Improving Growth and Productivity of Early-season High-tunnel Tomatoes with Targeted Temperature Additions

Britney Hunter, Dan Drost², and Brent Black
Department of Plants, Soils, and Climate, Utah State University, 4820 Old Main Hill, Logan UT 84322-4820

Ruby Ward
Department of Applied Economics, Utah State University, 3530 Old Main Hill, Logan, UT 84322-3530

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Abstract. In northern climates where the growing season is shortened by cool spring conditions, high tunnels make it possible to plant and produce tomatoes (Solanum lycopersicum L.) at least 1 month earlier than in the field. However, limited high-tunnel research has been performed in arid high-elevation regions that experience extreme diurnal temperature fluctuations. High tunnels are designed to be passively heated; therefore, additional protection from frost may be warranted if growers wish to plant significantly earlier than normal. Low tunnels built within a high tunnel reduce the energy requirement by concentrating heat around the plants, particularly when a heat source is placed inside the low tunnel. ‘Sunbrite’ tomatoes were transplanted through black plastic mulch in four high tunnels in North Logan, UT (lat. 41.73° N, long. 111.83° W, 1382 m elevation) on 17 Mar., 30 Mar., and 7 Apr. in 2009 and on 19 Mar., 30 Mar., and 9 Apr. in 2010. Low tunnels were constructed over each row, and three supplemental heat treatments (unheated, soil-warming cables, and soil-warming cables plus 40-W incandescent lights) were tested to improve plant performance. The highest total marketable yield was achieved for earliest planting dates in both 2009 and 2010. In 2009, early-season yield was significantly greater when both the soil + air were heated, but only for the earliest planting date. In 2010, soil heat alone and in conjunction with air heat significantly improved early-season yield. Information gathered in this study on planting dates, yield, and energy costs provides valuable production and economic information to growers in arid high-elevation climates who desire the benefits of growing early-season tomatoes in high tunnels.

High tunnel use throughout the United States is on the increase as a result of earlier crop production and the opportunity to exploit local markets with regionally grown produce (Carey et al., 2009; Knewtson et al., 2010). In regions with short growing seasons, extending the production period can have significant economic benefit (Rader and Karlsson, 2006; Rowley et al., 2010; Waterer, 2003). Tomatoes (Solanum lycopersicum L.) are the most commonly grown high-tunnel crop because early, local, high-quality tomatoes have a high value in the market (Knewtson et al., 2010; Ward et al., 2011). Tomato is a common high-tunnel vegetable crop in Utah, and growers regularly ask if tunnels provide enough early protection when day–night temperatures vary significantly and, if so, when to plant. Producing tomatoes before outdoor field production begins extends revenue into a normally unproductive period and allows growers to benefit from out-of-season price premiums (Ward et al., 2011).

For climates near zone 5 on the USDA hardiness scale, growing in a high tunnel makes it possible to plant and produce tomatoes more than 1 month earlier than outdoors (Wells and Loy, 1993). By protecting plants from rainfall, high tunnels facilitate uniform watering, which is important for preventing disorders such as fruit cracking, blossom end rot, and many foliar diseases. High tunnels also provide more optimal temperatures for growth and improve quality by preventing disorders associated with poor pollination such as cat-facing and pufiness (Dorais et al., 2001). Krizek et al. (2006) showed that high tunnel-grown tomatoes had a higher sensory score for sweetness, flavor, texture, taste, and overall eating quality when compared with field-grown fruit.

The benefits of high-tunnel production have been explored in other states including Missouri, Connecticut, and New Jersey (Chism, 2002; Gent, 1992; Reiss et al., 2004), but research in arid high-elevation regions is lacking. In arid high-elevation climates like Utah, daytime temperatures spring can be quite warm (10 to 20°C) even when nighttime temperatures are below freezing (Moller and Gillies, 2008). These extreme diurnal temperature variations can limit the length of the growing season for outdoor-grown vegetables. However, warm temperatures during the day and sunny skies could be used advantageously when high tunnels are incorporated into a farm’s production system. Utah gets more solar radiation on average than other parts of the United States that conduct high-tunnel tomato research. On average, the western United States receives 18–21.6 MJ m⁻² d⁻¹ of solar radiation in April and 21.6–25.2 MJ m⁻² d⁻¹ in May, whereas during the same period, regions of the central and eastern United States receive 14.4–18 and 18–21.6 MJ m⁻² d⁻¹, respectively (Wilcox and Marion, 1994). Increased solar radiation should result in more accumulated heat units in a high tunnel compared with climates with more cloudy conditions. Arid climates also have the advantage of low relative humidity that should limit the development of problematic diseases common to more humid regions (Lamont, 2005; Wells and Loy, 1993).

In most of the Great Basin region (USDA hardiness zones 5a to 6b), tomatoes are typically transplanted outdoors in mid- to late May and begin to ripen in early August, whereas high-tunnel tomatoes can be planted 5 to 7 weeks earlier. Choosing an appropriate planting date is an important decision for growers in these climates. A 2-week delay in planting was shown to delay ripening by 2 weeks for early high-tunnel tomatoes transplanted in Connecticut (Gent, 1992). However, early-season cold weather makes planting risky during late March and early April even when grown in high tunnels. Row covers and low tunnels have been shown to provide some frost protection for early field-planted tomatoes (Ankara, 2001; Emmert, 1956; Waggoner, 1958) and could be used in combination with high tunnels.

Typical outdoor early spring temperatures (March and April) in northern Utah range from 10 to 20°C during the day and –5 to 5°C at night (Moller and Gillies, 2008). Day temperatures inside a high tunnel normally reach 20 to 30°C, which is considered to be optimal for tomato (Kinnet and Peet, 1997). However, nighttime temperatures in a high tunnel are typically only 1 to 4°C warmer than the outside temperature, and consequently the high-tunnel environment is still susceptible to chilling or freezing conditions at night (Wien, 2009). Tomato plants are susceptible to chilling injury when exposed to temperatures below 10°C (Kinnet and Peet, 1997) and grow best when temperatures are 25 to 30°C during the day and 16 to 20°C.
at night (Csizinsky, 2005). Tomatoes are known to compensate growth when day or night temperatures are below optimum provided temperatures are optimal during the opposite period (Calvert, 1964).

The addition of rowcovers can increase temperatures 2 to 6 °C, and polyethylene rowcovers alone were shown to protect tomato plants from freezing when outside temperatures were −3.8 °C (Emmert, 1956; Waggoner, 1958). Low tunnels have also been shown to promote earlier tomato harvest and increase total yield within an unheated greenhouse, presumably by improving temperature conditions (Ankara, 2001). Waterer (2003) showed that heat unit accumulation, as measured by growing-degree-days, was similar for low and high tunnels and both provided adequate plant protection when crops were planted in late May. However, this was after the risk of significant frost was passed. In New Jersey, polyester energy curtains placed inside a high tunnel were found to increase average night air temperatures 2.3 °C compared with the open field. In tunnels without curtains, temperatures were only 0.9 °C warmer than in the field (Both et al., 2007).

In the arid, high-elevation regions of Utah, temperatures below −7 °C often occur from mid-March to late April when growers would be transplanting tomatoes into high tunnels (Moller and Gillies, 2008). These low temperatures may seriously limit early high-tunnel tomato production even when additional rowcovers are used. Therefore, targeted supplemental heat may aid in additional cold temperature protection during the early season.

Many high-tunnel production manuals advocate using protective structures like rowcovers and low tunnels inside high tunnels (Blomgren and Frisch, 2007; Byczynski, 2003; Lamont et al., 2005). However, few reports are available on the integration of supplemental heat additions and low tunnels within high tunnels. High tunnels typically do not use electricity; however, backup heating could provide the protection necessary to keep valuable plants alive in the early spring (Blomgren and Frisch, 2007). Supplemental heating is expensive, but costs may be reduced when used under low tunnels inside high tunnels, where heat would be concentrated around the plants. This approach has been used successfully for greenhouse tomatoes, where the amount of fuel needed to run the heating system was significantly reduced by targeting the heat at plant level using convection tubes (Hanna and Henderson, 2008). Soil warming has been shown to increase biomass accumulation and nutrient uptake for many crop greenhouse environments (Gosselin and Trudel, 1985; Hurewitz et al., 1984; Shedlosky and White, 1987). Although root zone heating can partially offset the adverse effect of low night air temperatures on greenhouse plants (Gosselin and Trudel, 1985; James and McAvoy, 1983), no published studies are known that assessed the effectiveness of root zone heating when high-tunnel air temperatures are near or below freezing.

The objectives of this project were to evaluate appropriate planting dates that provide early fruit production, to determine if low-cost supplemental heat sources can provide low-temperature protection for early-planted tomato, and to determine whether high-tunnel tomato production using these systems is economically viable.

Materials and Methods

Experiments were conducted in four identical high tunnels (replicates) on the Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT (lat. 41.77” N, long. 111.81° W, 1382 m elevation, 135 freeze-free days) during the spring and summer of 2009 and 2010. The four tunnels were 12.8 m long and 4.3 m wide and were built with polyvinyl chloride hoops covered with a single layer of 6-mil greenhouse plastic (Black et al., 2008a). Two of the tunnels were managed organically and the others by conventional approaches, which were a continuation of a previous study and to facilitate future studies (Reeve and Drost, 2012).

The organic tunnels were fertilized with composted chicken manure to provide 150 kg nitrogen (N)/ha. The compost contained 5.0 g of soluble N and 16.5 g of organic N/kg of compost. The conventionally managed tunnels were fertilized as recommended from soil analysis and provided with 150 kg N/ha; 50 kg phosphorus/ha, and 125 kg potassium/ha from various fertilizer sources. Compost and fertilizer were incorporated using a small tractor-mounted rototiller.

During the growing season, an additional 50 kg N/ha from fish emulsion or urea was injected with the irrigation water in the organic and conventionally managed tunnels, respectively. Prior research showed that there was no difference in tomato productivity between the organic and conventionally managed high tunnels (Reeve and Drost, 2012).

Supplemental heat. Each high tunnel had three 12-m long rows, which were divided into 4-m sections. Soil-warming cables were installed in six of the nine sections in each tunnel after the fertilizer application. Nonautomatic heavy duty soil-warming cables (Wrap-On Company Inc., Bedford Park, IL) were spaced 15 cm apart as directed by the product instructions and were buried 2.5 cm deep in the rows. The cables were attached to a Model 18500 heater control thermostat (Wrap-On Company Inc., Bedford Park, IL) with a remote soil sensor that was set to activate when soil temperatures dropped below 21 °C. Each soil warming cable used 700 W of electricity when activated. After the cables were installed, drip irrigation tape and black plastic mulch were laid in the tunnels to create three 90-cm wide beds with 60-cm walkways between the rows.

Three of the six soil-heated sections in each high tunnel were further modified to inexpensively warm the air around the planted tomatoes. Three rubber weatherproof pigtail sockets were spliced into heavy-duty extension cords and outfitted with 40-W incandescent light bulbs. Lights were spaced 1.2 m apart and were located 60 cm above the soil surface. The lights were programmed to turn on when the air temperature dropped below 16 °C. Thus three heat treatments were created within each high tunnel: the unheated control, soil heat only, and the combination of soil + air heat. Individual electricity use monitors (Kill-A-Watt EZ meters; P3 International, New York, NY) recorded the amount of energy used by the cables and lights. The cost of electricity was calculated by multiplying kilowatts per hour (kWh) used by the current cost of electricity in Logan, UT (2000–2002 per kWh for general commercial service).

Low tunnels. To further increase frost protection and help retain heat around each respective plot, plastic rowcovers (low tunnels) were installed inside the high tunnels. Low tunnel supports were constructed from 1.3 cm diameter 3-m long conduit. The tubing was bent to make a 1 m tall by 1-m wide square arch. The arches were secured over the rows by fitting them over 60-cm long rebar, which was inserted in the soil 40 cm. One arch was installed every 3.6 m to divide the plots. At the end of each plot, two arches were separated by 10 cm and the ends were covered with plastic to further separate the heat treatments. The low tunnels were covered with 2-mil construction-grade plastic, and all plants inside a high tunnel were grown under the low tunnels.

The low tunnels were ventilated each morning (if needed) and covered again at the end of each day to avoid excessive heat buildup. Low tunnels were removed in mid-May after the risk for frost. The high tunnels were ventilated as needed by opening the doors and lifting the side walls to regulate the temperatures between 20 and 30 °C. When the outdoor night temperature stayed above 12 °C (mid-June), the plastic on the high tunnels was removed and 40% shade cloth applied to minimize the potential for sunburn.

Watermark” sensors (Irrrometer Company, Riverside, CA) were used to monitor soil moisture and schedule irrigations. Sensors were placed at 15- and 30-cm soil depths and irrigation was applied when soil moisture readings approached 45 kPa as recommended for a silt loam soil (Creswell et al., 2011). Plants were irrigated immediately after transplanting and approximately one time per week early in the season. As the plants grew and temperatures increased, water was applied three to four times per week at a rate of ≈25 mm per irrigation.

Transplant production. ‘Sunbrite’ (Seminis Seeds, St. Louis, MO) tomatoes were seeded into 50-cell flats and grown for 8 weeks in a heated greenhouse before transplanting into the high tunnels. Seeding occurred on 23 Jan., 5 Feb., and 18 Feb. 2009 and on 15 Jan., 27 Jan., and 9 Feb. 2010. Transplants were grown in soilless mix containing equal parts peat moss, vermiculite, and perlite, and plants were fertilized to provide 100 mg N/kg at 48-h intervals after emergence. The greenhouse was maintained at
Temperature data were used to calculate growing degree-hours based on the ASYMCUR heat unit model (Anderson et al., 1986) modified according to Black et al. (2008b). Temperature data were also used to calculate hours of chilling. One hour of chilling was accumulated when the average hourly air temperature fell below 10 °C.

A laboratory experiment was performed to gauge the warming capability of incandescent light bulbs within a low tunnel. A 3.6-m long low tunnel similar to those used in the high tunnels was constructed. A black-painted copper plate, outfitted with five thermometer probes connected to a CR10 data logger (Campbell Scientific), was placed in the low tunnel and positioned 30 cm from the center light bulb. A sheltered type-E thermocouple sensor was used to monitor air temperature. Lights were turned on for 30 min and then turned off for 30 min and the plate temperature recorded every 5 s.

The labor required to set up tunnels, manage plant growth, and the time required for irrigation, ventilation, and harvest were recorded and materials and supply costs noted. Tomatoes were sold at the Logan Farmers’ Market (http://www.gardenersmarket.org/) for $4.40 to $5.50/kg. These data were used to generate an enterprise budget, which was published elsewhere (Hunter et al., 2011). The experimental design was a randomized split plot design with planting date as the whole-plot factor and heat treatment as the sub-plot. Analysis of variance (SAS Institute, Cary, NC) was used to identify differences between planting dates and heat treatments and orthogonal contrasts used to separate specific planting date (early vs. others and mid vs. late) and heat (control vs. heat and soil heat vs. soil + air heat) effects. The least significant difference test (α = 0.05) was used for multiple comparisons.

Partial budgeting was used to analyze the economic viability of soil heat and soil + air heat. Partial budgeting examines only what changes between new treatments (heat) over the base cost of high and low tunnels and thus assesses the potential profitability of the treatment. In this case the additional returns from increased yields from soil heat and soil + air heat combined are compared with the additional cost associated with the respective heat techniques. The result is the potential additional profit from the treatment.

Results and Discussion

Temperatures. Using low tunnels within high tunnels provided sufficient protection (across all planting dates and heat treatments) for 96% and 97% tomato plant survival in 2009 and 2010, respectively (data not shown). Temperatures inside and outside the tunnels in 2009 were as low as −3.5 and −8 °C, respectively. In 2009 and 2010, daily minimum temperatures inside the unheated low tunnels inside the high tunnel from 17 Mar. to 8 May were below 10 °C (Fig. 1A) with some overnight temperatures dropping below freezing. Although plant survival is important for early-season high-tunnel tomato production, temperatures should be warm enough during the day for growth to occur while avoiding
superoptimal temperatures that adversely impact productivity (Peterson and Taber, 1991; Wolfe et al., 1989). Daily average temperatures inside the unheated low tunnels were sufficiently high during the early season for growth to occur (Fig. 1B). In general, average temperatures in an unheated low tunnel from late March to early May 2009 were cooler than in 2010.

The diurnal change in temperature outside the high tunnel and under the low tunnels inside the high tunnel on 2 clear days in late March is illustrated in Figure 2. Temperatures inside the high and low tunnels increased rapidly after sunrise and ventilation was required by 1000 h to maintain temperatures in the range of 30 to 35 °C. By 1600 h, the temperature decreased so low tunnels were re-covered and high tunnel vents closed. On cloudy days, similar temperature patterns were noted under the low tunnels and inside the high tunnels, although the day–night temperature differences were not as extreme (data not shown). Without regular monitoring, low tunnel temperatures can quickly go from the optimal range for tomato to excessive, causing blossom loss or fruit abortion (Kinet and Peet, 1997; Peterson and Taber, 1991; Reiners and Nitzsche, 1993). Although flowering dates and blossom drop were not measured, tunnel temperatures were managed effectively (Fig. 2) and there were few episodes in which temperatures exceeded 35 °C. In addition, cull fruit losses were generally not symptomatic of heat injury.

Although high tunnels alone provided ≈4 °C of cold protection, temperatures were regularly below freezing when planting early tomatoes in the Great Basin region of the western United States. Shen and Li (1983) noted that tomato can be cold-acclimated by exposure to short periods of chilling conditions and survive quite cold temperatures (~3 °C). Temperature measurements in the low tunnels were comparable to earlier studies showing that low tunnels alone can protect tomato plants down to –3.8 °C (Emmert, 1956). On very cold nights (Fig. 1A), temperatures inside low tunnels were close to ambient air temperatures within the high tunnels. However, the addition of supplemental heat was enough to increase air temperature inside low tunnels by 2 to 3 °C when the soil + air were heated compared with unheated and soil heat alone (Fig. 2). Day temperatures were not different among the heat treatments.

The effect of diurnal temperature variations on productivity may be more complex than the effect of extreme temperatures in one direction. Gent and Ma (1998) reported that day/night differences in mean temperature (DIF) were greatest in March and April during vegetative, flowering, and early fruit growth periods. Our data support these findings and plants were regularly subjected to diurnal variations of more than 20 °C. For greenhouse-grown tomatoes, larger DIF saves on heating costs (Gent et al., 1979) but may adversely impact earliness and productivity (Gosselin and Trudel, 1985). In this study, day temperatures would often increase by more than 25 °C (Fig. 2) while average temperatures (Table 1) increased steadily as environmental conditions improved through-out April. Hurd and Graves (1985) also reported large diurnal temperature shifts and suggested that these diurnal cycles imparted increased cold temperature survival. Our plant survival data tend to support these conclusions.

Because the patterns of accumulated growing degree-hours (GDH) were similar in both years, only the results from 2009 are presented (Table 1). We did not analyze the differences between years because the seasonal temperature differences were expected (Fig. 1B). Each planting date was analyzed separately as a result of different time intervals between the planting dates and arbitrary measurement periods (every ≈15 d). Planned comparisons indicated that more GDH accumulated when heat was added compared with the unheated controls for all planting dates. However, there were fewer differences in accumulated GDH between the soil heat and the soil + air heat treatment with later planting dates (Table 1).

The influence of the light bulbs on air temperature in this study may have been underestimated as a result of the location of the temperature sensors. The sensors likely could not pick up the heat radiating from the incandescent light bulbs as a result of interception by the sensor shield and the plant canopy. In the laboratory evaluation, a 40-W incandescent light inside a low tunnel caused the temperature of a flat black-painted copper plate to increase by 2 °C above ambient temperature in ≈15 min. The temperature of the copper plate returned to the ambient temperature ≈20 min after the lights turned off. The infrared absorptivity of the flat black-painted copper plate (0.97) is similar to the absorptivity of a green leaf (0.96) because the albedo for each surface is similar. Therefore, incandescent lights may affect leaf temperature more than air temperature as a result of their location above the plants, and this should be investigated more carefully.

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Fig. 2. The effect of targeted soil heat and soil + air heat on diurnal air temperature cycles within the tomato plant canopy under a low tunnel in a high tunnel in March when overnight air temperatures outside the high tunnel were below freezing.
In 2009, soil + air heat significantly reduced the accumulated hours of chilling (average hourly temperature less than 10 °C) for tomatoes transplanted on 17 Mar. compared with heated soil only and the unheated control (Table 2). No significant differences in accumulated hours of chilling occurred between the heat treatments when planting on 30 Mar. or 7 Apr. 2009; however, plants with soil + air heat experienced 20% to 30% fewer hours of chilling. In 2010, accumulated hours of chilling were less than in 2009 (data not shown) although the general pattern was similar, because spring temperatures were generally warmer in 2010 than 2009 (Fig. 1A–B).

**Plant growth.** Early biomass accumulation was significantly greater with heat additions. Others have shown that low tunnels accelerate plant development, flowering, and improve early yields (Peterson and Taber, 1991; Reiners and Nitzsche, 1993). Plants with combined soil + air heat had greater pruning biomass compared with unheated or soil heat treatments for the first and last planting dates. Pruning biomass did not differ statistically among treatments when planted 30 Mar. 2009 as a result of increased plant-to-plant variability (Table 3). In 2010, uniform sampling times (38 d after transplanting) provided more accurate comparisons of pruning biomass between planting dates and heat treatments. Although pruning biomass differed significantly among the three planting dates (Table 3), there was no significant interaction between planting date and heat treatments. Orthogonal contrasts indicate that plants receiving additional heat produced significantly more biomass than the unheated controls. However, there was no difference in pruning weight between the soil heat and the soil + air heat, suggesting that either heat treatment provided similar growth improvements.

**Tomato yields.** Early planting dates had a significant positive effect on early marketable yield. Fruit harvest began on 7 July for all planting dates in 2009 and on 14 July 2010, ~5–6 weeks before local outdoor production. The early harvest achieved in our study (7 July 2009 and 14 July 2010) was comparable to the earliness achieved in previous studies in which tomatoes were grown in high tunnels under rowcover cloth instead of low tunnels (Reeve and Drost, 2012) and comparable to the earliness achieved in pre-harvest cold and soil heat treatments for the first and last planting dates. Pruning biomass did not differ statistically among treatments when planted 30 Mar. 2009 as a result of increased plant-to-plant variability (Table 3). In 2010, uniform sampling times (38 d after transplanting) provided more accurate comparisons of pruning biomass between planting dates and heat treatments. Although pruning biomass differed significantly among the three planting dates (Table 3), there was no significant interaction between planting date and heat treatments. Orthogonal contrasts indicate that plants receiving additional heat produced significantly more biomass than the unheated controls. However, there was no difference in pruning weight between the soil heat and the soil + air heat, suggesting that either heat treatment provided similar growth improvements.

### Table 1. The effect of targeted heat treatments on accumulated growing degree-hours (base 10 °C) for three planting dates in 2009.*

| Planting date | 1 Apr. | 15 Apr. | 1 May | 15 May |
|---------------|--------|---------|-------|--------|
| 17 Mar.       |        |         |       |        |
| Unheated control | 704    | 1404    | 2859  | 4702   |
| Soil heat     | 769    | 1549    | 2961  | 4818   |
| Soil + air heat | 953    | 1989    | 3574  | 5475   |
| 30 Mar.       |        |         |       |        |
| Unheated control | 82     | 745     | 2084  | 3930   |
| Soil heat     | 107    | 915     | 2335  | 4129   |
| Soil + air heat | 97     | 958     | 2489  | 4320   |
| 7 Apr.        |        |         |       |        |
| Unheated control | —      | 557     | 2082  | 3844   |
| Soil heat     | —      | 547     | 2278  | 4499   |
| Soil + air heat | —      | 666     | 2295  | 4180   |

**Analysis of variance**

| df | P values |
|----|---------|
|    |         |
| 17 Mar. |        |         |       |        |
| Heat treatments | 2 | 0.016 | 0.037 | 0.049 | 0.085 |
| Unheated vs. heat | 1 | 0.021 | 0.047 | 0.083 | 0.127 |
| Soil heat vs. soil + air | 1 | 0.019 | 0.042 | 0.041 | 0.070 |
| 30 Mar. |        |         |       |        |
| Heat treatments | 2 | 0.232 | 0.117 | 0.109 | 0.440 |
| Unheated vs. heat | 1 | 0.128 | 0.012 | 0.057 | 0.231 |
| Soil heat vs. soil + air | 1 | 0.465 | 0.451 | 0.346 | 0.847 |
| 7 Apr. |        |         |       |        |
| Heat treatments | 2 | —      | 0.111 | 0.494 | 0.439 |
| Unheated vs. heat | 1 | —      | 0.285 | 0.264 | 0.281 |
| Soil heat vs. soil + air | 1 | —      | 0.063 | 0.930 | 0.525 |

*Planting dates were analyzed separately. ANOVA = analysis of variance.

### Table 2. The effect of targeted heat treatments on accumulated chilling degree-hours (base 0 °C) for three planting dates in 2009.*

| Planting date | 1 Apr. | 15 Apr. | 1 May | 15 May |
|---------------|--------|---------|-------|--------|
| 17 Mar.       |        |         |       |        |
| Unheated control | 138    | 365     | 647   | 956    |
| Soil heat     | 142    | 376     | 665   | 980    |
| Soil + air heat | 99     | 257     | 444   | 647    |
| 30 Mar.       |        |         |       |        |
| Unheated control | 21     | 138     | 290   | 370    |
| Soil heat     | 17     | 133     | 263   | 321    |
| Soil + air heat | 22     | 111     | 209   | 260    |
| 7 Apr.        |        |         |       |        |
| Unheated control | —      | 39      | 147   | 253    |
| Soil heat     | —      | 36      | 122   | 176    |
| Soil + air heat | —      | 31      | 109   | 174    |

**ANOVA**

| df | P values |
|----|---------|
|    |         |
| 17 Mar. |        |         |       |        |
| Heat treatments | 2 | 0.005 | 0.004 | 0.003 | 0.003 |
| Unheated vs. heat | 1 | 0.030 | 0.030 | 0.024 | 0.022 |
| Soil heat vs. soil + air | 1 | 0.003 | 0.003 | 0.002 | 0.002 |
| 30 Mar. |        |         |       |        |
| Heat treatments | 2 | 0.705 | 0.286 | 0.069 | 0.072 |
| Unheated vs. heat | 1 | 0.744 | 0.301 | 0.065 | 0.051 |
| Soil heat vs. soil + air | 1 | 0.481 | 0.223 | 0.093 | 0.141 |
| 7 Apr. |        |         |       |        |
| Heat treatments | 2 | —      | 0.366 | 0.342 | 0.135 |
| Unheated vs. heat | 1 | —      | 0.278 | 0.189 | 0.058 |
| Soil heat vs. soil + air | 1 | —      | 0.366 | 0.592 | 0.967 |

*One chilling hour was accumulated when the average hourly temperature was between 0 and 10 °C. Planting dates were analyzed separately. ANOVA = analysis of variance.
Table 3. The effect of targeted heat treatments on pruning biomass for three planting dates in 2009 and 2010.\(^a\)

| Planting date   | Dry wt (g) | 2009 | 2010 |
|----------------|-----------|------|------|
| Early          |           |      |      |
| Unheated control | 57.7      | 16.4 |      |
| Soil heat      | 56.2      | 27.3 |      |
| Soil + air heat | 118.2     | 39.9 |      |
| Midseason      |           |      |      |
| Unheated control | 53.4      | 21.6 |      |
| Soil heat      | 37.7      | 26.2 |      |
| Soil + air heat | 45.0      | 44.2 |      |
| Late           |           |      |      |
| Unheated control | 7.4       | 32.5 |      |
| Soil heat      | 6.2       | 69.9 |      |
| Soil + air heat | 14.1      | 61.5 |      |

ANOVA  

df  
P values  

Early  
Heat treatments  2  0.003  0.084  
Unheated vs. heat  1  0.016  0.035  
Soil heat vs. soil + air  1  <0.001  0.138  
Midseason  
Heat treatments  2  0.422  0.125  
Unheated vs. heat  1  0.120  0.112  
Soil heat vs. soil + air  1  0.423  0.077  
Late  
Heat treatments  2  0.258  0.052  
Unheated vs. heat  1  0.446  0.012  
Soil heat vs. soil + air  1  0.096  0.466  

\(\text{aAll plants were pruned on 12 May 2009 and thus analyzed separately. In 2010, all plants were pruned 38 d after planting. The interaction of planting date and heat treatment in 2010 was not significant. ANOVA = analysis of variance.}\)

Table 4. The influence of planting dates and targeted heat treatments on early and total marketable tomato yields in 2009 and 2010.

| Planting dates | Marketable yield (kg/plant) | Early\(^b\) | Total\(^c\) | Early\(^b\) | Total\(^c\) |
|----------------|----------------------------|-------------|-------------|-------------|-------------|
| Early          |                           | 2009        | 2010        | 2009        | 2010        |
| Early          |                           | 2.04        | 5.14        | 1.21        | 4.55        |
| Midseason      |                           | 1.71        | 4.62        | 0.81        | 4.34        |
| Late           |                           | 0.72        | 4.15        | 0.61        | 4.08        |

Heat treatments  
Unheated control | 1.20 | 4.34 | 0.67 | 4.34 |
Soil heat | 1.39 | 4.60 | 1.00 | 4.38 |
Soil + air heat | 1.87 | 4.96 | 0.96 | 4.25 |

ANOVA  
df  
P values  

Planting dates\(^d\)  
Early vs. other  1  <0.001  0.022  <0.001  0.104  
Midseason vs. late  1  <0.001  0.196  <0.001  0.149  

Heat treatments  
Unheated vs. heat  1  0.002  0.163  0.014  0.875  
Soil heat vs. soil + air  1  0.006  0.326  0.750  0.592  

Planting × heat Interaction  4  0.012  0.178  0.665  0.585  

\(\text{\(^a\)Early marketable yield (first six harvests each year).}\)  
\(\text{\(^b\)Total marketable yield includes the sum of No. 1 and No. 2 quality fruits (small, medium, large) only.}\)  
\(\text{\(^c\)Planting dates: early (17 Mar. 2009 or 19 Mar. 2010); midseason (30 Mar. 2009 and 2010); late (7 Apr. 2009 or 9 Apr. 2010).}\)  

ANOVA = analysis of variance.
should consider inexpensive ways to heat the soil and/or air. The results of this study showed significantly higher early-season growth and yields, resulting in positive economic returns. However, supplemental heating was not economically beneficial for later plantings and did not significantly increase total marketable tomato yield. Although more research is needed for detailed enterprise budgets that include heating options, it appears from our research that earlier production generated from modest targeted heat additions was more than sufficient to provide a good return on the investment.

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