettuce was not (Galinato and Miles, 2013). The increased muskmelon yields in high tunnels did not offset the cost of high tunnel production (Rader and Karlsson, 2006). In this northern region study, lettuce was more marketable when grown in high tunnels in comparison to field grown lettuce. Strawberry plants grown in high tunnels in the midwestern U.S. had higher yields and superior quality in comparison to field grown plants (Kadir et al., 2006).

To protect against low temperature extremes, minimal heating may be used in high tunnels (Lamont, 2005). Tomatoes grown under extreme diurnal temperature fluctuations promoted significantly greater yields in high tunnels (Hunter et al., 2012).

Row covers are fabric-like materials laid over the top of crops for cold and pest protection. Common materials include spunbonded polyester, spunbonded polypropylene, and polyethylene (Wells, 1996). These materials are available in various widths and thickness. Thin materials (10 g m^{-2}) maximize light and air transmission and protect plants from insects (Adams et al., 1990). Medium weight material (17 to 20 g m^{-2}) offers some light freeze protection to -2.2 °C and enhances plant growth (Wells, 1996). The heaviest weight covers (34 to 59 g m^{-2}) protects plants from freeze injury to -4.4 °C according to one distributor (Johnny's Selected Seeds; Winslow, ME). Row cover material is either supported by hoops or wire, or floats on the surface of the crop, pushed up as the crop grows. Spunbonded materials allow water to pass through and do not absorb moisture, therefore keeping the covers light during rain or overhead watering (Wells, 1996). Some crops like tomatoes, peppers and squash may be damaged by friction in floating row cover systems (Wells, 1996). Disease suppression, (Brown et al., 1989) as well as wind and animal protection are other benefits of row covers (Wells, 1996).

In order to extend the growing season or grow year-round, active heating is commonly used in greenhouses but less commonly used in high tunnels (Bumgarner et al., 2011). The three most popular systems for greenhouse heating are unit heaters, central heating systems and radiation heating (Castilla, 2013). With unit heaters, a box is heated and greenhouse air is forced through the box with a fan. Heated air may be distributed through a polyethylene tube with holes. Central heating systems are generally more efficient than unit heaters, especially when large or multiple greenhouses are heated (Castilla, 2013). With central systems a boiler heats water and hot water or steam is distributed through pipes to heating elements inside the greenhouse like metal fins or tubing placed above or below ground (Castilla, 2013). Radiation heaters burn natural gas or propane in thin pipes hanging from the greenhouse ceiling and heat is directed down on plants. In this system since only the surface of the soil and the plants are heated, lower air temperatures are possible and fuel is saved (Castilla, 2013).

Central heating systems commonly employ root zone heating by distributing hot water through buried cross-linked polyethylene (PEX) piping or ethylene propylene diene monomer (EPDM) tubing laid above ground and on bench tops. More energy intensive, electric heating cables or electric heating mats are also available(Hassanien et al., 2016). Warming the root zone stimulates root starch, nutrient mobilization and uptake, and canopy growth (Kawasaki et al., 2014). Root and shoot zone heating increased lettuce biomass production in a double layer high tunnel, with up to 40 times more biomass with combined heating and canopy cover

(Bumgarner et al., 2011). In this experiment, electric heating elements were buried 10 cm in the soil, spaced at 7.5 cm and triggered to function at 23 °C. The canopy cover consisted of 0.8 ml slitted polyethylene stretched across wire hoops and secured to the ground with landscape staples (Bumgarner et al., 2011). The second experiment examined the effects of these treatments on plant microclimate (Bumgarner et al., 2012). Results showed that root zone heating had little effect on above-ground temperatures except when used in combination with low-tunnels. Growing-degree days and nighttime minimum temperatures were raised the most with root zone heating in low tunnels. Soil temperatures were greater in high tunnel treatments compared to control, but not as high as in treatments with root zone heating.

Another experiment examined above-ground temperatures when geothermal water at 28 °C was circulated through pipes under a 50 μm thick transparent polyethylene blanket supported over the plants by wires in a high-tunnel style greenhouse (Barral et al., 1999). The combination of treatments produced an estimated nighttime temperature of 13 °C under blankets when exterior ambient temperatures were 3°C and interior high tunnel temperatures were 12 °C (temperature estimated from graph in Fig. 4, Barral et al. 1999). However, the experiment didn't compare blankets with and without heating tubes inside the high tunnel.

Heat application of 7 °C, 16 °C and 21°C to soil and air applied through heated water in polyethylene pipes were beneficial to crop growth in comparison to controlled ambient temperatures maintained using thermal blankets in greenhouses (White et al., 1987). The authors also determined that applying heat for 4-hours at night was just as beneficial as applying heat for 8 and 14 hours (White et al., 1987). The split night treatments would save considerable energy but not protect susceptible plants from nighttime minimums occurring during early morning hours. Younger stages of seedling development also benefited the most from heat application.

Growers typically utilize high tunnels in areas with variable spring and fall temperatures from year to year. Combining bottom heat with inexpensive fabric covers improves yields and prevents cold damage with crops such as lettuce(Bumgarner et al., 2011) cabbage, eggplant, pepper, tomato, marigold, pansy, petunia, and snapdragon (White et al. 1987). Combining bottom heat with plant covers in horticultural systems is a new and emerging field and large information gaps exist. A review of the current literature found no reports of previous research to evaluate the effects of placement and distribution of heat and heating cables on vegetable crop growth. In addition, cover material and thickness and placement of cover material (floating vs. elevated on wires) and placement of heating cables (buried and on surface) have not been researched.

Previous research described above examined electric heating cables buried in the soil with polyethylene low tunnels instead of more commonly used fabric row cover material. The objective of this research was to evaluate the effectiveness of commonly used EPDM tubing to apply heat from hot water to plants grown under floating row covers. The tubing was placed on the surface of the soil unlike previous research using buried heating elements. The surface placement of tubing facilitates removal for tillage operations. The following research also examines the relationship between air temperature and distance to heating tubes.

METHODS AND MATERIALS

Two experiments were conducted at the Clemson University Student Organic Farm in Clemson, South Carolina (lat. 34.67 long. -82.84). The experiments were conducted in sequence and differed in treatment; the first experiment was conducted during January 2015 and the second experiment during February the same year. Both experiments employed a random block design. Hydronic heating was the whole plot factor and row cover was the split plot factor. The experiments were conducted in a high tunnel measuring 3.7 m wide by 13.7 m long by 2.6 m high with galvanized steel tubing framework and a single layer of three year old 6 mil greenhouse plastic. Plants (discussed below) were grown in organic soil created from decomposed wood chips and leaf litter placed 30 cm deep. Prior to transplanting, the beds were fertilized at a rate of 45 kg nitrogen per acre using a standardized 8-5-5 fertilizer (Nature Safe™, Irving, TX). The beds were manually raked to incorporate fertilizer and raised 4 cm above the height of the pathway.

In Experiment 1, "Defender" romain lettuce and "New Red Fire" lettuce seeds were first grown in 5.08 cm cells and lettuce seedlings were manually transplanted at a spacing of 30.5 cm in row and between row spacing of 30.5 cm. Block size was 3.05 m long by 1.5 m wide and contained 2 rows of each lettuce variety for a total of 4 rows per block with each variety alternated between rows. Each block contained a total of 20 plants of each variety of lettuce. Weeds were manually removed during the growing season with a single cultivation using a collinear hoe at 14 days after transplanting.

Spunbonded polypropylene medium thickness row covers (Agribon® AG-30, 28 g m-2; Berry Plastics Corp. Evansville, IN) were used for row cover treatments. The row cover was applied at approximately 1700 in the evening and removed at approximately 0900 in the morning and secured to the ground along the edges with PVC pipe laid on top of the cover. The covers were applied in a floating fashion laid directly on top of the plants. For the hydronic heating treatments, a single loop of EPDM tubing of dimensions 0.45 cm inside diameter and 0.76 cm outside diameter was used to convey the heat to the beds. The tubing was placed on top of the soil and between the outer and inner rows of lettuce spaced 15 cm from the temperature sensors and plants (Fig. 1). Tubing was absent between the two middle rows and along the outer edge of the beds. Water for the hydronic heating system was heated with a 151 l electric hot water heater containing two 2,400 watt heating elements. Water exiting the hot water heater was at a maximum average temperature of 52 °C. The hydronic heat was turned on at approximately 1700 and turned off at approximately 0900.

Air temperatures were measured using HOBO™ 12 bit smart sensors (Onset Computer Corp., Bourne, MA) connected to a HOBO™ U30 ethernet data logger. Temperature was measured in fifteen minute intervals throughout the experimental timeframe. To measure air temperature inside the greenhouse, a single data logger was placed 60 cm below ceiling height and 3 m from the north end of the greenhouse inside a solar radiation shield. To measure outside air temperatures a single data logger was placed 1.52 m above the ground inside a radiation shield, 5 m from the high tunnel. To measure temperature within the treatment blocks a single data logger was placed at the center of each block 10 cm from the ground and 30 cm from the hydronic heating tubes. Nighttime minimum temperatures for all treatment plots were recorded using HOBO™ software. To measure the temperature of the hydronic heating fluid, temperature sensors were placed inside thermocouplers embedded in the hydronic heating lines as they entered and exited the greenhouse. Temperature of the hydronic heating system fluid was recorded every 15 minutes to ensure that heat was being provided on all sampling dates.

Plants were sampled at harvest (31 days after transplanting) by selecting every other plant in the plot starting at a randomly generated number. Harvest was done on all plots at the same time when the earliest maturing plot achieved harvestable size. The final height, width and weight were recorded for twelve plants per plot. Width was included as a growth metric that was multiplied by plant height to provide an overall measure of plant growth. This was done to account for the possibility that floating row covers on top of plants may have influenced plant height measurements.

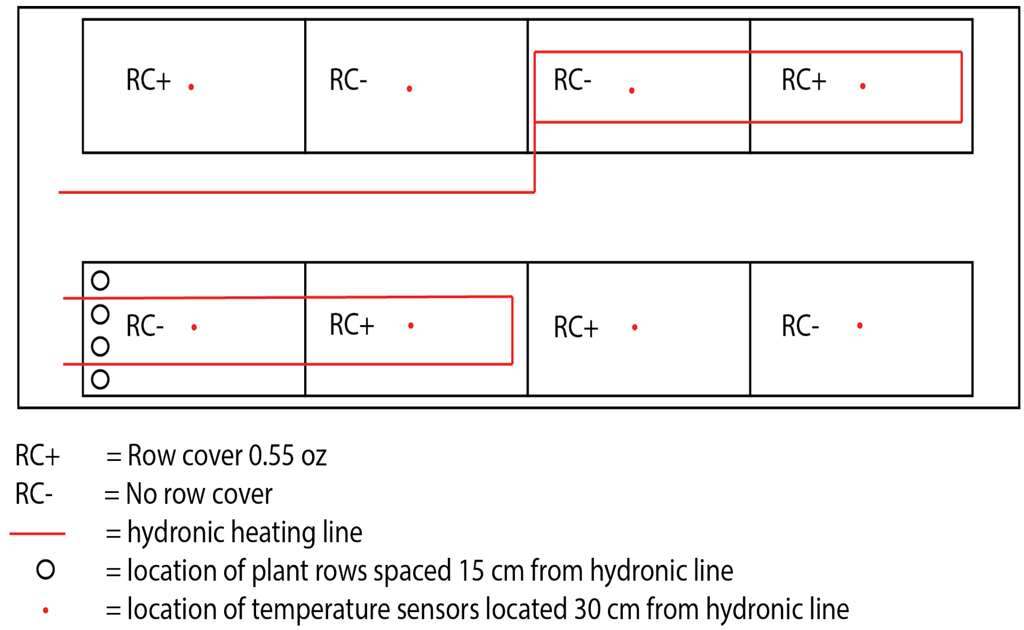

Figure 1. Design for Experiment 1 with lettuce to examine the effects of medium thickness row covers with and without hydronic heating lines spaced 30cm from temperature sensors and 15cm from plants.

The second experiment was designed and implemented as in the first experiment with the following exceptions. Arugula (organic Johnny's Selected Seeds variety not stated) was directly seeded into four rows spaced 30.5 cm apart across the plots. Seeds were spaced using an Earthway® seeder (Bristol, Indiana) using the fine seed plate distributing approximately 1.1 seeds per cm. The hydronic heating lines were placed directly on top of the planted seeds over the center two rows and the outer rows were spaced 30.5 cm from the hydronic lines. Temperature sensors were placed over the hydronic lines elevated at a distance of 10 cm from the ground. Plant weights from a 30 cm section of the two inner rows were measured at final harvest 22 days after directly seeding the arugula. Harvest was done on all plots at the same time when the earliest maturing plot achieved harvestable size.

The second experiment compared medium and thick grades of row covers with and without hydronic heat against a control of no row cover. Medium thickness row covers were made from spunbonded polypropylene Agribon® AG-30 28g m^{-2} and thick covers were Agribon® AG-70 62g m^{-2} (Berry Plastics Corp. Evansville, IN).

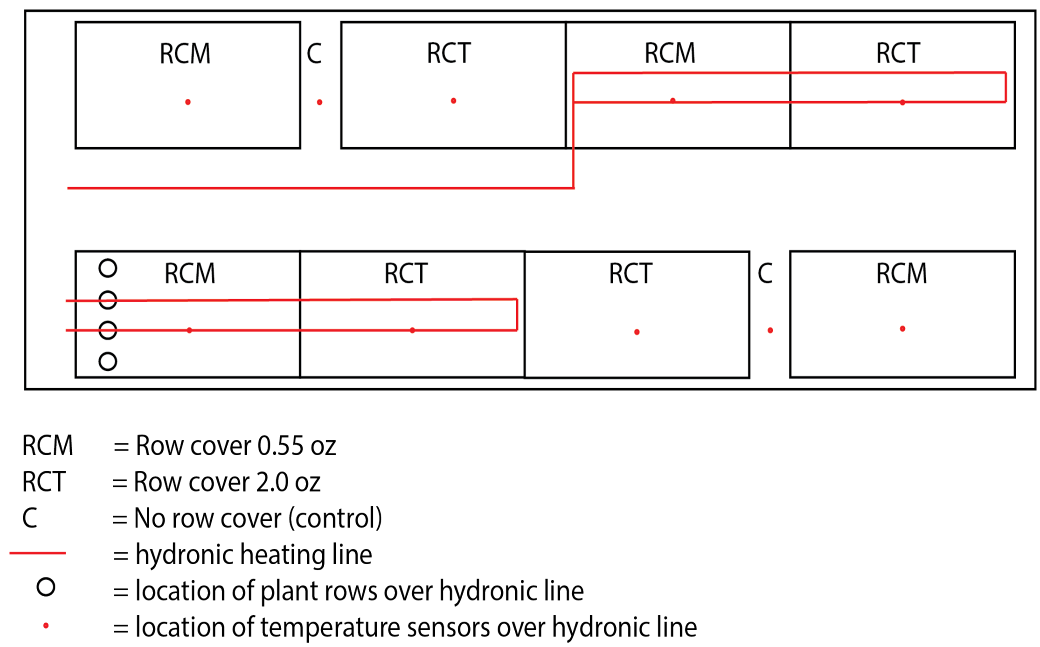

Figure 2. Design for Experiment 2 with arugula to compare row covers of different thickness with and without heating hydronic lines. Temperature sensors were placed directly over plants and hydronic lines.

Statistical Analysis

An ANOVA was performed on data from each temperature sampling date to test for the effects of heating, cover, and the interaction. The ANOVA model was designed to adjust for the split plot nature of the study i.e., hydronic heating was the whole plot factor and row cover was the split plot factor. If the effect of heating, cover, or the interaction was found to be significant, the Fisher's least significant difference test was used to compare the means of the factor levels. All statistical tests used a significance level of P=0.05 and all statistical calculations were performed using JMP Statistical Discovery™ software (SAS; Cary, NC). To display the data, line or column graphs were created and letters or asterisk symbols assigned to denote statistical difference between treatments.

Statement of Value	Degrees of Freedom
Hydronic Heat	1
Rep	1
$Error_a$	1
Cover	1
Cover*Hydronic Heat	1
$Error_b$	2

Figure 2a. ANOVA table for the split plot experimental design.

RESULTS AND DISCUSSION

Experiment One

The first experiment examined hydronic heat with and without medium thickness row covers with temperature sensors placed 30 cm horizontally from the heating tubes. Temperature data are presented in Figures 3-7 where graph lines represent minimum temperatures in the various treatments over a series of sampling nights. All treatments are represented in Figure 3 without standard error bars or significance letters to make treatments easier to distinguish. Select treatment comparisons are presented in Figures 4-7 with standard error and significance letters/symbols included.

Outside minimum temperatures averaged -1.2 °C, 1.3 °C for control plots, 1.7 °C for hydronic heat plots, 4.5 °C for row covers and 5.6 °C for combined row covers and hydronic heat plots (Figure 3). The single sensor placed above the hydronic tube had an average minimum temperature of 1.4 °C.

On any night, hydronic tubes alone did not significantly increase nighttime minimum temperatures compared to treatments without hydronic tubes (Figure 4). On the coldest night (-11.1 °C), temperature from the control treatment with no hydronic heat was -6.2 °C, compared -5.79 °C in the hydronic heat treatment.

Slight variation between temperatures in hydronic treatments was probably based on the position of the sensor in relation to the length of the tubing. As hot water travels through a pipe, heat is dispersed and the water will be cooler exiting the pipe than it was when it entered. Temperatures of hydronic fluid exiting the greenhouse were on average 11°C cooler than when the hydronic fluid entered. Sensor placement in relation to the start of the hydronic tubing in the high tunnel was not recorded but would have provided useful information in relation to the slight temperature difference between hydronic treatments. The manufacturer recommends that tubing runs should be 13.8 meters and less.

Hydronic heating lines attracted fire ants to bed areas and promoted colonization around the tubing. Careful attention to fire ant control is necessary when susceptible plants or seeds are grown. Hydronic tubes also attracted rodents especially when combined with row cover material. Rodent damage to plants and beds occurred during our preliminary research. To prevent rodent entry and protect the inner high tunnel area from excess moisture, a ground gutter was installed on the sides of the high tunnel for the actual two experiments.

When the hydronic heating tubes were combined with medium thickness row covers, nighttime minimum temperatures were significantly higher than row covers alone on 3 of the 26 recording nights (Figure 5). Average mean nighttime minimum temperatures were 5.75 °C warmer than outside temperatures under row covers, and adding hydronic heat increased the temperature 1.1 °C. Regardless if heat was applied, average nighttime minimum temperatures were significantly greater in treatments with row covers (4.5 °C) compared to treatments without row covers (1.3 °C) on all sampling nights (Figures 6 and 7).

Research by Ward et al. (2013) into the effects of row covers on diurnal temperature flux in high tunnels showed high tunnels provided 4.3 °C of cold protection compared to outside temperatures and row covers gave an additional 3.1 °C of protection. On the coldest night of -18 °C, temperature in the high tunnel was 7.4 °C warmer than outside with an additional 4.9 °C temperature increase under the row cover (Ward et al., 2013). In our experiments on average high tunnels provided 2.5 °C of cold protection and the row covers gave an additional 3.3°C of protection. On the coldest night, with a temperature of -11 °C, our high tunnel gave 6.2°C of protection and the row cover gave an additional 5.67°C of protection. The larger differences in cold protection in high tunnels reported by Ward et al., 2013 may be related to the larger sized double layer high tunnels used in those experiments. Row cover thickness used in the two studies was similar, but brands were different. The difference in row cover temperatures may be related to row covers being elevated with wires in the Ward experiment as opposed to the floating position of our row cover treatments. Our temperature sensors were also 8 cm higher than the Ward experiment sensors. The row covers in the Ward experiment were left on during the day, reducing daytime maximum temperatures under the covers (Ward et al., 2013). Since our nighttime minimum temperatures were higher under row covers than without row covers, removing row covers during the daytime may promote more nighttime heat through increased solar gain onto the soil especially in single layer high tunnels.

High tunnel temperatures in our experiments could have been influenced by the addition of the hydronic heat. Based on the temperature of the hydronic fluid approximately 3,680 BTUs/hour were contributed to the greenhouse possibly raising the nighttime minimum temperatures recorded in the high tunnel.

Lettuce weight and size differed by cultivar across all treatments: 'New Red Fire' yielded the highest weights and 'Defender Romaine' produced the largest size (Figures 8 and 9). Average plant sizes were significantly different across treatments and ranged in the following order from smallest to largest: control plants (300 cm^2), plants with hydronic heat (365 cm^2), plants with row covers (456 cm^2), and the combination of row covers and hydronic heat produced the largest plants (508 cm^2) (Figure 8). Average weight followed a similar pattern with control plants weighing 98 g, plants receiving hydronic heat weighing 115 g, plants receiving row covers weighing 167 g and, plants receiving a combination of row covers and hydronic heat weighing 184 g (Figure 9).

Experiment Two

The second experiment with arugula plants examined hydronic heat combined with either medium or thick row covers with the temperature sensors placed 10 cm directly above the heating tube. The single layer high tunnel provided an average of 2.7 °C of cold protection (Figure 10). Adding medium weight fabric row covers provided an additional average 3.5°C of protection and thick row covers provided an additional 0.6 °C more than medium row covers. Average nighttime minimum temperatures were not significantly different between medium (4.5 °C) and thick (5.4 °C) row cover treatments on all nights (Figure 10). Adding hydronic heat increased average nighttime minimum temperatures 3.4 °C under medium row covers and 3.2 °C under thick row covers. With the exception of the last two nights, nighttime minimum temperatures were significantly higher in treatments combining row covers and hydronic heat compared to the treatments with row covers only and the control treatment (no row covers or hydronic heat) (Figure 10).

On the coldest night with outdoor minimum temperatures of -11 °C, the high tunnel provided 4.3 °C of protection with medium row covers giving 5.9 °C more; the thick row covers provided 0.6 °C more protection than the medium thickness cover. Adding hydronic heat increased nighttime minimum temperatures 5.7 °C under medium row covers and 5.2 °C under thick row covers.

The thick row cover material blocks 70% of solar energy and the medium thickness row cover blocks 30% (manufacturer statement). Because the row covers were placed on top of the plants before the sun set and removed after the sun rose, it is likely that more solar energy was available under medium thickness covers thereby contributing to little mean temperature difference between medium and thick covers. Supporting this hypothesis, a pattern of decreased temperature variability among treatments toward the end of the growth period was seen with both experiments. Because plants were larger during this time they provide more shade over the soil surface thus possibly reducing solar gain.

Plants under hydronic tubes were 1 cm in height when all other planted seeds were just emerging from the ground, indicating that heat promoted early germination and growth. Arugula weight was greater under medium thickness row covers (135 g) compared to thick covers (102 g), suggesting that increased sunlight intensity under the thinner covers promoted plant growth. Adding hydronic heat under row covers increased yields to 180 g with medium row covers and 163 g with thick row covers. Thick row covers may not provide greater cold protection or plant growth when compared to medium thickness row covers used in high tunnels in the Piedmont region of South Carolina. Although the increase in arugula weight from medium row cover to row covers with heat was not significant, it may be of financial significance. However an economic assessment was not completed to determine this.

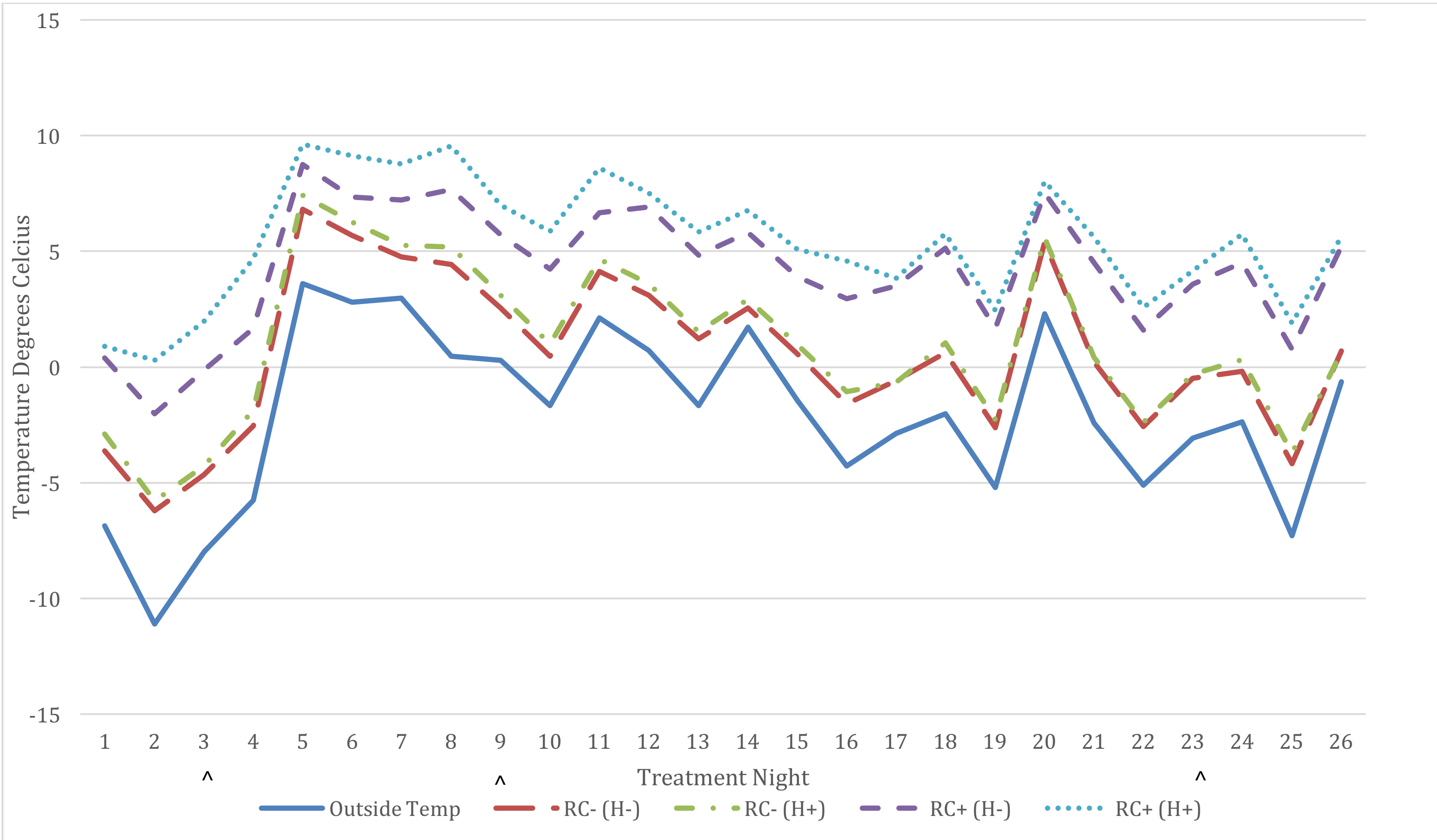

Figure 3. Effects of hydronic heat and row covers on mean nighttime minimum temperatures inside high tunnels. H+ = hydronic heat added: H- = hydronic heat not added: RC+ = row cover added: RC- = row cover not added: ^ = Irrigation applied prior

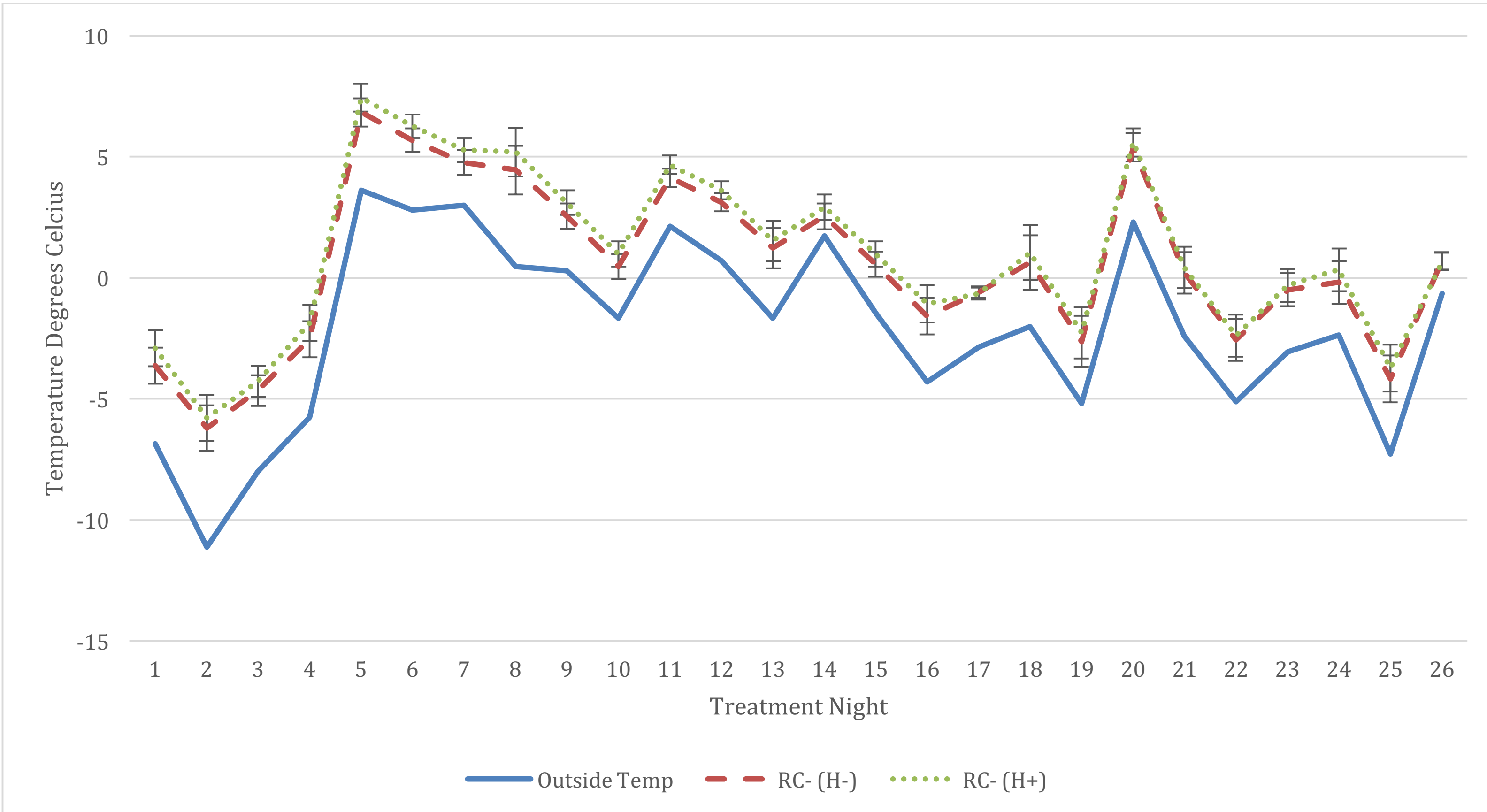

Figure 4. Effects of hydronic heat on mean nighttime minimum temperatures inside high tunnels with no row covers. Temperature sensors were placed 30 cm from the heating tubes. Outside temperature data recorded from one sensor and was not subjected to statistical analysis. Means for each date were not significantly different as determined by Fisher's LSD test $p \leq 0.05$. Error bars show standard error. H+ = hydronic heat added: H- = hydronic heat not added

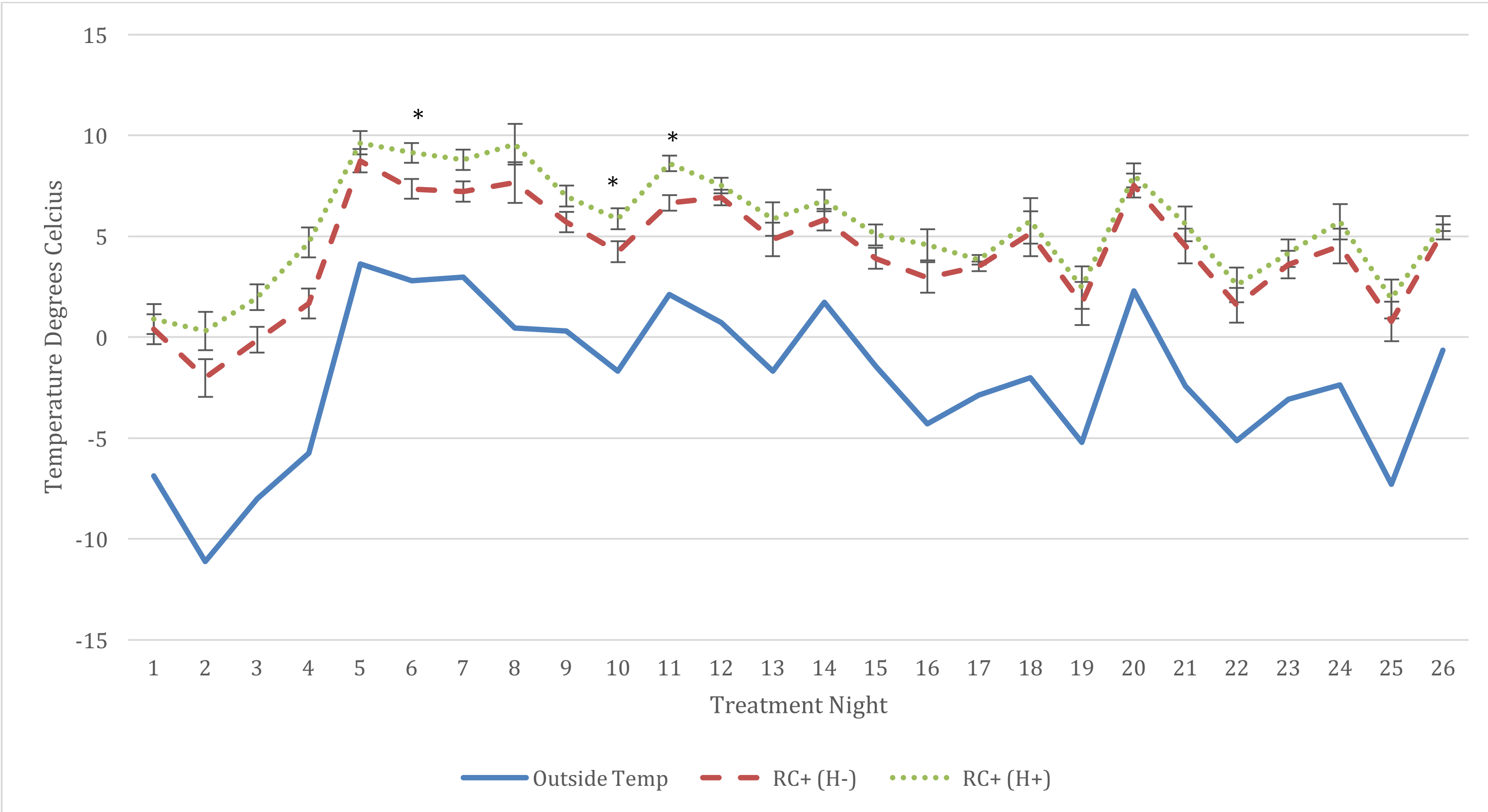

Figure 5. Effects of row covers with and without hydronic heating on nighttime minimum temperatures inside high tunnels. Temperature sensors were placed 15 cm from the heating tubes. Outside temperature data recorded from one sensor and was not subjected to statistical analysis. Error bars show standard error. Days with * indicates significant difference in the temperature means as determined by Fisher's LSD test $p \leq 0.05$. H+ = hydronic heat added: H- = hydronic heat not added: RC+ = row cover added

Figure 6. Effects of medium thickness row covers on nighttime minimum temperatures inside high tunnels. Outside temperature data recorded from one sensor and was not subjected to statistical analysis. Error bars show standard error. All nights were significantly different in the temperature means as determined by Fisher's LSD test $p \leq 0.05$. RC+ = row cover added: RC- = row cover not added: H- = hydronic heat not added

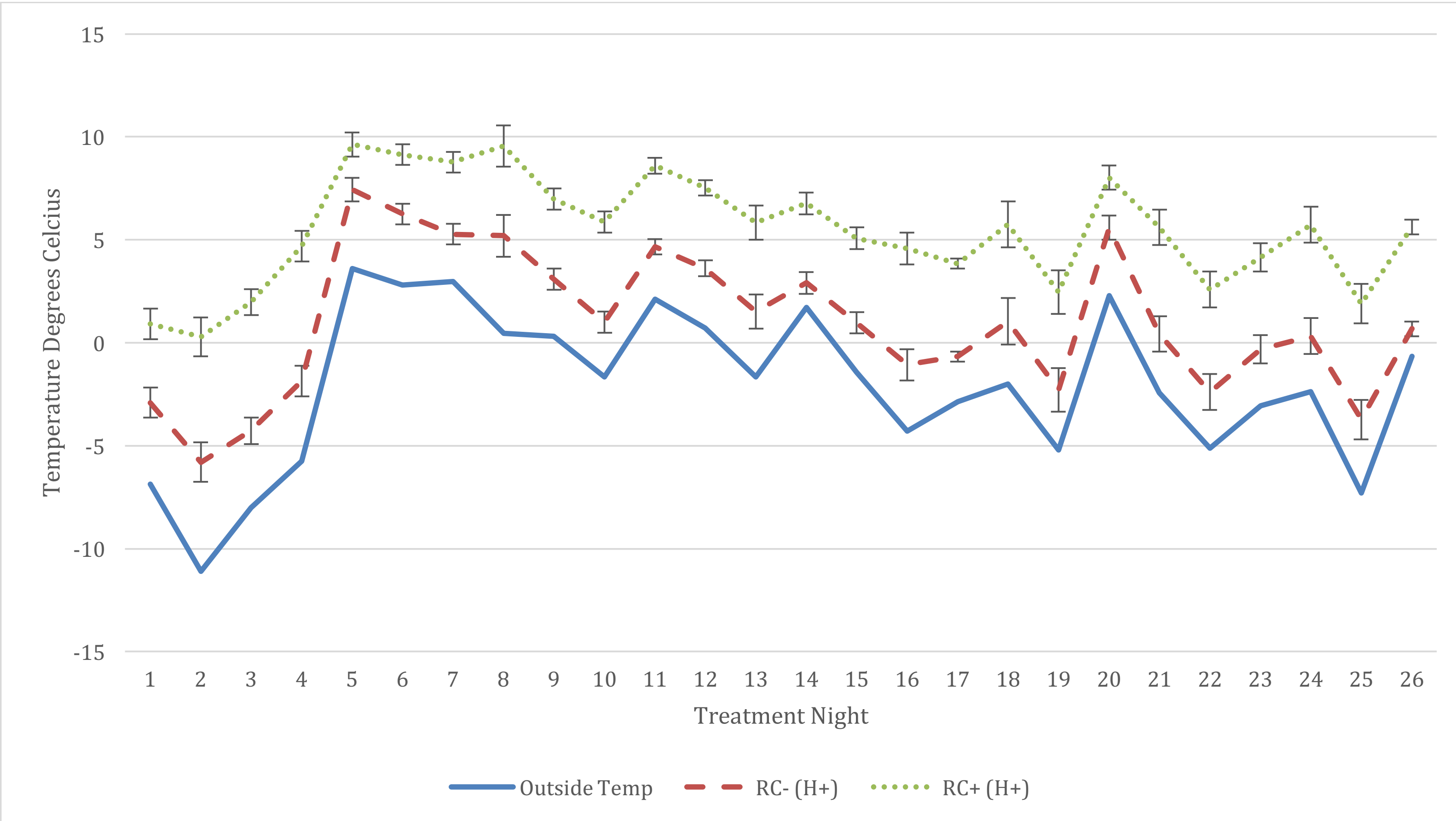

Figure 7. Effects of hydronic heat with and without medium thickness row covers on nighttime minimum temperatures inside high tunnels. Outside temperature data recorded from one sensor and was not subjected to statistical analysis. Error bars show standard deviation. All nights were significantly different in the temperature means as determined by Fisher's LSD test $p \leq 0.05$. RC+ = row cover added: RC- = row cover not added: H+ = hydronic heat added

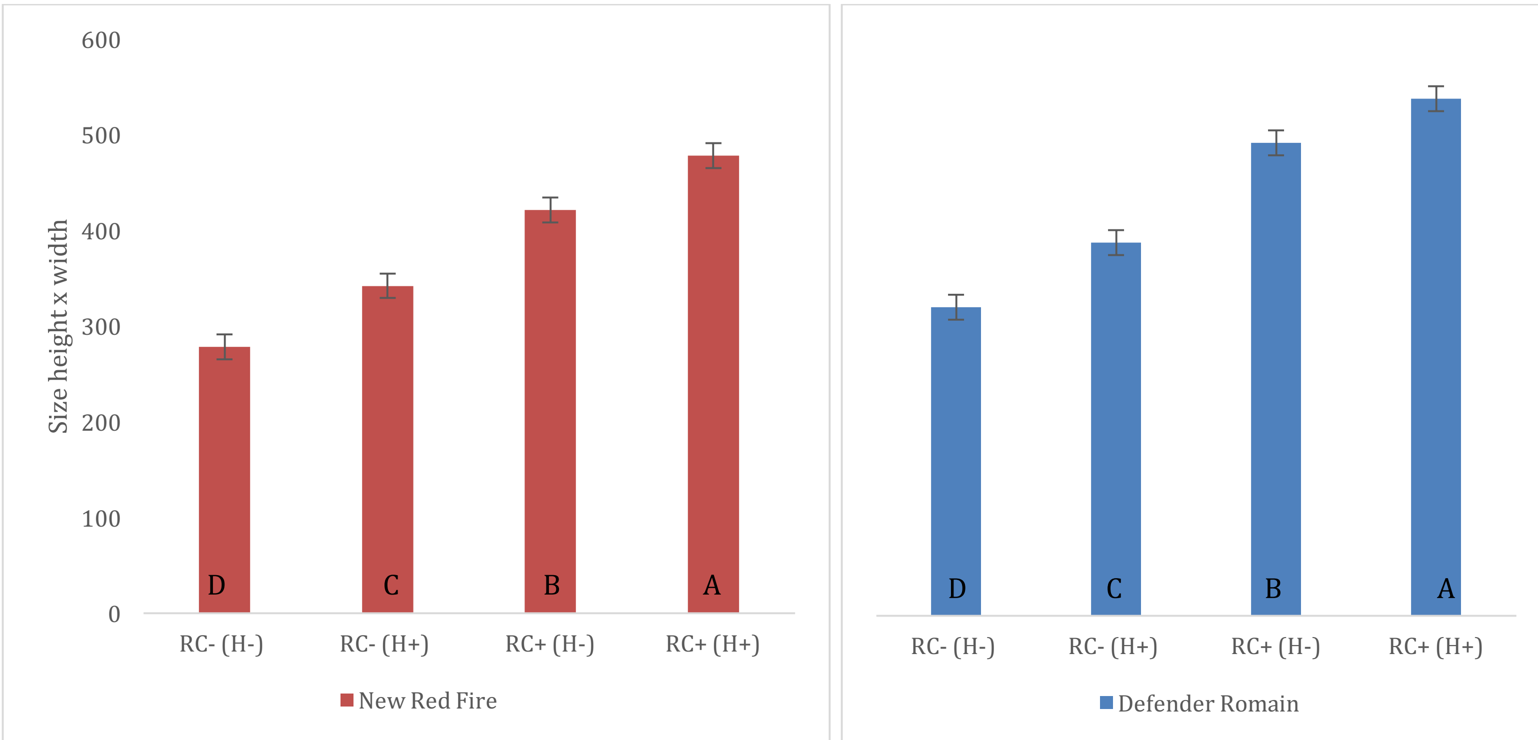

Figure 8. Effects of hydronic heat, medium thickness row covers, and a combination of hydronic heat and row covers in high tunnels on mean lettuce size. Plants grown 15cm from the heating tubes. Error bars show standard error. Compared across all treatments within a variety, means with the same letter are not significantly different as determined by Fisher's LSD test $p \leq 0.05$. Varieties were significantly different. RC+ = row cover added: RC- = row cover not added: H+ = hydronic heat added

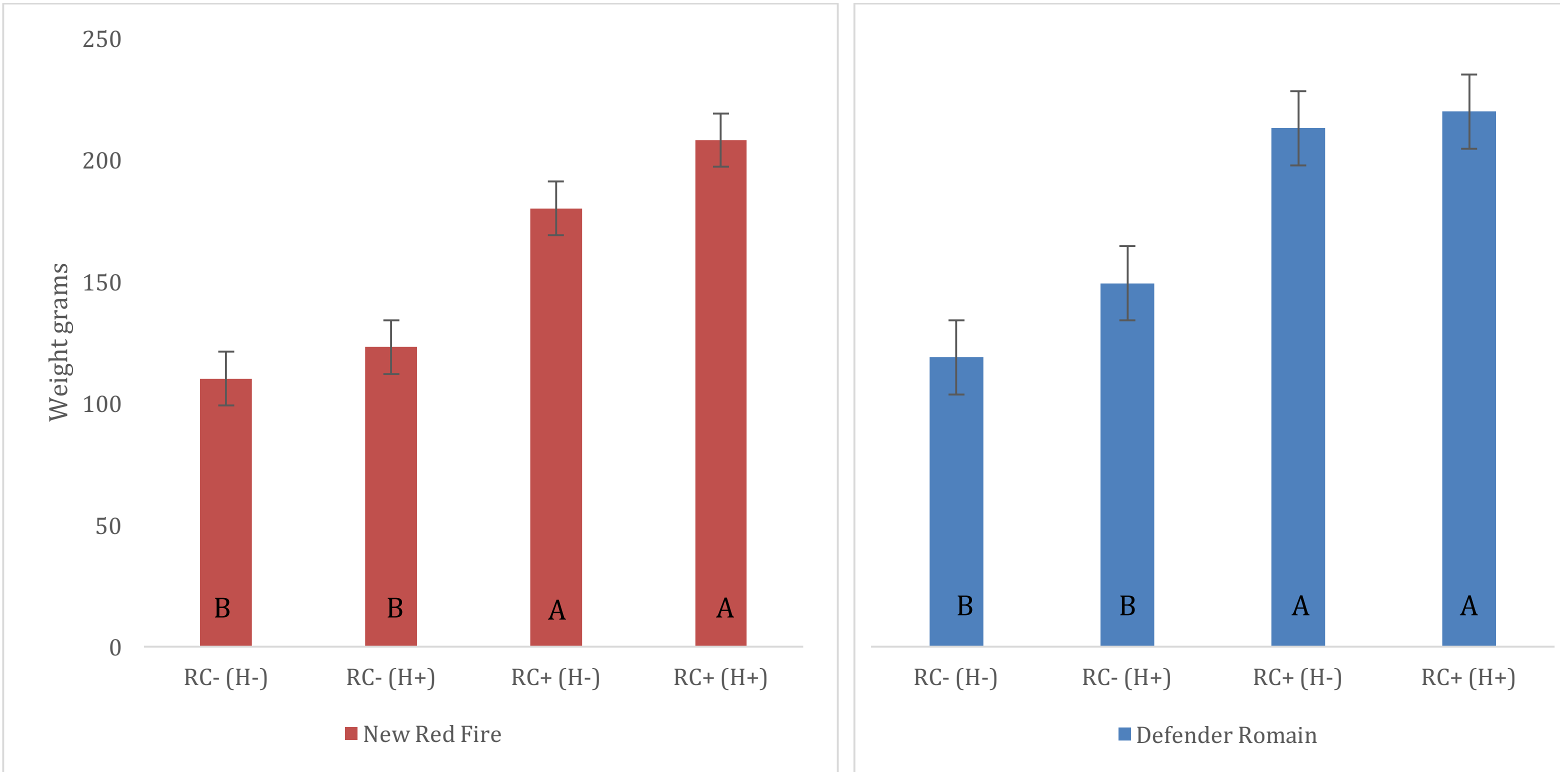

Figure 9. Effects of hydronic heat, medium thickness row covers and a combination of hydronic heat and row covers in high tunnels on mean lettuce weight. Plants grown 15cm from the heating tubes. Error bars show standard error. Means with the same letter are not significantly different within a variety as determined by Fisher's LSD test $p \leq 0.05$. Varieties were significantly different. RC+ = row cover added: RC- = row cover not added: H+ = hydronic heat added

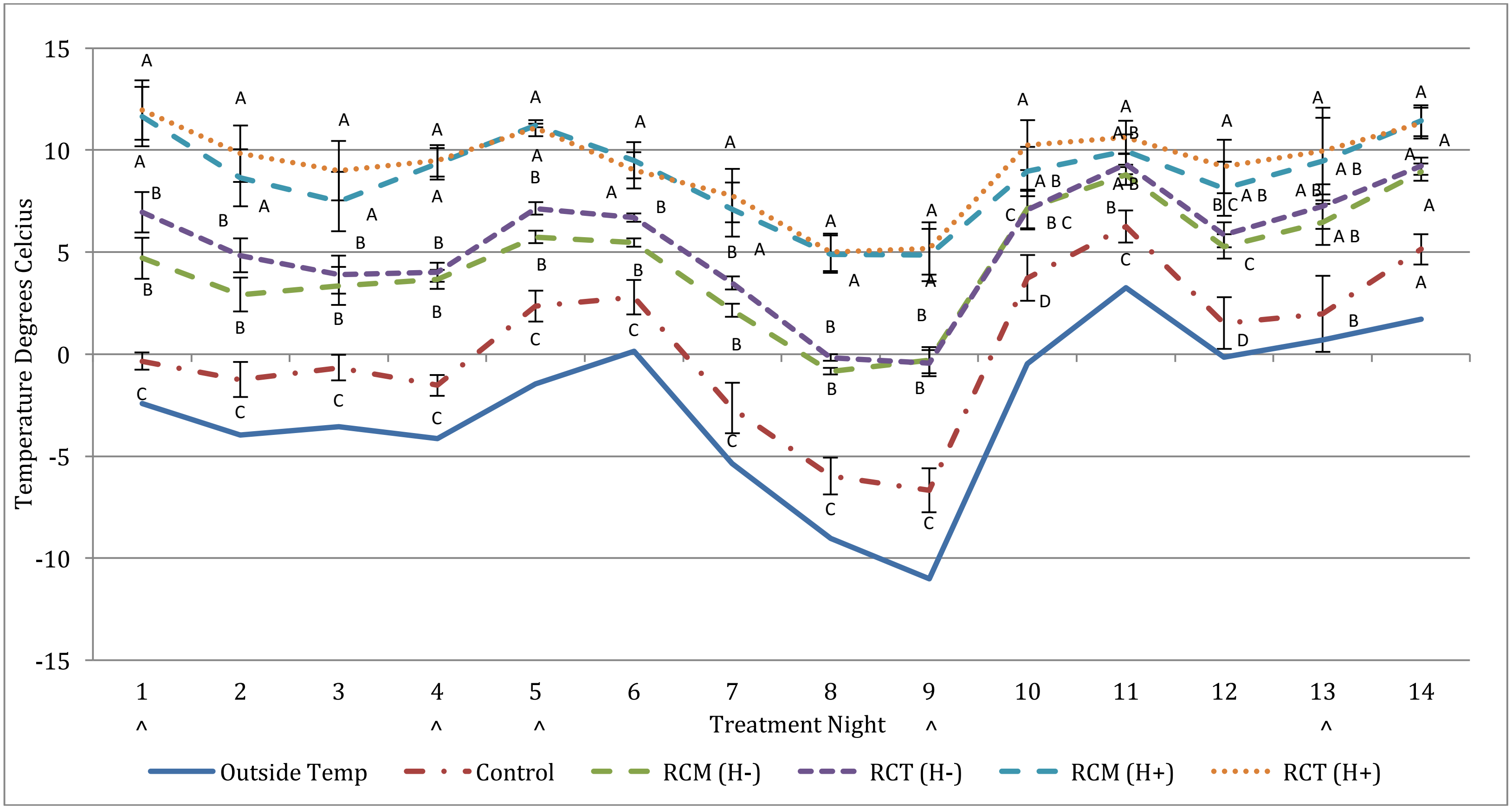

Figure 10. Effects of hydronic heating, medium and thick fabric row covers, and a combination of row covers and hydronic heat on nighttime minimum temperatures in high tunnels. Temperature sensors placed 10cm above hydronic heating tubes. Outside temperature data recorded from one sensor and was not subjected to statistical analysis. Means with same letter are not significantly different as determined by Fisher's LSD test $p \leq 0.05$. RCM = row cover medium: RCT = row cover thick: H+ = hydronic heat added: Control = sensor placed in area without hydronic heat or row cover: ^= irrigation applied prior

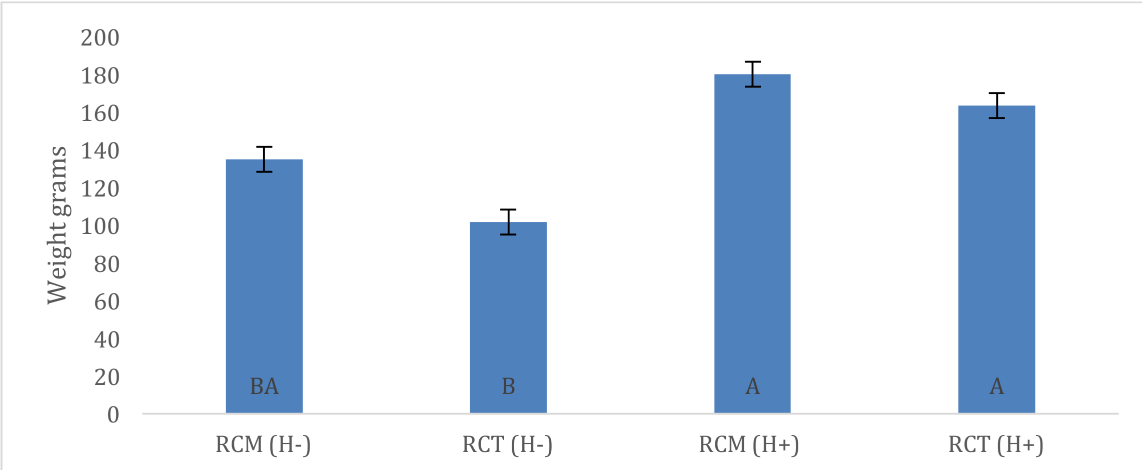

Figure 11. Effects of hydronic heating with medium and thick row cover on arugula mean weight. Hydronic heating tube placed in plant row. Means with the same letter are not significantly different as determined by Fisher's LSD test $p \leq 0.05$. RCM = row cover medium, RCT = row cover thick, H+ = hydronic heat added.

CONCLUSIONS

Floating row covers are used to protect plants from nighttime temperature extremes inside high tunnels. Row covers removed during the daytime allow maximum sunlight exposure for plant growth and soil heating. Combining row covers with hydronic heat is a novel idea with potential economic benefits. Determining the degree of cold protection provided by row covers and hydronic heat in relation to nighttime minimum temperatures and the relationship between the degree of cold protection and distance from heating tubes will allow growers to optimize heating systems and heating tube placement.

Previous research examined low tunnel structures in combination with root zone heating and high tunnels in Ohio field-grown lettuce production (Bumgarner et al., 2011). Results of these studies indicated that root zone heating with low tunnels created microclimates that supported increased yields of lettuce, particularly when root zone heating was used with low tunnels in fields without high tunnels. Our research examined the effects of floating row covers combined with hydronic heating tubes placed above ground and adjacent to plants grown in high tunnels.

Combining high tunnels with row covers and hydronic heating systems creates distinct microclimates that vary by distance to heating tubes as indicated by nighttime minimum temperature data. Hydronic heat alone did little to protect plants from extreme nighttime minimum temperatures and therefore should not be used for cold protection inside high tunnels. Row covers offer moderate protection and combining row covers with hydronic heat doubled the cold protection of the row cover. Thick row covers did not significantly outperform medium row covers.

The microclimates associated with row covers and hydronic heat were associated with differences in the yield and size of lettuce and the yield of arugula plants. Plant weight and size was greatest when row covers were combined with hydronic heat. Row covers alone increased size and weight of plants more than hydronic heat alone.

Additional research into depth of heating tube placement could determine optimum depth to facilitate growth. A shallow or surface placement as was done in the present study would allow ease of removal during mechanical tillage and may provide more protection from extreme nighttime minimum temperatures.

Another technique for applying row covers to plants employs wires strung 2' above the crops the entire length of the greenhouse. The row cover is bunched at the end of the greenhouse during daytime to allow maximum sunlight for plants. Before night, the cover is pulled over the plants with a single cover spanning the entire greenhouse. Additional studies to compare row covers placed in floating positions, suspended over the plants using wire hoops and suspended over the entire greenhouse floor using greenhouse length wires may provide valuable information to optimize growth and cold protection.

Hydronic heat is possibly enhanced by the addition of solar energy when thinner row covers are used. This suggests that use of black plastic mulch systems with row cover treatments may enhance row cover performance more than additions of hydronic heat alone. Future studies to evaluate black plastic mulch systems combined with heat and fabric row cover arrangements may help to identify combinations of such components in systems that can be utilized to provide optimal cold protection for plant production inside high tunnels.

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