Heating requirements for winter hydroponic lettuce production

Alex Miller
Graduate student,
Horticulture and Landscape Architecture
Purdue University

Krishna Nemali
Assistant Professor,
Controlled Environment Agriculture
Horticulture and Landscape Architecture
Purdue University

Winters in the Midwest are generally harsh. The daily average temperature during winter months (November to February) in Indiana is 41.2°F, with many nights falling below 23.8°F (https://iclimate.org/climate_fact_sheet/). This average is significantly lower than the optimal growth temperature (65 to 75°F) for many crops, and few crops would survive below 28°F (Hatfield and Prueger, 2015). Thus, heating is essential to increase survivability and provide optimal growth environment during winter in Indiana greenhouses. Lettuce is one of the major leafy greens grown in hydroponic greenhouses and can provide year-round income to Indiana hydroponic growers. However, the cost of heating can be high during winter, making it a very risky crop for greenhouse growers. It is important for growers to know how to calculate whether the cost of heating is worth the increase in yield for their crop. The purpose of this Extension article is to (i) Increase grower's knowledge on heating requirements/costs in hydroponic lettuce production; and (ii) Develop fundamental information on the effectiveness of using heated hydroponic solution while maintaining a relatively cooler air temperature in hydroponic lettuce production.

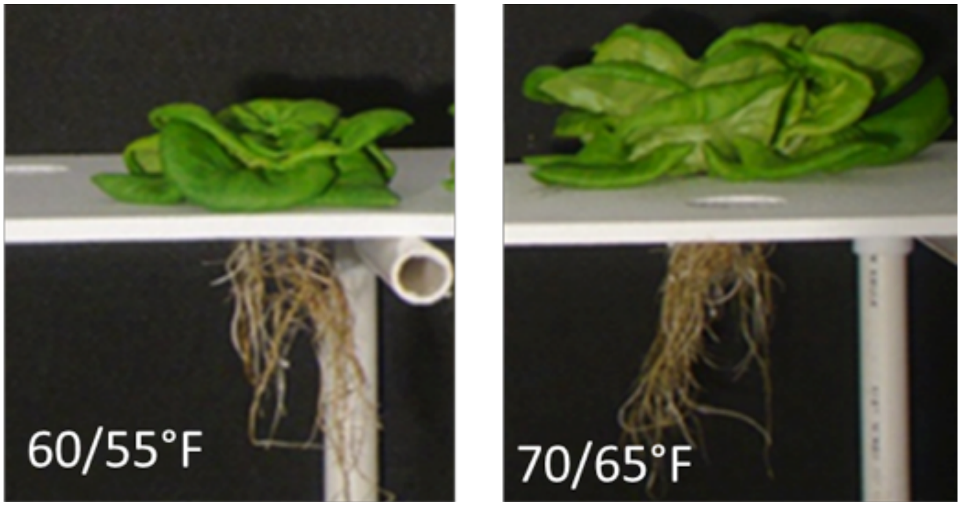


Figure 1. Butterhead lettuce var. Rex grown continuously under tightly maintained air temperature of 60/55°F and 70/65°F for 28 days.

(i) Heating requirements in hydroponic lettuce production

a. Can lettuce grow normally at cooler air temperature? Being a cool season crop (Maynard and Hockmuth, 2007) lettuce may grow normally at a lower temperature. In our experiment, we tightly maintained air temperature for butterhead lettuce var. Rex at 60/55°F (cooler conditions) and 70/65ºF (warmer conditions) during light/dark periods, respectively, for a period of 28 days and found that plants grown at 70/65ºF were considerably larger than plants grown at 60/55ºF (Figure 1). The average shoot fresh weight per plant was 0.04 and 0.16 lbs. when grown at 60/55ºF and 70/65ºF, respectively. Results from this study suggests that lettuce growth is nearly three times faster at greenhouse temperature of 70/65°F than at 60/55°F. However, higher temperatures require additional heating costs, which will affect profits. Growers need to have knowledge on calculating heating costs for maintaining a specific temperature in the greenhouse.

b. Calculating greenhouse-heating costs. To help growers calculate heating costs, the United States Department of Agriculture has developed software called "Virtual Grower." It can be downloaded for free from the internet at www.virtualgrower.net (Frantz et al., 2010). Details of calculations are described below.

To calculate the heating cost, we must first estimate the heat requirement, or Q (BTU/hr), for maintaining a target air temperature inside a greenhouse. For this, we need to know information on the following three variables:

(i) difference between target temperature and outside air temperature (ΔT)

(ii) surface area (A) of the greenhouse, and

(iii) overall heat transfer co-efficient (U) of the greenhouse covering material.

From this information, heat needed to maintain desired temperature inside the greenhouse is calculated as follow:

$Q = U \times A \times \Delta T$

For calculating the difference between target and outside air temperatures, one can assume an average winter temperature for the region. For more accurate calculations, growers can use daily average temperature. If growers are interested in identifying the required capacity of a heating unit, it is recommended that the lowest air temperature observed in the region be used in calculations.

The following formulas can be used for calculating surface area of common designs, such as A-frame (glass) and Quonset (high-tunnel) style single-bay greenhouses (Figure 2):

$$Surface\ area_{AFrame} = 2(A \times C) + 2(B \times C) + 2(E \times B) + (A \times D)$$

$$Surface\ Area_{Quonset} = \frac{\pi}{2}(A \times B) + \pi(\frac{A^2}{4})$$

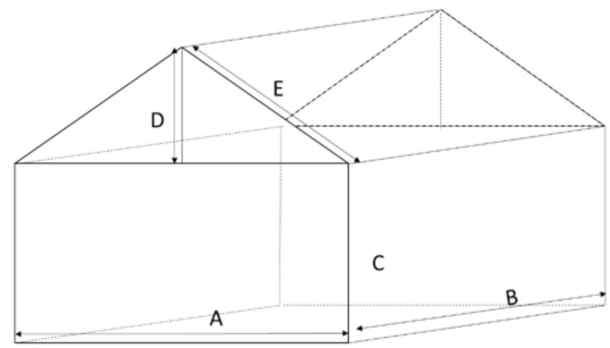
In the above formula, π is 3.14, and A, B, C, D and E are dimensions of the structure (Figure 2).

The U-value indicates BTU/hr heat lost through the material through conduction and radiation from an area of one ft^2 for every °F difference in temperature between the inside and outside air (approximate value). The values for different covering materials can be found at this link (https://www.greenhousecatalog.com/greenhouse-insulation).

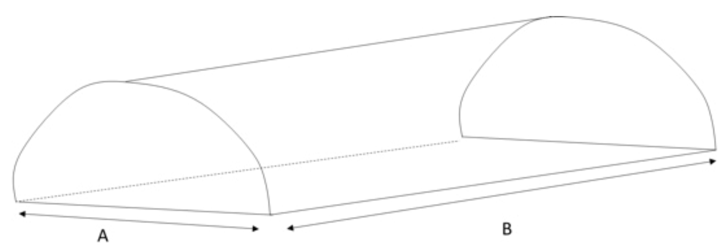
Now let's calculate the heating requirement (BTU/hr) for the A-frame and Quonset structures as shown in Figure 2. Let's assume that the air temperature is maintained at 70°F for 16 h during the light period and at 60°F for 8 h during the dark period, to maintain a daily average air temperature of 66.6°F {[(70 × 16 h) + (60 × 8 h)]/24 h}. We further assume that the average outside air temperature is 30°F during the 24-h period, and the A-frame and Quonset structures are covered with 10 mm double polycarbonate sheeting and 6 mm double polyethylene film, respectively. U-values for 10 mm double polycarbonate and 6 mm double polyethylene sheets are 0.55 and 0.70 BTUft2/hr/°F, respectively (Sanford, 2011). In both cases, let's assume that propane is used as fuel to heat the air.

The heating requirement for maintaining an A-frame or Quonset greenhouse (Figure 2) at 66.6°F is 135,878 or 170,860 BTU/hr, respectively (see Table 1 and notes). A gallon of propane will approximately produce 91,000 BTU/hr, and the price of propane is approximately $2.50/gal. By using these values, the daily cost to maintain an A-frame or Quonset greenhouse at the target temperature is therefore $89.40 and $112.80, respectively. These costs are achieved by multiplying ΔT, U and A values (see Table 1) to obtain Q value and later dividing Q values by 91,000 (i.e., BTUs produced by a gal of propane) to obtain gallons of propane used per hour. Then gal/hr is multiplied with 2.5 (i.e., dollar cost of propane) and 24 (as heating is needed entire day to maintain target temperature) to obtain heating cost per day. The cost per day can be used to estimate heating costs for a production cycle.

The higher heating cost of the Quonset greenhouse (seen in Table 1) is attributed to higher U-value of the double polythene compared to the double polycarbonate. However, the cost can be lowered in a Quonset greenhouse by selecting polythene film that has an Infra-Red (IR) blocker, which will lower the U-value from 0.7 to 0.5.



A = 30', B= 100', C = 10',
D = 5' and E =20'



A = 36' and B= 100'

Figure 2. A-Frame and Quonset style greenhouse structures used for heating calculations in Table 1

Table 1. Heating costs to maintaining the A-Frame and Quonset style greenhouses as shown in Figure 2 at set temperatures (70°F/60 for 16 h and 60°F dark) for 8 hours.

Structure	Inside Temp.	Outside Temp.	ΔT[1]	U[2]	A[3]	Q[4]	Propane Used[5]	Cost[6]
	(°F)	(°F)	(°F)	(BTU/ft^2 °F hr)	(ft^2)	(BTU/hr)	(gal/hr)	($/day)
A-frame	66.6	30	36.6	0.55	6,750	135,878	1.49	89.40
A-frame	66.6	30	36.6	0.7	6,669	170,860	1.88	112.80

[1] ΔT is difference between inside and outside temperature; 2 U-value is overall heat transfer co-efficient; [3] Surface area (include sides and top but not floor); [4] Heat energy needed is calculated as $Q = U \times A \times \Delta T$; [5] 1 gal of Propane gives 91,000 BTU/hr; [6] Cost of Propane is $2.50/gal.

(ii). Effectiveness of using heated hydroponic solution

The "conventional method" of heating greenhouse air is not efficient because plants occupy a small space inside the greenhouse while the entire greenhouse is heated. Published research indicates that lettuce growth can be significantly affected by changes in nutrient solution temperature when ambient air temperature is constant (Sakamoto and Suzuki, 2015). We conducted an experiment using butterhead lettuce and heated nutrient solution under suboptimal air temperature conditions. In this experiment, we wanted to (a) identify the optimal temperature of the nutrient solution for maximizing butterhead lettuce growth when air temperature is maintained at 60/55ºF (light/dark) and (b) compare heating efficiency (crop yield per ºF rise in temperature) for different solution temperatures.

This study was performed in a climate-controlled growth chamber (Model E15, Conviron) to ensure tight control of ambient air temperature and light intensity during production. Seeds of butterhead lettuce (*Lactuca sativa* var. 'Rex') were germinated at 68 (°F) in 1-inch rockwool cubes placed on sub-irrigation trays. After 10 days of germination, seedlings were transferred to a custom-built hydroponic culture system (Figure 3). This system consisted of a reservoir (Sterilite Tote, 15 gal; 25.75" x 17.25" x 11.875") and production tray (Uline, Tote Boxes, 22" x 17" x 5"). A one-inch thick styrofoam sheet (24" x 12") with holes for net pots (FasterHarvest, 2.3" x 2.3" x 2.1") was placed on top of the tray. Germinated seedlings were placed inside the net pots, which were spaced 8" x 6" apart in each tray. A total of six plants were grown in a tray. The reservoir contained approximately 10 gallons of nutrient solution. An inch of nutrient solution, simulating a constant flood table system, was recirculated between the reservoir and trays using a submersible pump (Aquanique, 50 GPH). Flexible tubing from the pump was connected to the inlet of the tray. The outlet of the tray drained directly into the reservoir. An aquarium heater (Uniclife, 50 watt) was used to increase the nutrient solution temperature in the reservoir (Figure 4). Four similar production systems were built to conduct the experiment.

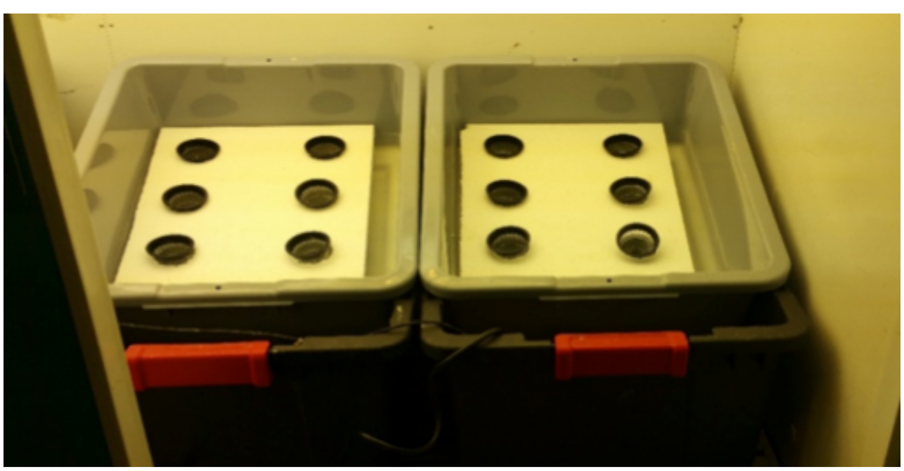


Figure 3. Custom built hydroponic production systems consisting of reservoirs, trays, styrofoam sheets and net pots

The ambient temperature was maintained at 60/55ºF (light/dark) inside the growth chamber. Plants received approximately 11.5 mol m^{-2} d^{-1} of light during a 16-hour photoperiod. The nutrient solution was maintained at an EC of 1.2 and pH range of 5.5 to 6.5. The nutrient solution was prepared by mixing 20-10-20 (20N, 4.4P, 16.6K) and

Figure 4. Aquarium heater used for increasing the temperature of nutrient solution inside the reservoir. Note the dial for temperature set points on the aquarium heater.

15-5-15 (15N, 2.2P, 12.5K) water-soluble formulations (Peters Professional) in a 3:1 ratio. Fresh nutrient solution was added to the reservoirs twice a week during the study. In a single replication, plants were grown under four different nutrient solution temperature treatments. The solution temperature set points were 60, 63, 67 and 70ºF, while the measured average solution temperatures were 60.5, 64.5, 66.3, and 71.4ºF. The lowest temperature treatment was not heated. Nutrient solution temperature inside the reservoirs was measured twice a week for four weeks using an infra-red radiometer (Apogee, MI-230). This sensor measures the surface temperature of the solution, which is likely the lowest temperature due to increased evaporative cooling at the surface. The plants were grown for a period of 28 days. At harvest, the shoots and roots were separated, and shoot fresh and oven-dried weight was determined. In addition, we measured dry weight of roots.

Results show that crop growth was enhanced when the nutrient solution temperature was increased in our experiment (Figure 5). Maximum crop growth was observed under hydroponic solution temperature of 71.4 ºF

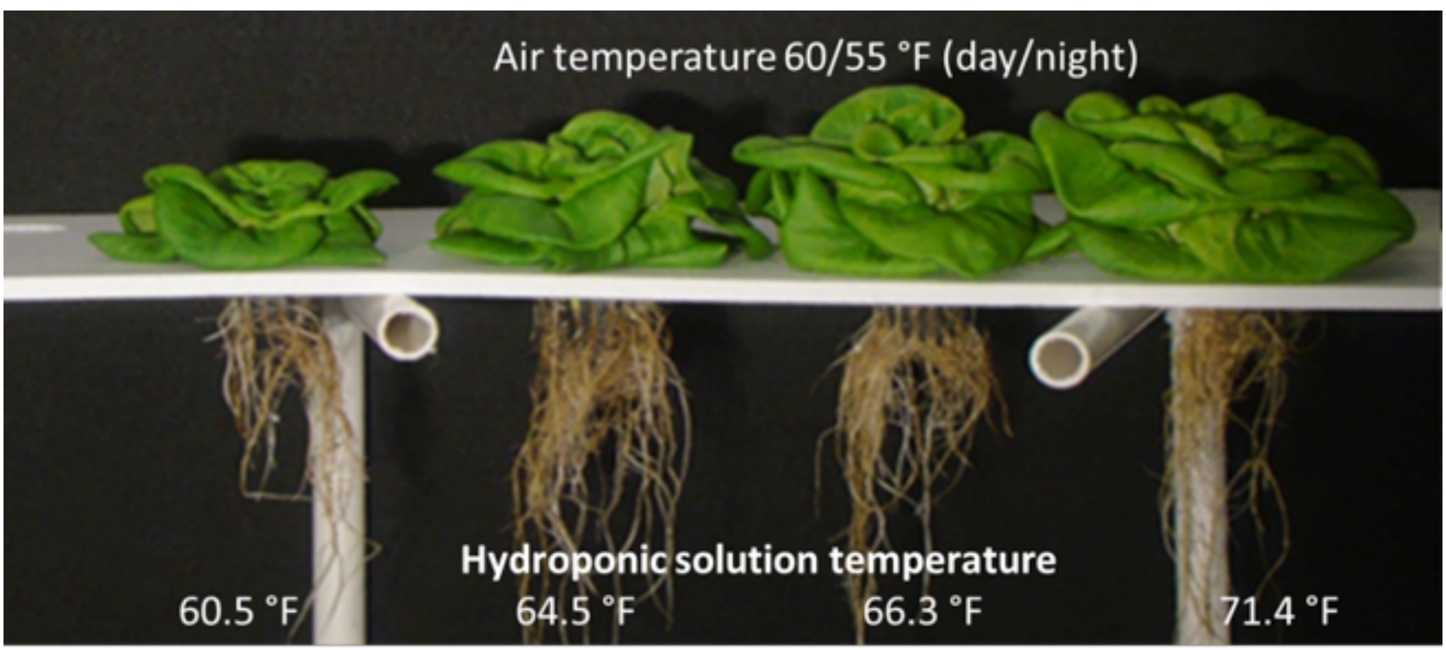


Figure 5. Butterhead lettuce var. Rex grown under different hydroponic solution temperatures when air temperature was maintained 60/55ºF (light/dark).

(Figure 6 and Table 2).

Our results indicate that shoot fresh weight increased when the nutrient solution temperature was increased, (Figure 5A). However, the increase in fresh weight was not linear but curvilinear with increasing solution temperature. This indicates that although fresh weight increased with increasing solution temperature, the increase was less at higher solution temperatures. The effect was more pronounced for shoot dry weight (Figure 5B), which clearly showed a solution temperature optimum of 68°F for maximum shoot dry weight and a decrease in shoot dry weight at a higher solution temperature level. Root dry weight showed an exponential increase with increasing solution temperature (Figure 5C). This suggests that more and more root growth happened with increasing solution temperature and may have been partly responsible for increased shoot fresh weight with increasing solution temperature. Better root growth may have aided in increased nutrient uptake, thereby enhancing shoot growth with increasing hydroponic solution temperature. We did not find any clear trends in shoot temperature of plants among different treatments, although it is not completely ruled out that high solution temperature may have increased shoot temperature.

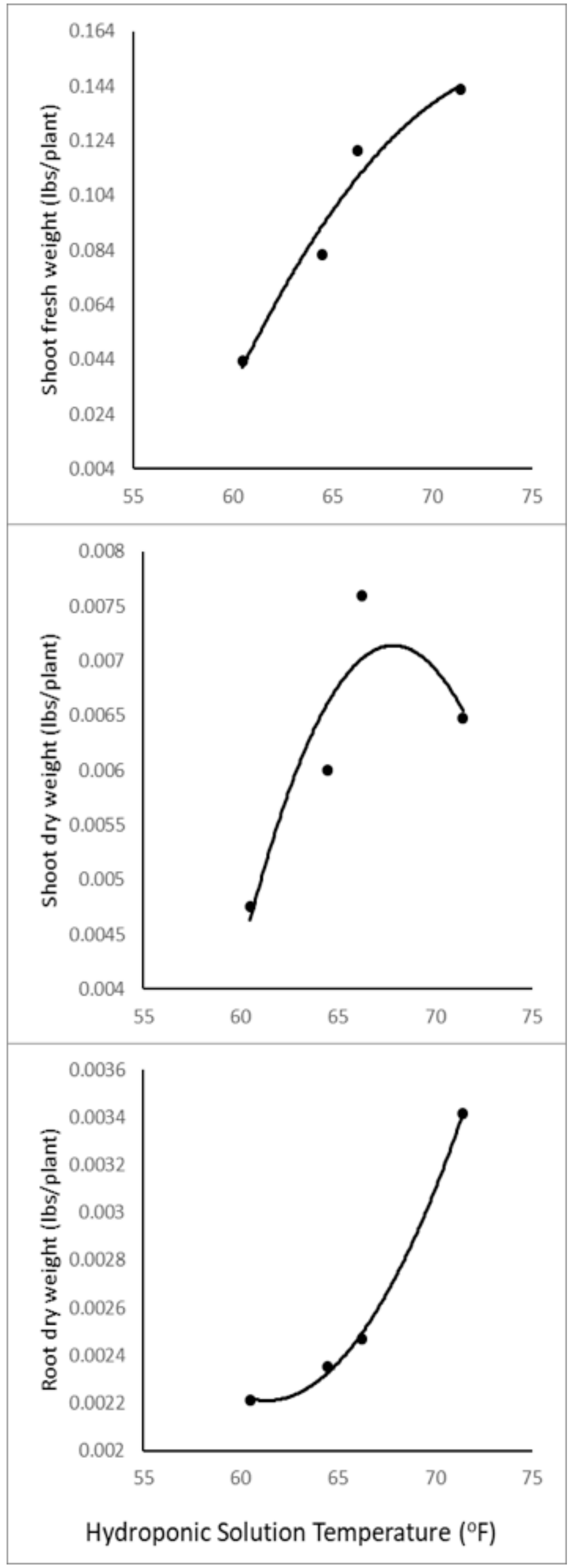


Figure 6. Relationship between increasing nutrient solution temperature and shoot fresh weight (A), shoot dry weight (B) and root dry weight (C) of butterhead lettuce var. Rex after 28 days of growth when air temperature was maintained at 60/55°F.

Heating efficiency (H_{eff}) was calculated as the ratio of the difference in crop yield (CY) over the difference in hydroponic solution temperature (T) between heated and unheated treatments.

Compared to the unheated treatment, heating efficiency increased with increasing nutrient solution temperature up to 66.3°F and decreased at the higher solution temperature (Table 2). This indicates that the optimal solution temperature for maximizing heating efficiency at an air temperature of 60/55°F is in the range of 66.3°F.

$$H_{eff} = \frac{CY_{treatment} - CY_{unheated}}{T_{treatment} - T_{unheated}}$$

Table 2. Observed differences in crop fresh weight and heating efficiency with increasing nutrient solution temperature

Solution Temp		Crop Fresh Weight	Heating Efficiency
(°C)	(°F)	lbs/ft²	lbs/°F ft²)
15.8	60.5	0.13	n.a.
18.1	64.5	0.24	0.027
19.0	66.3	0.36	0.040
21.9	71.4	0.42	0.027

In conclusion, our experimental results suggest that, despite being a cool season crop, warmer air temperature of 70/65ºF (light/dark) can result in faster growth of hydroponic lettuce than cooler air temperature (65/50ºF). Increasing nutrient solution temperature can be an effective way to enhance the growth of butterhead lettuce when cooler air temperature is maintained (60/55ºF light/dark). Maximum growth was observed when nutrient solution temperature was maintained at 71.4°F. However, heating efficiency was maximum when nutrient solution temperature was maintained at 66.3°F.

Acknowledgements

We would like to thank Drs. Petrus Langenhoven and Liz Maynard for their help as reviewers in writing this Extension article. We also would like to extend gratitude to the Indiana State Department of Agriculture for sponsoring research.

Sources

1. Climate Fact Sheet. (n.d.). Retrieved from https://iclimate.org/climate_fact_sheet/

2. Frantz, J. M., Hand, B., Buckingham, L., & Ghose, S. (2010). Virtual Grower: Software to Calculate Heating Costs of Greenhouse Production in the United States. HortTechnology, 778-785. doi:10.21273/horttech.20.4.778

3. Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. Weather and Climate Extremes, 10, 4-10. doi:10.1016/j.wace.2015.08.001

4. Maynard, D. N., & Hochmuth, G. J. (2007). Knotts handbook for vegetable growers. S.l.: Wiley InterScience.

5. Sakamoto, M., & Suzuki, T. (2015). Effect of Root-Zone Temperature on Growth and Quality of Hydroponically Grown Red Leaf Lettuce (Lactuca sativa L. cv. Red Wave). American Journal of Plant Sciences, 06(14), 2350-2360. doi:10.4236/ajps.2015.614238

6. Sanford, S. (2011). Reducing Greenhouse Energy Consumption - An Overview. In Energy Efficiency in Greenhouses (Ser. 4). ANRE.