Urban Food Production Season Extension Techniques

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Abstract: Urban food production has demonstrated many benefits to a city including improved nutrition (Reynolds et al., 2007), catalysts for economic redevelopment of disadvantaged communities through increased homeownership (Been and Voicu, 2006), and providing local jobs. This research extends these benefits year-round by providing season extension techniques such as a site selection process, structural design, and energy assessment. A process was developed to efficiently choose site locations that are good for urban food production. A structural loading analysis tool was developed to determine the dimensions of greenhouse ribbing needed to withstand snow load and the cost of the greenhouse. Season extension with a simple hoop-type greenhouse was documented at various set point temperatures and varying energy availability. For example, with a 23' x 50' simple hoop single glazed structure with 10' height, the growing season above 35 degrees F can be extended 72 additional days by adding the structure alone. With an additional 50,000 BTU heating energy, the growing season extends an additional 31 days.

Keywords: growing season extension, urban food production, site selection

Introduction

Urban, community food production is beneficial to the health, growth, learning, and wellbeing of a community. The surrounding community can produce fresh fruits and vegetables, leading to healthier food options. Typical food options for inner city neighborhoods, such as corner stores or gas stations, may be lacking in nutritional choices. Without readily accessible healthy food choices, obesity is an issue in these communities. Food production in the neighborhood gives the community a sense of belonging, and creates jobs. A boost in morale for the community will give the community a sense of pride and willingness to keep the neighborhood nice, leading to better neighborhood security.

Community garden research has shown the benefits of a garden and their significance in inner city neighborhoods. Community gardens have been shown to promote social health and community cohesion, as well as improved access to food, improved nutrition, increased physical activity and improved mental health of the community (Reynolds et al., 2007). Community gardens provided constructive activities, promoted developmental assets, and improved access and consumption of healthy foods for youth who were involved (Alaimo et al., 2008a). Gardens in low-income neighborhoods were four times as likely as non low-income gardens to lead to other issues in the neighborhood being addressed, reportedly due to organizing facilitated through the community gardens (Armstrong, 2000). Community gardens have a statistically significant positive impact on houses near the garden. The opening of a garden was linked to increasing rates of homeownership, becoming a catalyst for economic redevelopment of disadvantaged communities. (Been and Voicu, 2006). Community gardens decreased common barriers of fruit and vegetable consumption by lowering the cost of produce, increasing access, and eventually increasing acceptance of fruits and vegetables (Dibsdall, 2002). Adults with a household member who participated in a community garden consumed fruits and vegetables 1.4 times more per day than those who did not participate, and they were 3.5 times more likely to consume fruits and vegetables at least 5 times daily" (Alaimo et al., 2008b).Cleveland, Ohio is a good choice for an urban food production project because of its many vacant lots. The vacant lots are an eyesore to the community; using them for the food production project location is ideal.

The goal of this research is to extend growing season for urban food production. Season extension extends the benefits of community gardens year-round. It encourages local buyers to keep buying produce from local sources, rather than being forced to find another source during the winter season. Year-round production in community gardens will provide gardening and management jobs in the gardens year-round. Year-round positions are easier for management to fill and more convenient and beneficial to workers. This research will develop a method for selecting an optimal food production site location, design an optimal protective structure, quantify the energy requirements for various season extension growing needs, and investigate potential passive heating and heat storage solutions.

Importance of Developing Site Selection Process

Location of a food production site is very important. This analysis sought to identify the best site locations for food production based on criteria developed from literature review and current site location greenhouse practices. The Hough neighborhood in Cleveland, Ohio was analyzed to develop a method for selecting an optimal food production site location. Developing a method for analyzing various sites is useful to screen the large number of possible sites in an efficient process. For example, there are more than 500 vacant lots in the Hough area that was analyzed in this research. The method developed in this research can be used to efficiently narrow down a large number of potential food production sites in the future.

Site location criteria must consider horticulture criteria for crop yield and plant growth. City infrastructure must also be analyzed for potential energy sources. Factors such as sunlight, energy, human factors, watering access and site preparation must be taken into consideration. Nearby buildings influence energy access, wind break, and sunlight availability. Deciduous trees will let sunlight in during the winter months, unlike evergreen trees. Nearby retail stores are important for resale of produce. Nearby schools or high density population buildings (large apartment complexes) are important for human labor availability and sale of produce. Nearby sewer lines may be a viable source of residual heat energy. Site terrain must be considered for drainage and site preparation feasibility.

Importance of Structure Design Process

Using structures as a method of extending the growing season has been investigated in previous research including field tunnels, hoop houses, high tunnels, and floating row covers. Improved frost protection, wind protection, improved fruit/vegetable production, quality, and size have all been demonstrated varying costs for each of these types of structures (USDA NRCS, 2009). Previous research provides a general description of season extension techniques. The purpose of this research is to quantify season extension with different types of structures at different set point temperatures. This will allow growers to predict the amount of energy required for a specific structure type and crop selection. Depending on the crop desired, different heating and cooling set points will be required. A structure can extend the growing season at various set points, and supplementary heating combined with that structure will extend the growing season to the desired extension. A good protective covering is passive, low-cost, and extends the growing season by providing maximum energy from solar gain and minimum energy loss. The year-round production a structure gives will provide fresh produce and job opportunities all year. A protective cover can also help in reducing and reusing storm water waste. An optimal structure design is important to provide cost-effective season extension. The optimal structure design may also differ according to the specific site. For example, a lean-to structure requires a north-facing wall, but a wide-open site may require a hoop or gable type house. Providing a method for analyzing energy gain and cost of different structures is useful for urban food production purposes.

This research provides expectations for season extension and energy requirements based on different desired temperatures. Heating requirements can be determined for a desired crop selection or set point temperature and a certain structure type. This research allows the grower to pick crop selection based on desired season extension, or available energy sources. This research also provides an expectation of the energy required for a specific crop selection and season extension.

Importance of Energy Assessment for Season Extension

Some research has been done on winter crop selection, both with and without supplementary heating. Current literature states that some cold-hardy vegetables (such as spinach, lettuce, and other leaf or root crops) can be grown in a Maine located, non-heated greenhouse year-round (Coleman, 2009). Here, Coleman uses protected cultivation of the cold houses combined with floating row covers allowed the soil to act as a heat storage medium during the winter months. The same literature notes that minimal supplementary heat used to bring the temperature above the freezing point has a substantial positive effect on plant growth. Time from planting to maturity doubles in early February compared to the normal growing season for cool (above freezing) greenhouse and triples in a cold (unheated) greenhouse. Supplementary heating techniques will be investigated in this research, including grey water heat energy harvesting and using soil for energy storage. Year-round production has been demonstrated in cold weather climates, but additional heating (such as residual city waste heat) will allow broader crop selections. This research aims to investigate the feasibility of season extension with the availability of residual energy sources in the Hough neighbor and the typical weather data. This research will provide the optimal location and protective structure to maximize season extension with cost effectiveness.

Odum (2006) indicates that much investigation and research has been done in supplementary energy sources for greenhouses. Composting greenhouses heated with waste heat generated by compost, animal heated or bio-heated greenhouses, and using greywater heat energy have all been investigated. Greywater is seen as a possible energy source in Cleveland and will be investigated. Otherwise wasted energy from greywater systems of hotels, restaurants, or hospitals may also be a viable heat source for the greenhouse (RTC, 2008). Many thermal mass storage mediums are used in current practices including water, rocks, and concrete walls, but existing, on-site soil may be a viable alternative for heat storage.

Goals and Objectives

The goal of this research is to extend growing season by providing a protective structure and meeting heating requirements with residual energy from city buildings/infrastructure.

Objectives:

1. Develop an efficient site selection methodology for year-round food production in urban environments.
2. Design a low-cost passive protective structure for year-round food production in for urban food production.
3. Determine energy requirements for season-extension growing needs and investigate potential passive heating and heat storage solutions.

Methods:

Site Selection Process

Approximately 500 vacant lots from the Cleveland Land Bank database online were analyzed. This preliminary analysis covered from Superior Ave. to Chester Ave. between 55th St. to 105th St. in Hough, Cleveland, OH. A preliminary analysis was done using Google Earth (Google, 2009) to find the vacant lots and Google Street View to analyze surrounding buildings and trees.

The first analysis step was based on the sunlight criterion. A potential site location with houses or buildings directly south of the vacant lot can be eliminated immediately because light is obstructed from reaching the plants all day, especially in the winter with low sun elevation angles. This narrowed the list down to about 80 sites.

These sites were then analyzed with additional criteria and narrowed down further into the best sites of each type or category. Categories used included 1) wide open 2) greywater access 3) surrounding trees for summertime shading 4) proximity to brick houses for thermal mass heat collection and 5) proximity to schools. This was done to clean up the list. After a first round through the list, it was more clear what sites were good or bad. This narrowed the list down to 57 sites.

On-site visits verified the accuracy of Google Earth as a virtual site selection tool. In the future, this tool can be used to analyze sites for a variety of purposes with good accuracy. An on-site visit will be used to verify the criteria quickly, rather than analyze the site, tediously. Sites can be narrowed down earlier, in the virtual analysis stage. This should allow for fast analysis virtually rather than slow, tedious on-site analysis.

To quantify the data collected, a spreadsheet with data for each site analyzed was perfected. This spreadsheet (Figure 1) can be used to analyze different sites in the future, or to view data about an existing site for purposes other than this project.

An analysis weighting each of the criteria according to importance narrowed down the list to the 10 best locations. For this project's purposes, greywater energy access and evening (southwest) sunlight are the most important factors, while proximity to schools may be less important. Sewer line info was requested from the city about these 10 sites, to see if greywater residual energy can be captured. According to each site, certain structure types may be better than others. For example, a lean-to type structure requires a north-facing wall, while a hoop structure may better suit a wide-open lot. This is the reason it is useful to record data about each site, and why the process of developing criteria is confusing.

An ideal site can be quantified generally as the following: located on the north side of a street running east and west, with multiple vacant lots. Proximity to schools, retail areas, and high density populated areas are a plus. City lots typically have a house in the middle, and trees/vegetation (if any) in the back of the lot. Multiple lots on an east-west street will allow for maximum sunlight from morning to evening by reducing the chance of shading by nearby houses. This also increases the chance of house on the north side, for thermal mass or rain collection purposes. Using this general form, the first step can be performed in a quicker, more general way, instead of viewing each site individually. Irregular lots, such as corner lots, or multiple through-lots on a north-south bound street may be an exception to this general rule and should be noted.

Structure Design and Season Extension Assessment Process

Next, requirements for season extension are analyzed. The analysis showed season extension potentials of a protective structure, and two levels of supplemental heat. Adding a covering or structure to a site with no additional supplementary heating can extend the typical growing season by solar gain. Typical growing season for Cleveland urban community gardens is assumed to be May 1 through October 31. This analysis assumed that no extra heating requirements were needed for these 184 days. The analysis focused on the remaining 181 days left in the year, from November 1 – April 31. Season extension that can be expected with a simple hoop structure (both single and double glazed were analyzed) and typical local weather data was determined using the Greenhouse Energy Harvesting Analysis Tool (GEHAT, Figure 2) (Lee, 2010).

Season extension was analyzed both before and after the typical growing season. Cumulative heating requirements before May 1st and cumulative heating requirements after October 31st were determined. This data will determine the total amount of energy required for a desired length of season extension at a specified temperature.

Typical weather data was taken from the National Solar Radiation Database (NSRDB) online, from the Typical Meteorological Year Files (TMY3) for the Cleveland Hopkins International Airport. The TMY3 data described here were produced using input data for 1976-2005 from the 1961-1990 NSRDB, Version 1.1 and the 1991-2005 NSRDB update. The NSRDB method for selecting the most typical weather data is explained below.

"The Sandia method is an empirical approach that selects individual months from different years of the period of record. For example, in the case of the NSRDB that contains 30 years of data, all 30 Januarys are examined, and the one judged most typical is selected to be included in the TMY. The other months of the year are treated in a like manner, and then the 12 selected typical months are concatenated to form a complete year. Because adjacent months in the TMY may be selected from different years, discontinuities at the month interfaces are smoothed for 6 hours on each side. The Sandia method selects a typical month based on nine daily indices consisting of the maximum, minimum, and mean dry bulb and dew point temperatures; the maximum and mean wind velocity; and the total global horizontal solar radiation. Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns" (NREL, 2008).

This GEHAT analysis used NSRDB data for solar radiation, relative humidity, and air temperature. Solar radiation is described as the "amount of solar radiation received from the sky (excluding the solar disk) on a horizontal surface during the 60-minute period ending at the timestamp," measured in W/m^2. Relative humidity is described as the "relative humidity at the time indicated," measured in percent. The air temperature is described as "the dry-bulb temperature at the time indicated," measured in degree C.

The structure assumed in this analysis was a simple hoop greenhouse with a 23' x 50' footprint and 10' height. This analysis analyzed season extension with a single glazed structure and a double layer glazed structure for comparison. Materials assumed for the single glazed structure were single layer plastic film roof area (U-Factor = 1.2), single layer plastic film end wall area (U-Factor = 1.2), and an uninsulated perimeter (U-Factor = 0.8). Construction type assumed was a new construction, which assumes an air exchange rate of 0.4 changes/hour. A net solar transmittance value of 0.76 was experimentally determined using light sensors and solar radiation weather data (OARDC, 2010) over a period of three days in a single layer plastic film high tunnel greenhouse. Materials assumed for the single glazed structure were double layer plastic film roof area (U-Factor = 0.7), double layer plastic film end wall area (U-Factor = 0.7), and an uninsulated perimeter (U-Factor = 0.8). Construction type assumed was a new construction, which assumes an air exchange rate of 0.4 changes/hour. A net solar transmittance value of 0.54 was assumed.

All weather data and structure assumptions were analyzed using the GEHAT tool. GEHAT gives values for Daily and Hourly Heating Requirements, as well as Daily and Hourly Cooling Requirements for any specified set points. Four different set points were used. Heating set points were set at 35, 45, 55, and 65 degrees F. Cooling set points were set at 45, 55, 65, and 75 degrees F, respectively. Any specific day was determined to extend the growing season if every hour in that day (midnight to midnight) was above the heating set point. In other words, the extra heating requirement was zero for that specific day.

This research analyzed season extension without a structure (typical growing season), with a structure (and no supplementary heating), with a structure and 50,000 BTU supplementary heating per day, and with a structure and 100,000 BTU supplementary heating per day.

When adding a structure, energy gain from solar radiation inside the structure must be assumed. This analysis assumed that the 10 percent of the solar heat trapped in the protective structure (amount of energy needed to satisfy the cooling set point) per day can be stored for later heating need. If this value (ten percent of the daily cooling requirements) is greater than the daily heating requirements, the day can be counted toward season extension. The number of days that a structure can extend the season with certain levels of available supplementary heating energy was also determined.

In addition to analyzing heating and cooling energy requirements, cost of the structure should be analyzed. Several different types of protective structures were analyzed with the criteria of cost of materials, solar gain, and energy loss. Snow load and glazing angle influence cost of materials. The glazing angle also is directly linked to solar gain. Energy loss is related to the structure surface area. Hoop, Gable, and A-frame structure types were analyzed with these criteria. A Structure Loading Analysis Tool (SLAT) (Figure 3) was developed to help any user determine the minimum diameter of ribbing material required for a specified material, greenhouse dimensions, snow load, and safety factor. This tool will also calculate the surface area based on changing the glazing angle. A user can input glazing angle, greenhouse width, rib spacing, number of ribs, a snow load (assumed 30 lbs/ft^2 for this analysis), an allowable bending stress (based on the materials chosen by the user) and a safety factor. SLAT will output the diameter required to hold the snow load, and the greenhouse roof and endwall surface area. Diameter required is important information relating to the cost of materials and the surface area directly relates to energy loss. The glazing angle is set as an input rather than greenhouse length, width, and height, so that the user can choose the optimum glazing angle according to location of greenhouse, giving maximum energy gain. The user can calculate estimated cost of the greenhouse by inputting cost of materials. This tool does not account for wind load or snow sliding off the structure. Higher roof angles will shed snow but are more vulnerable to wind load. The SLAT tool can be used in conjunction with the GEHAT tool to calculate energy considerations.

Heat Storage Investigation

After the heating requirements are determined, it is necessary to design an energy harvesting system. Designing a system to capture solar energy is beyond the scope of this research at this time, but soil was investigated as a heat energy storage medium, after energy collection. An experiment measured soil temperatures over several days to determine the feasibility of using wet or dry, existing on-site soil as a heat energy storage medium.

The first experiment collected temperature data from four soil locations, two inside the greenhouse, and two outside the greenhouse. Temperatures were taken at the surface and 6 inches below the surface at each of the four locations. Temperatures were recorded every hour as an average hourly temperature. Outside and inside solar radiation, outside and inside air temperature, and relative humidity were also recorded for the same time period. A hose dripped water onto one location inside and one location outside. The wet soil was expected to show an increased heat transfer efficiency over the dry soil.

Another purpose of the soil temperature experiment is to find lag times between peak air temperature and peak soil temperatures. Lag times will show us the typical lag between air temperature and soil temperatures. Soil temperature data will not be available for the potential site locations, so potential heat storage must be predicted using typical weather data for each site.

Dry soil is expected to show poor heat transfer compared to wet soil. This means the heat energy is not transferred as efficiently from the air to the surface soil and then to the soil below the surface. In this case, the difference between the peak surface soil temperature and the peak below surface soil temperature will be high. Adding water is expected to increase the heat transfer efficiency. This will be shown if the peak surface soil temperature and the peak below surface soil temperature are closer in value than before. If the wet surface soil moves heat below the surface more efficiently, the wet soil is better suited as a heat storage medium.

Results:

The site selection process detailed in the Methods section provided a good list of criteria that can be used to narrow down the best of new potential site locations, as well as a good quantification of data on the list of sites already analyzed. Sewer line information was requested from the city for the top ten best site locations to determine the feasibility of capturing residual energy at these locations. This methodology can be applied to any list of potential food production site locations for an efficient and effective process.

The effect of season extension using various treatments at different set point temperatures is shown in Figures 4, 5, 6, and 7 for a single glazed 23’ x 50’ hoop house, assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. The same data is shown for an identical *double glazed* hoop house in Figures 8, 9, 10, and 11. The GEHAT tool analyzed the structures using typical weather data for the Cleveland Hopkins International Airport (NREL 2008). This analysis assumes no heat energy is required during the typical urban garden growing season of

May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

Expected heating requirements per day with various temperature set points is shown in Figures 12, 13, 14, and 15 for a a single glazed 23' x 50' hoop house, assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. The same data is shown for an identical *double glazed* hoop house in Figures 16, 17, 18, and 19. This GEHAT analysis shows the daily Heating Requirements to keep the structure above the set point for each day after October 31 using typical weather data for the Cleveland Hopkins International Airport (NREL 2008). The graph can determine the number of days the growing season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

Total cumulative heating requirements for season extension earlier than May 1 at various temperature set points. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy, as shown in Figures 20 and 21. The same data is shown for an identical *double glazed* hoop house in Figures 22 and 23. This analysis shows the cumulative total heating requirements to keep the structure above the set point for a certain number of days before May 1. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy. The graph can determine the amount of energy required for a certain desired season extension at any set point. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31.

The soil temperature experiment graphs show outside above soil temperatures (Figure 24), outside below soil temperatures (Figure 25), inside above soil temperatures (Figure 26), and inside below soil temperatures (Figure 27). This same set up was repeated in a second experiment collecting data for wet soil. The graphs for the wet soil experiment are: inside above temperatures (Figure 28), inside below temperatures (Figure 29), outside above temperatures (Figure 30), and outside below temperatures (Figure 31).

Using soil as an energy storage medium was seen to be a viable option. The soil temperatures are all more stable than air temperature, making soil a good energy storage medium. As expected, air temperature lags solar radiation: outside lagging more than inside temperatures. Soil temperatures taken below the surface lag surface soil temperatures, with similar results inside and outside the greenhouse. The peak soil temperature, inside at the surface is surprisingly higher than the peak inside air temperature as shown in Figure 26. This is because the black ground covering absorbs heat at a high efficiency.

Dry soil was expected to show poor heat transfer. This means the heat energy is not transferred from the air to the surface soil and then to the soil below the surface. In this case, the difference between the peak surface soil temperature and the peak below surface soil temperature will be high. Figure 32 shows that the difference between the peak above and below temperatures in the dry soil are similar to the wet soil. This shows no difference in heat transfer efficiency. However, the wet soil temperatures above and below had a faster time to peak than dry soil. The dry soil temperatures decreased more rapidly throughout the night than wet soil temperatures. The wet soil temperatures below held their temperatures longer than dry soil. All of this allows for a better temperature gradient between the soil and air temperature: more convenient for the purposes of this research.

Adding water will increase the heat transfer efficiency. This is shown by the less rapid decrease in temperature throughout the night, as well as the faster times to peak temperatures. The wet surface soil moves heat below the surface more efficiently so the wet soil is better suited as a heat storage medium.

Discussion:

The site selection process detailed in this research saves time and money when choosing good sites for food production. For example, the virtual selection narrowed the initial 500 sites down to 57. This eliminates almost 90 percent of the field before site visits. In practice, this method was found to be very efficient when comparing site visits to virtual expectations. This means that the virtual assessment can be trusted to narrow down potential sites to the best sites. Site visits are still necessary to validate the current status of these lots, as satellite imagery may be outdated if lots are sold and built on. Virtual site assessment will prove to be more cost-effective at narrowing the initial list of potential sites than on-site visits, with similar accuracy.

The next step in the site location process is taking the sewer line information and determining the feasibility of capturing residual energy at each of the ten sites best locations marked using the Site Criteria spreadsheet. These sites should be paired with a good protective structure design according to the type of site and the SLAT tool's suggestions. Using the GEHAT tool with typical weather data, and the amount of residual energy that can be captured through the sewer line, exact energy predictions can be made. In the future, it will also be useful to add criteria developed from entomology and horticulture considerations to existing criteria to provide a more complete site selection analysis process.

Adding a structure was seen to extend the growing season for all set points. Benefits of different types of structures can easily be determined. Cost of materials can be determined, as well as cost of heating energy, for any type of structure. This research is very useful in finding the cost of a specific structure and determining the expected growing season of that structure.

The SLAT tool can use some improvements. Wind loading should be considered in addition to show loading. It would also be useful to add different shapes of ribbing pipe material, such as hollow tube piping or rectangular members. Adding a lean-to type greenhouse to structure types would also be useful.

The next step for the soil temperature experiment is to collect more data to verify and clarify results. The outside temperatures seem to peak twice per day, which is not consistent with solar radiation. There is consistently another peak at night. Some outside heat source may be affecting our experiment. Also, the dry soil temperatures have a similar difference between peak surface and below temperatures than the wet soil, indicating the dry soil has as efficient heat transfer than wet soil. This is not expected. The wet soil is shown to be more efficient at holding heat energy longer and has a faster time to peak temperature, indicating a better heat transfer efficiency.

Conclusions

Virtual site assessment was found to be an accurate, cost-effective, and efficient to quickly analyze a large number of potential sites for urban food production. The process uses criteria relating to growing concerns, energy concerns, and sale concerns that are most useful for an urban food production project. The structure design process used in this research will provide the most cost-effective structure for a specific urban food production project, both energy efficient and materials efficient. Cost is an especially limiting factor in disadvantaged neighborhoods that are possible candidates for food production. The energy assessment techniques provided in this research can give expectations for season extension with a certain energy supply. It also can be useful in calculating the energy required for a certain desired growing season. On-site soil was found to be a good option for heat storage, but some unexpected results require additional study.

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Attachments:

		Light		Energy			Water/Site Preparation		Human (Labor/Sale)		Other
Category	Size	Orientation	Anything Blocking Light, Morning/evening sunlight?	Residential Greywater Sources?	Sewer Line Considerations	Wind Break	Terrain Considerations	Watering Access	Schools, community centers, churches	Retail Stores	Status of Neighborhood, other

Figure 1: A sample of the Site Criteria spreadsheet and the categories of criteria recorded for each site analyzed.

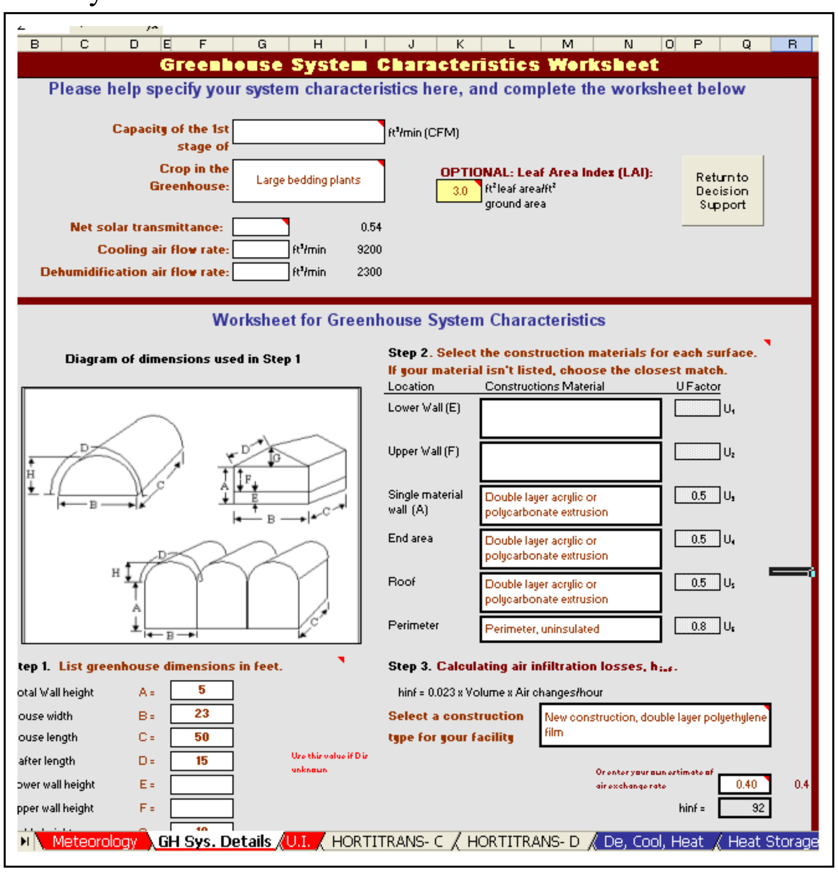
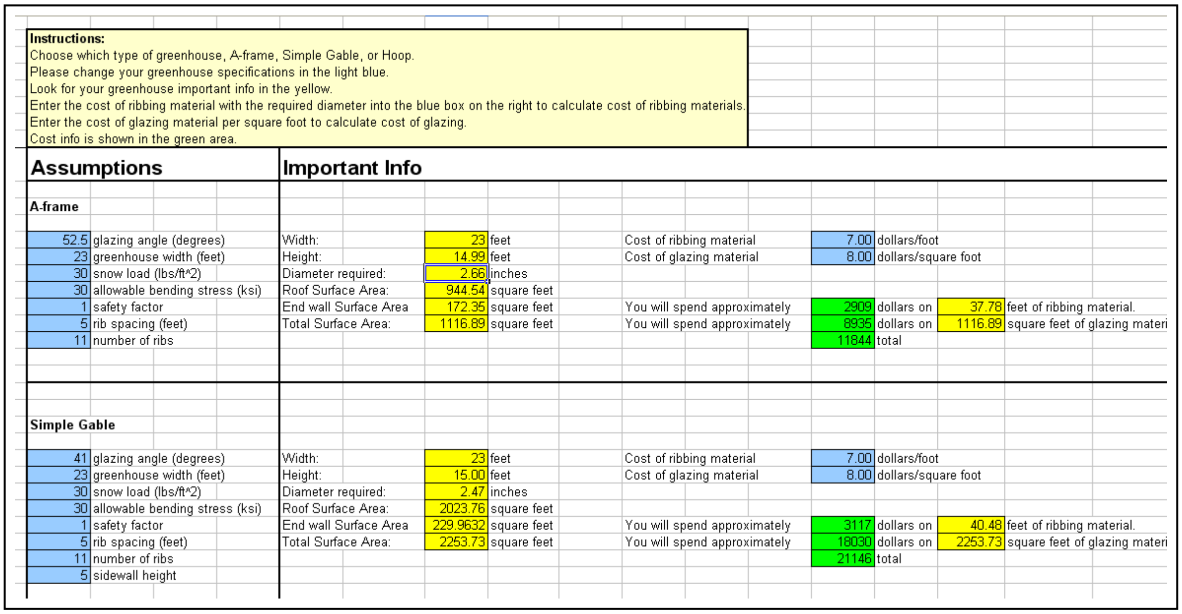


Figure 2: A screenshot of the Greenhouse Energy Harvesting Analysis Tool (GEHAT)



Instructions:
Choose which type of greenhouse, A-frame, Simple Gable, or Hoop.
Please change your greenhouse specifications in the light blue.
Look for your greenhouse important info in the yellow.
Enter the cost of ribbing material with the required diameter into the blue box on the right to calculate cost of ribbing materials.
Enter the cost of glazing material per square foot to calculate cost of glazing.
Cost info is shown in the green area.

Assumptions		Important Info								
A-frame										
52.5	glazing angle (degrees)	Width:	23	feet	Cost of ribbing material	7.00	dollars/foot			
23	greenhouse width (feet)	Height:	14.99	feet	Cost of glazing material	8.00	dollars/square foot			
30	snow load (lbs/ft^2)	Diameter required:	2.66	inches						
30	allowable bending stress (ksi)	Roof Surface Area:	944.54	square feet						
1	safety factor	End wall Surface Area	172.35	square feet	You will spend approximately	2909	dollars on	37.78	feet of ribbing material.	
5	rib spacing (feet)	Total Surface Area:	1116.89	square feet	You will spend approximately	8935	dollars on	1116.89	square feet of glazing materi	
11	number of ribs					11844	total			
Simple Gable										
41	glazing angle (degrees)	Width:	23	feet	Cost of ribbing material	7.00	dollars/foot			
23	greenhouse width (feet)	Height:	15.00	feet	Cost of glazing material	8.00	dollars/square foot			
30	snow load (lbs/ft^2)	Diameter required:	2.47	inches						
30	allowable bending stress (ksi)	Roof Surface Area:	2023.76	square feet						
1	safety factor	End wall Surface Area	229.9632	square feet	You will spend approximately	3117	dollars on	40.48	feet of ribbing material.	
5	rib spacing (feet)	Total Surface Area:	2253.73	square feet	You will spend approximately	18030	dollars on	2253.73	square feet of glazing materi	
11	number of ribs					21146	total			
5	sidewall height									

Figure 3: A screenshot of the Structural Loading Analysis Tool (SLAT)

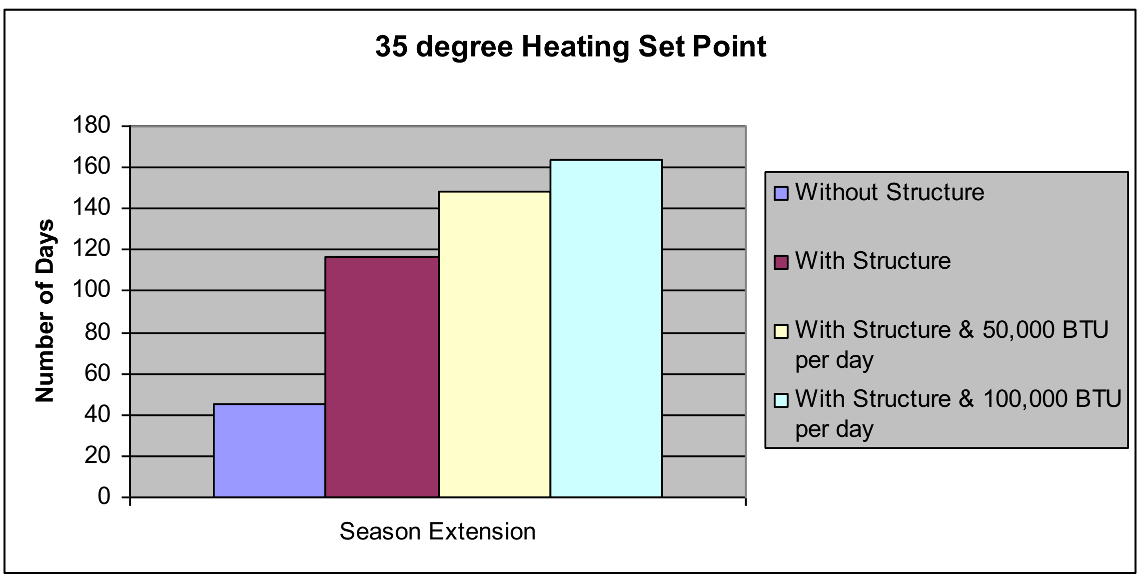


Figure 4: Effect of various treatments on the number of days that can be maintained above 35 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23’ x 50’ hoop house assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (35 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating(50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

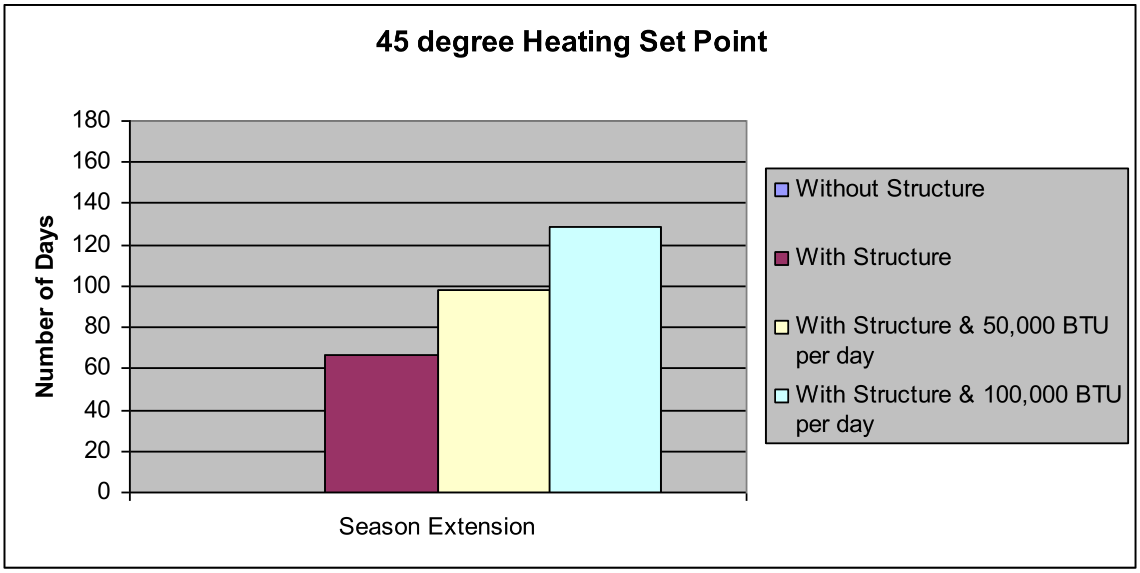


Figure 5: Effect of various treatments on the number of days that can be maintained above 45 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (45 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating(50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

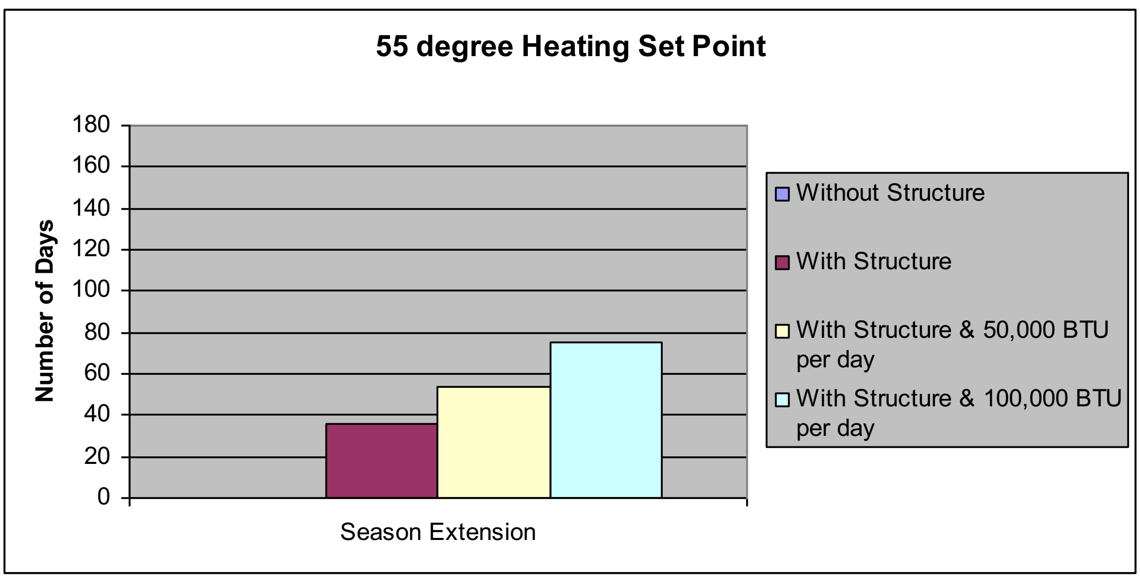


Figure 6: Effect of various treatments on the number of days that can be maintained above 55 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (55 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating(50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

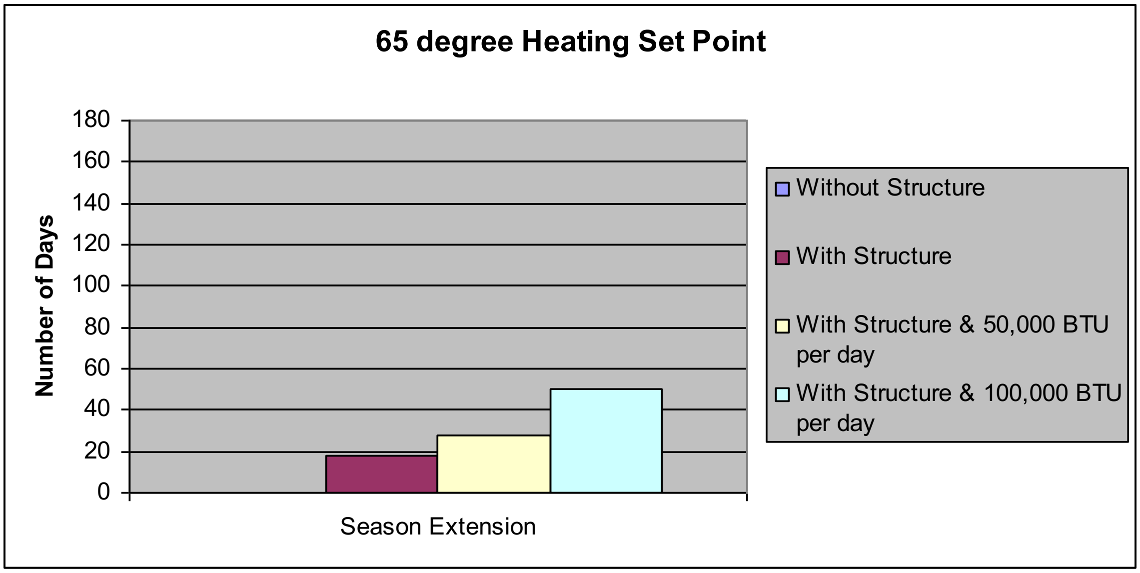


Figure 7: Effect of various treatments on the number of days that can be maintained above 65 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (65 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating(50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

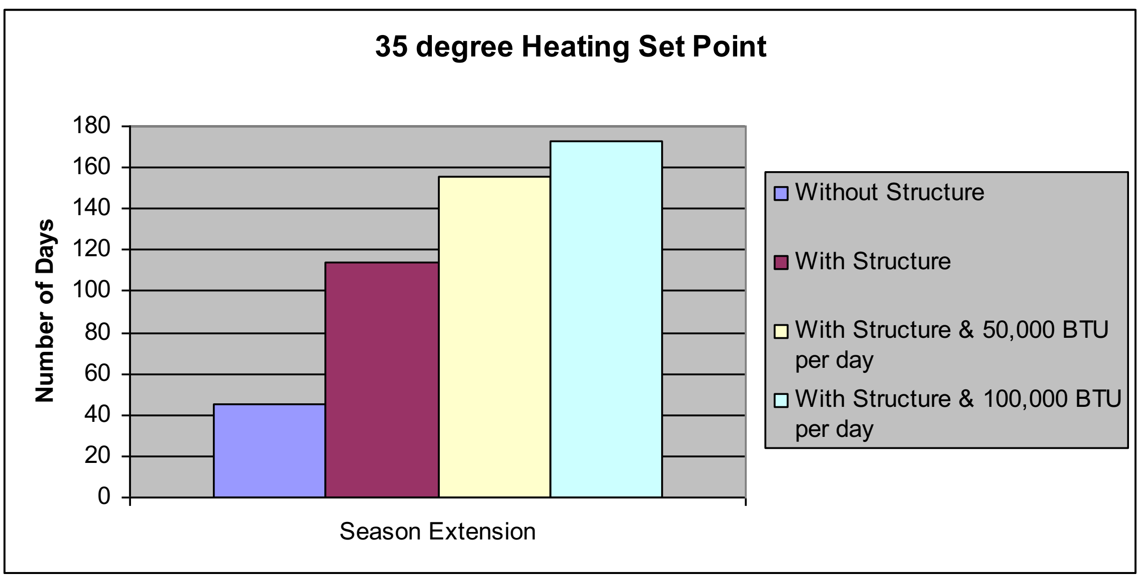


Figure 8: Effect of various treatments on the number of days that can be maintained above 35 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (35 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating (50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

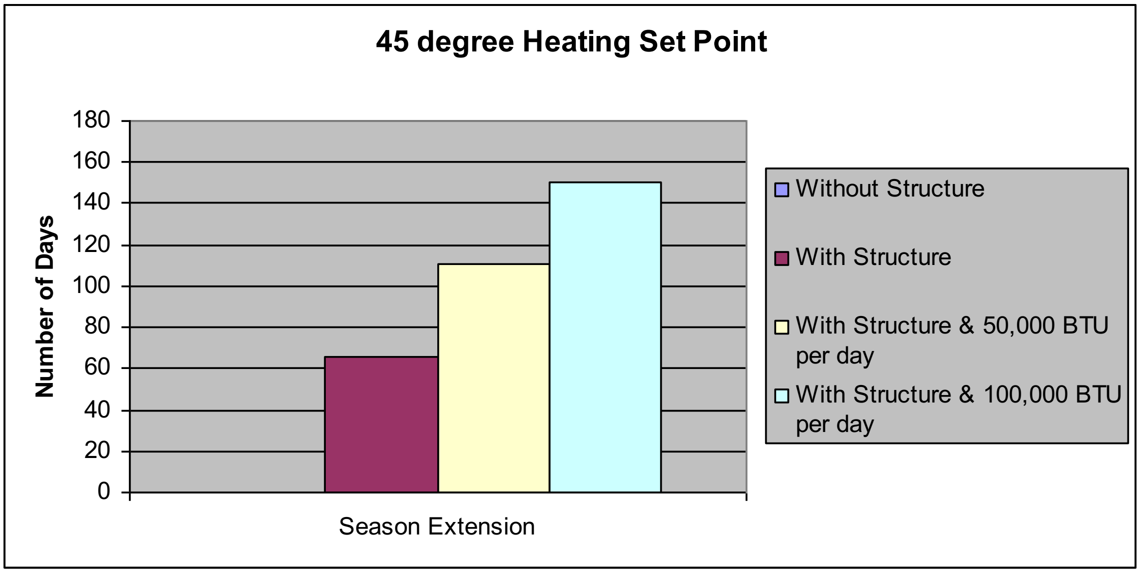


Figure 9: Effect of various treatments on the number of days that can be maintained above 45 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (45 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating (50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

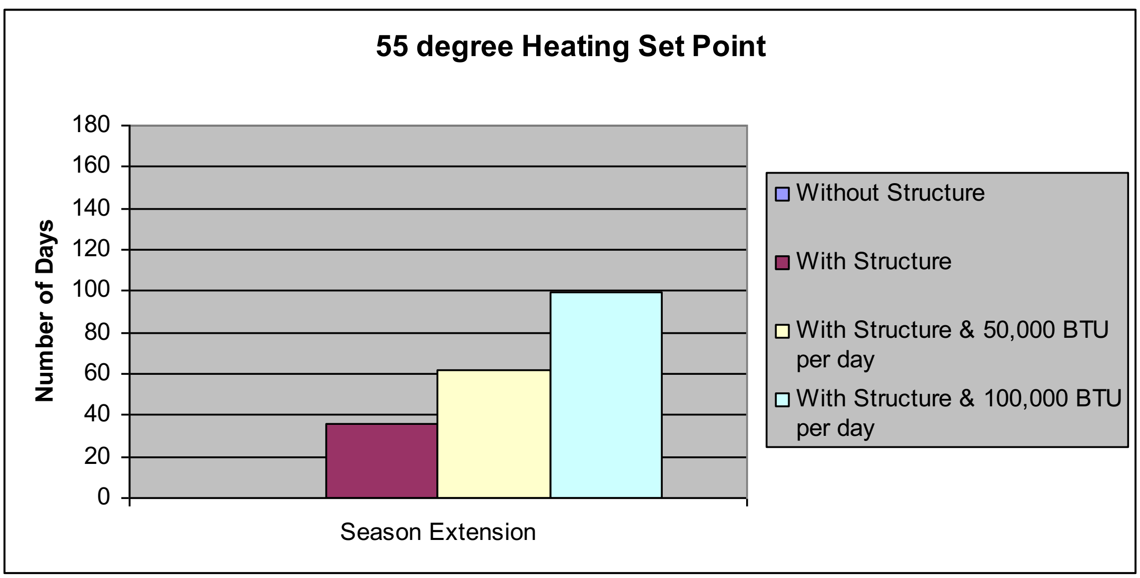


Figure 10: Effect of various treatments on the number of days that can be maintained above 55 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (55 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating (50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

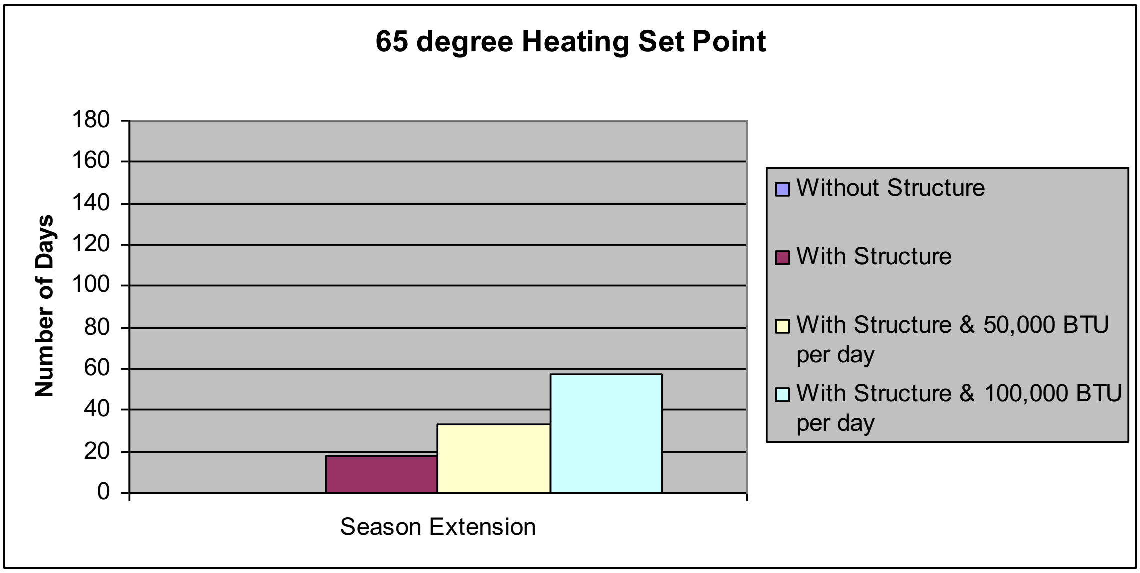


Figure 11: Effect of various treatments on the number of days that can be maintained above 65 ˚F between November and April in Cleveland, OH. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23’ x 50’ hoop house assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. This analysis shows the number of days that each of the 24 hourly average temperatures for that day (midnight to midnight) are above the Heating Set Point (65 degrees) without this structure, with this structure, and with the structure plus some amount of supplementary heating (50,000 BTU and 100,000 BTU). This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

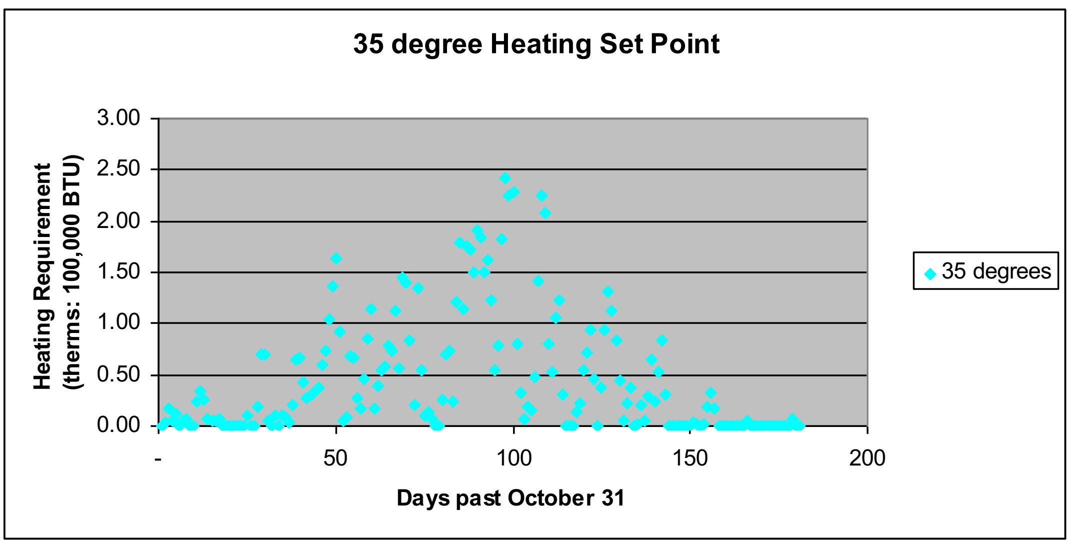


Figure 12: Expected Heating Requirements per day with a 35 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23’ x 50’ hoop house assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (35 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days (November 1 – April 31).

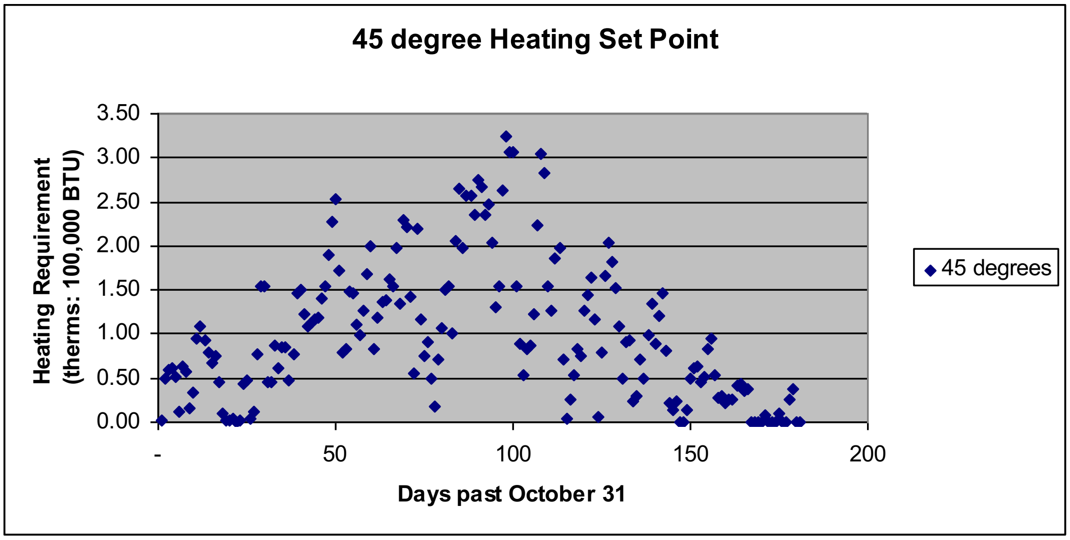


Figure 13: Expected Heating Requirements with a 45 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (35 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

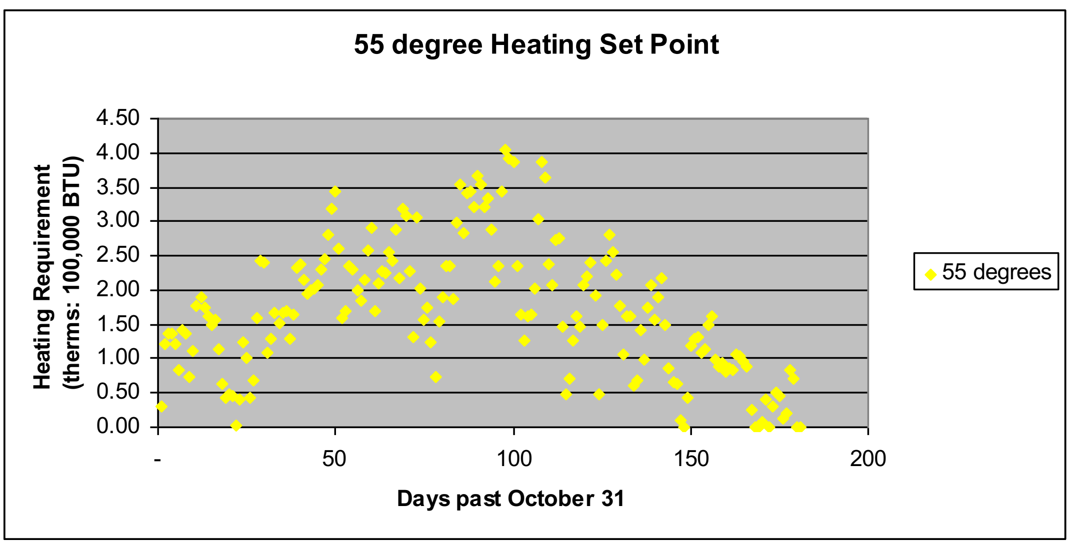


Figure 14: Expected Heating Requirements with a 55 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (35 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

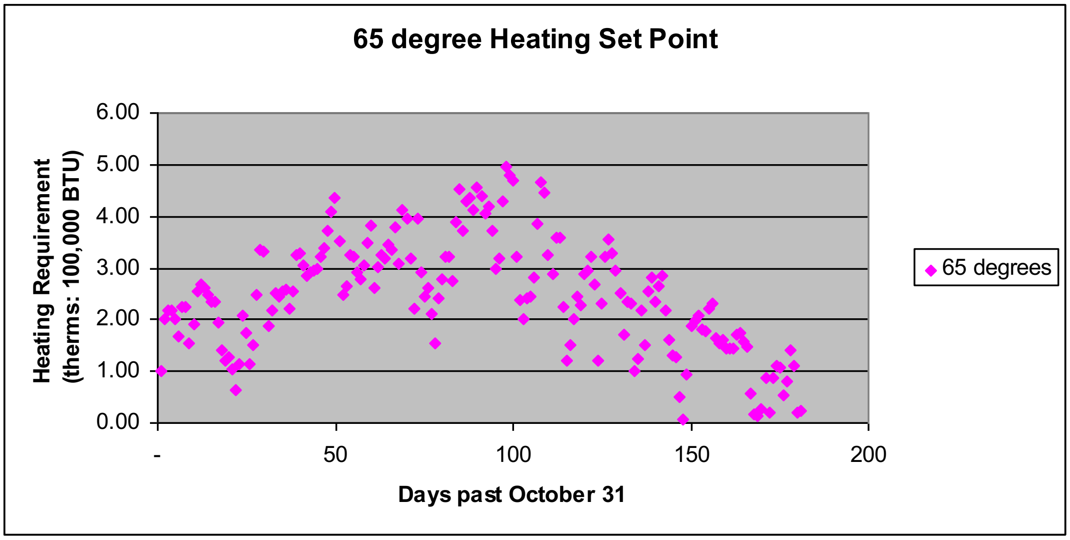


Figure 15: Expected Heating Requirements with a 65 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (35 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

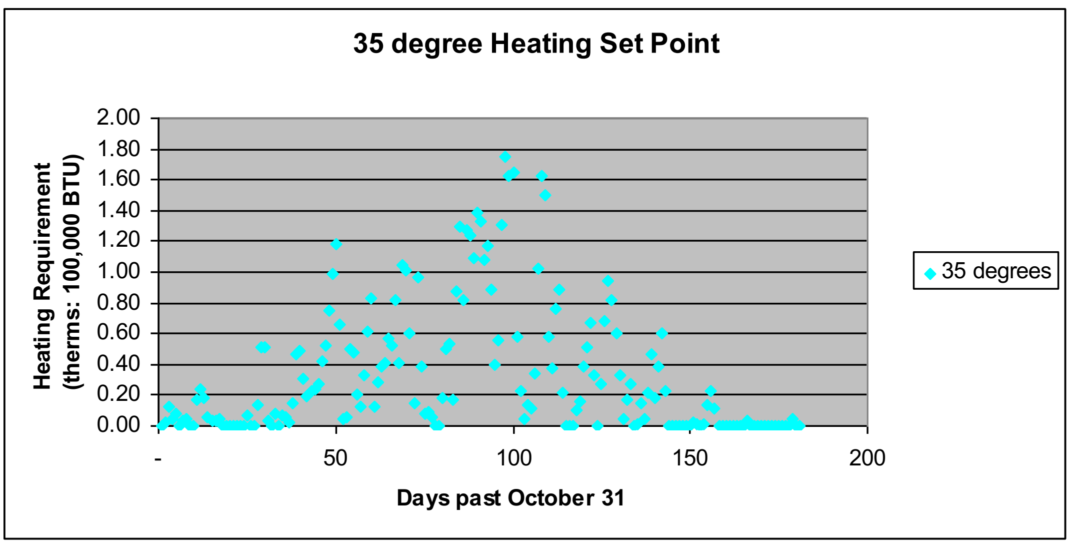


Figure 16: Expected Heating Requirements per day with a 35 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (35 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

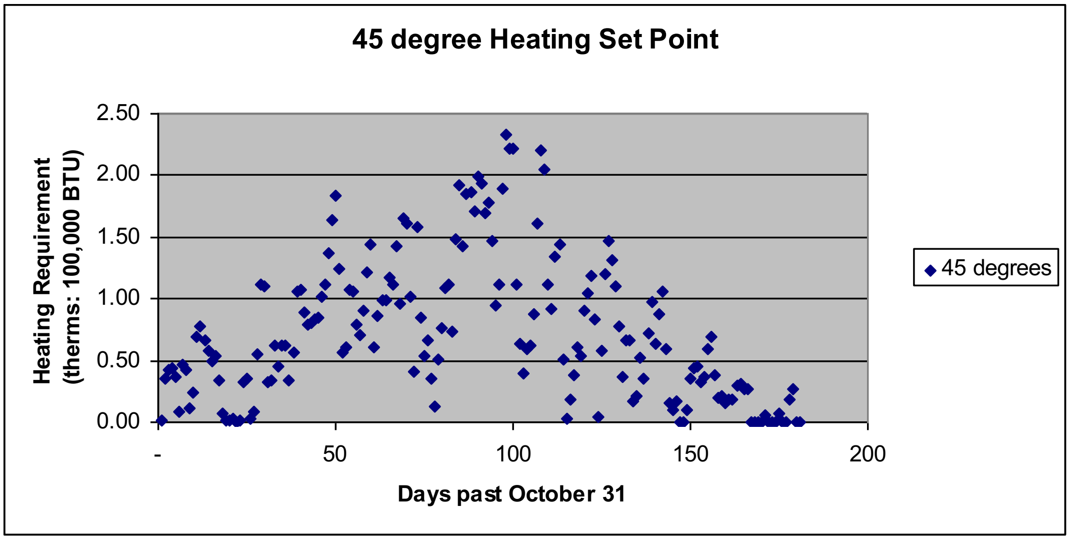


Figure 17: Expected Heating Requirements per day with a 45 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (45 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

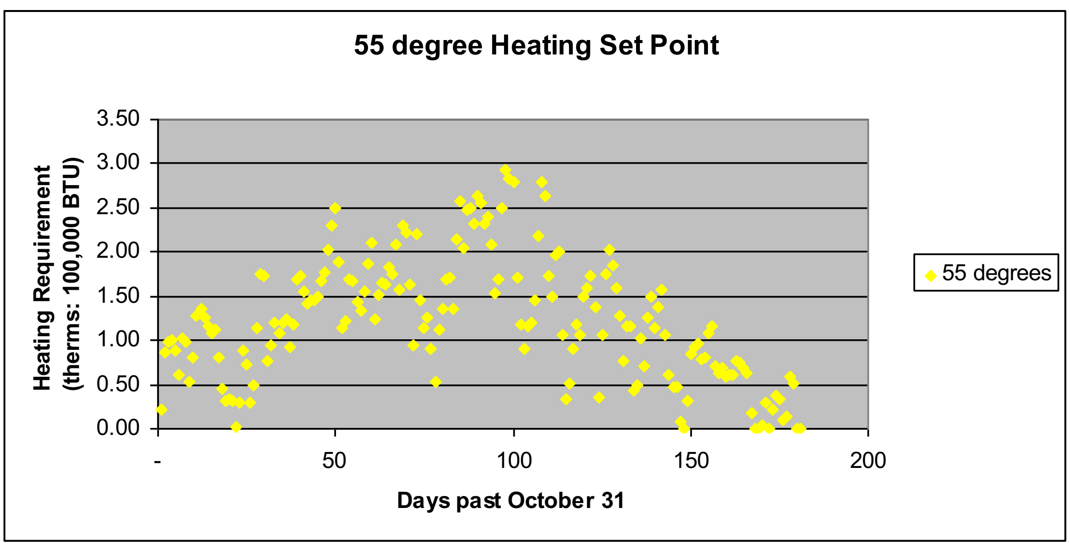


Figure 18: Expected Heating Requirements per day with a 55 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (55 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

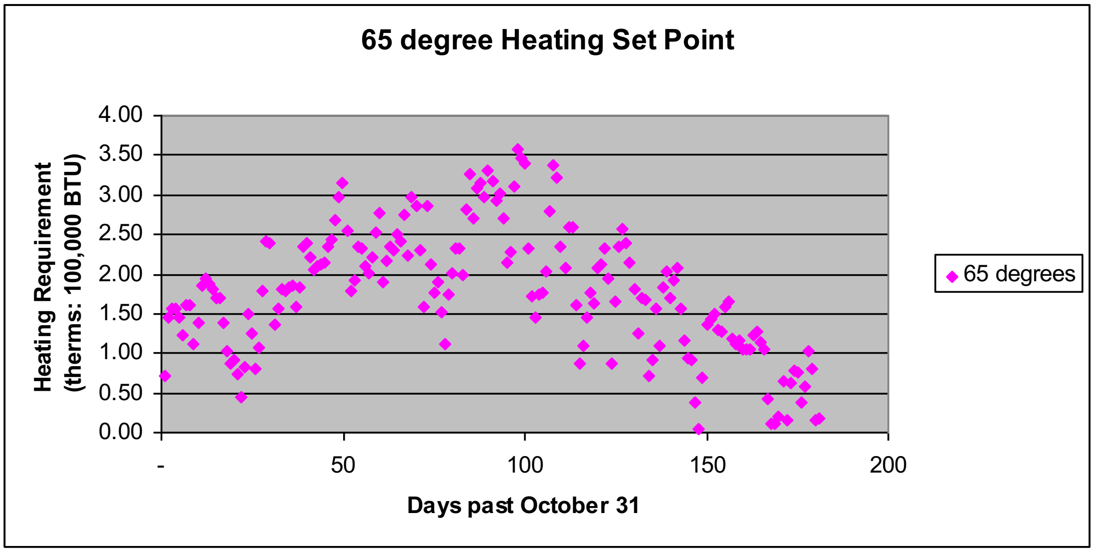


Figure 19: Expected Heating Requirements per day with a 65 degree Heating Set Point. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a double glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the daily Heating Requirements to keep the structure above the set point (65 degrees F) for each day after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy per day. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31. This means that the maximum season extension is 181 days from November 1 – April 31.

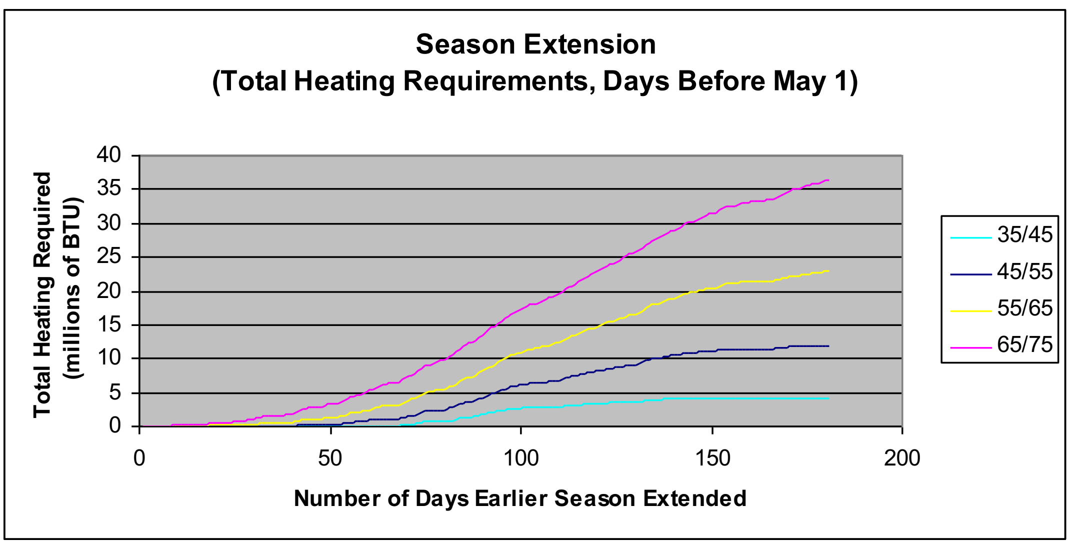


Figure 20: Total cumulative heating requirements for season extension earlier than May 1 at certain heating set points, 35, 45, 55, 65 degrees F. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the cumulative total Heating Requirements to keep the structure above the set point (35 degrees F) for a certain number of days before May 1. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy. The graph can determine the amount of energy required for a certain desired season extension at any set point. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31.

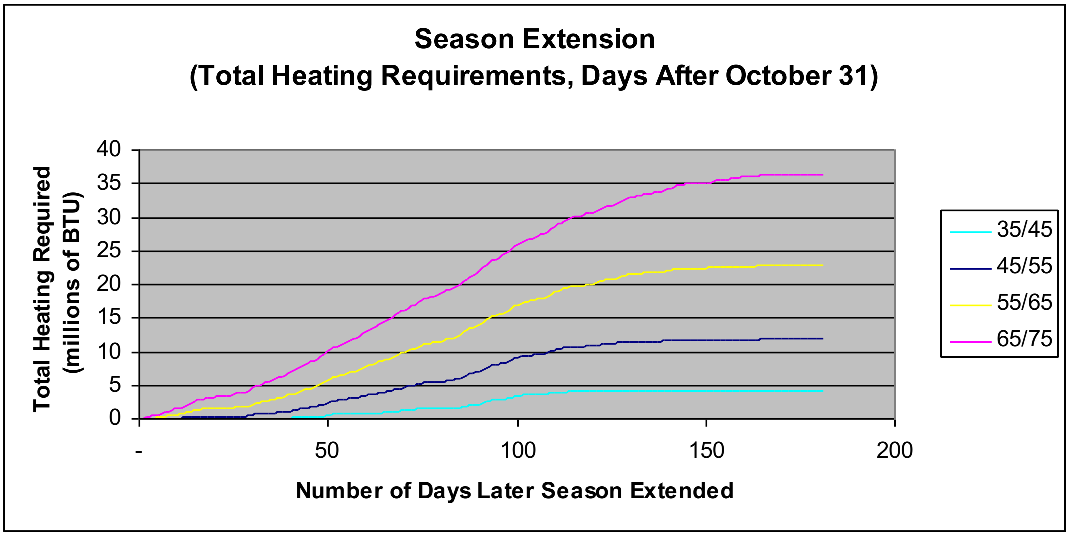


Figure 21: Total cumulative heating requirements for season extension later than October 31 at certain heating set points, 35, 45, 55, 65 degrees F. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23’ x 50’ hoop house assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. This analysis shows the cumulative total Heating Requirements to keep the structure above the set point (35 degrees F) for a certain number of days after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy. The graph can determine the amount of energy required for a certain desired season extension at any set point. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31.

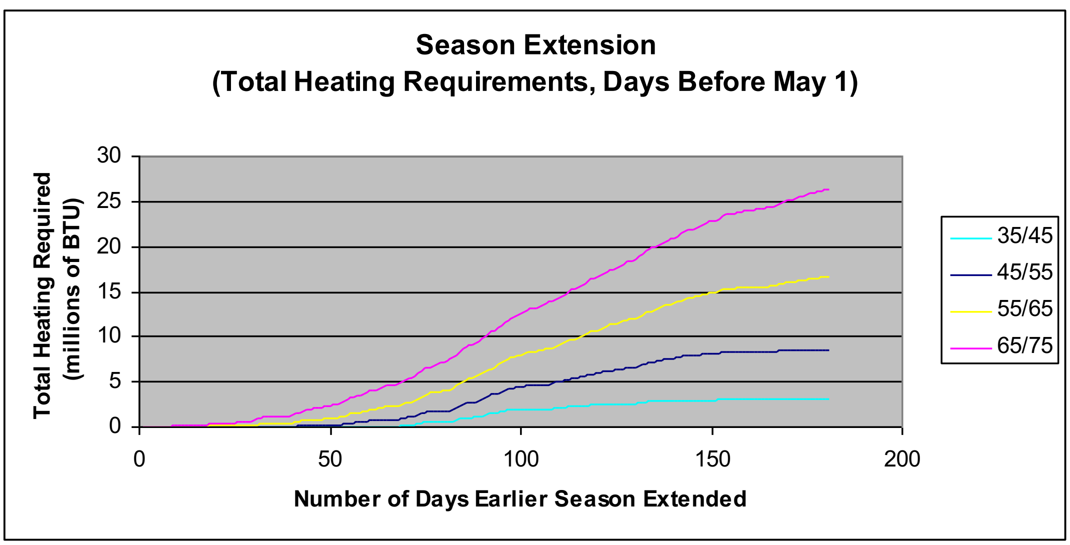


Figure 22: Total cumulative heating requirements for season extension earlier than May 1 at certain heating set points, 35, 45, 55, 65 degrees F. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23’ x 50’ hoop house assuming 10% of daily extra solar energy available (described as “cooling requirements”) captured and used as heat energy. This analysis shows the cumulative total Heating Requirements to keep the structure above the set point (35 degrees F) for a certain number of days before May 1. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy. The graph can determine the amount of energy required for a certain desired season extension at any set point. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31.

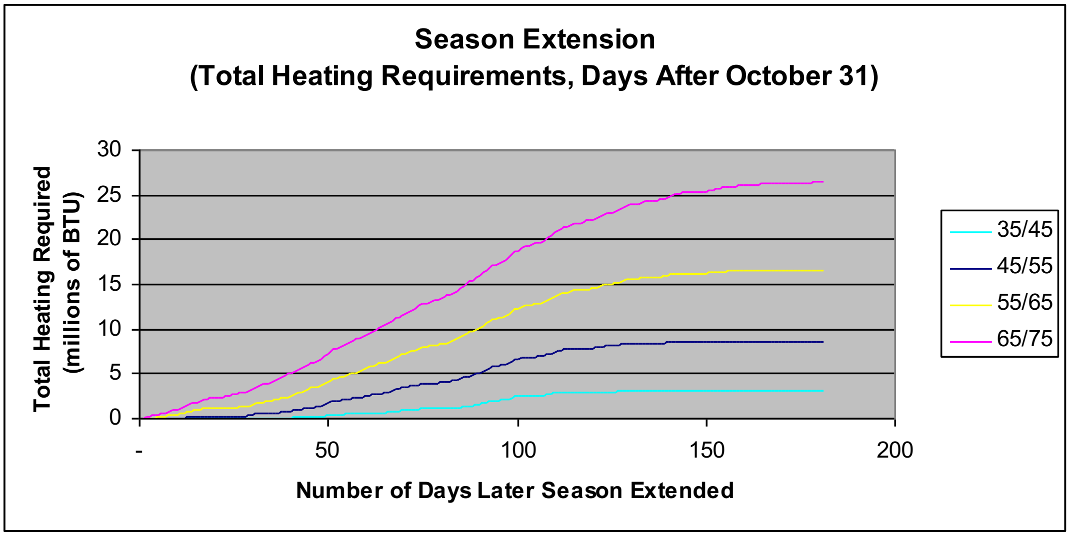


Figure 23: Total cumulative heating requirements for season extension earlier than October 31 at certain heating set points, 35, 45, 55, 65 degrees F. Using typical weather data for the Cleveland Hopkins International Airport (NREL 2008), the GEHAT tool analyzed a single glazed 23' x 50' hoop house assuming 10% of daily extra solar energy available (described as "cooling requirements") captured and used as heat energy. This analysis shows the cumulative total Heating Requirements to keep the structure above the set point (35 degrees F) for a certain number of days after October 31. The graph can determine the number of days the season can be extended with access to a specific amount of BTU of energy. The graph can determine the amount of energy required for a certain desired season extension at any set point. This analysis assumes no heat energy is required during the typical urban garden growing season of May 1 – October 31.

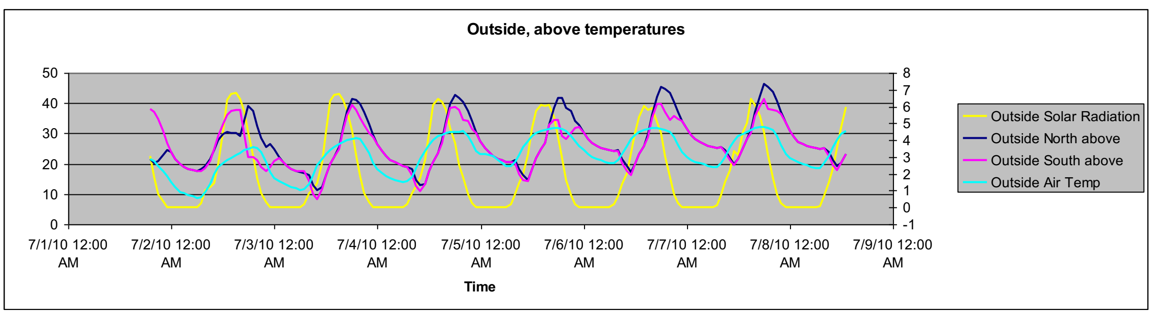


Figure 24: Dry soil temperatures over time for outside the greenhouse, at the surface locations.

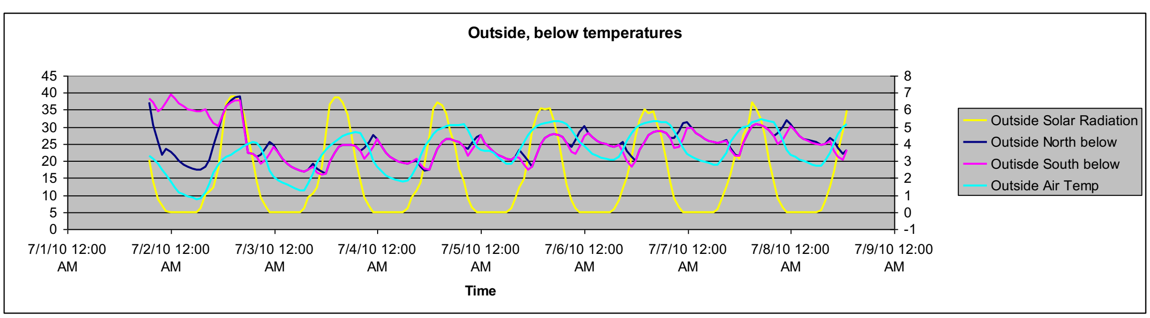


Figure 25: Dry soil temperatures over time for outside the greenhouse, below the surface locations.

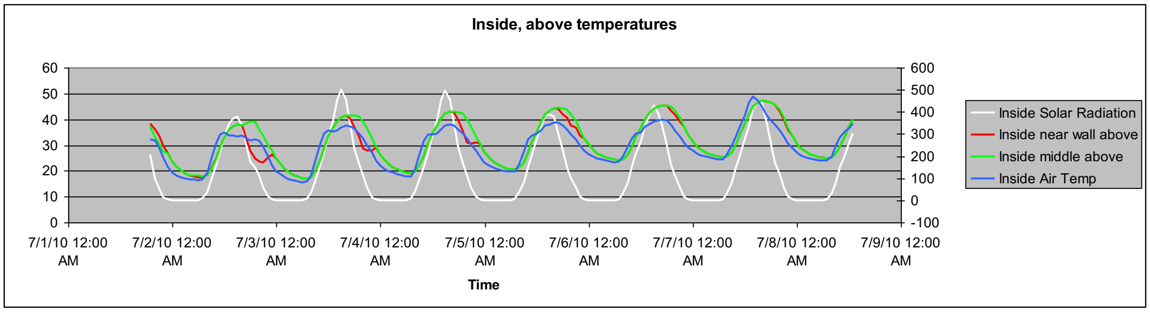


Figure 26: Dry soil temperatures over time for inside the greenhouse, at the surface locations.

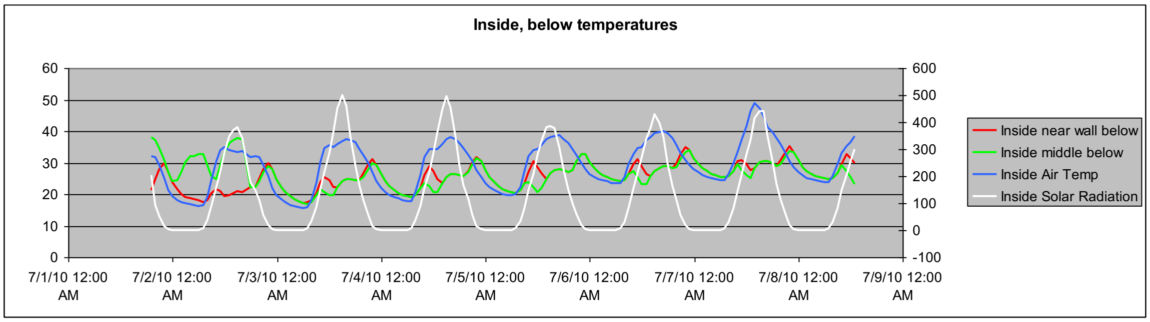


Figure 27: Dry soil temperatures over time for inside the greenhouse, below the surface locations.

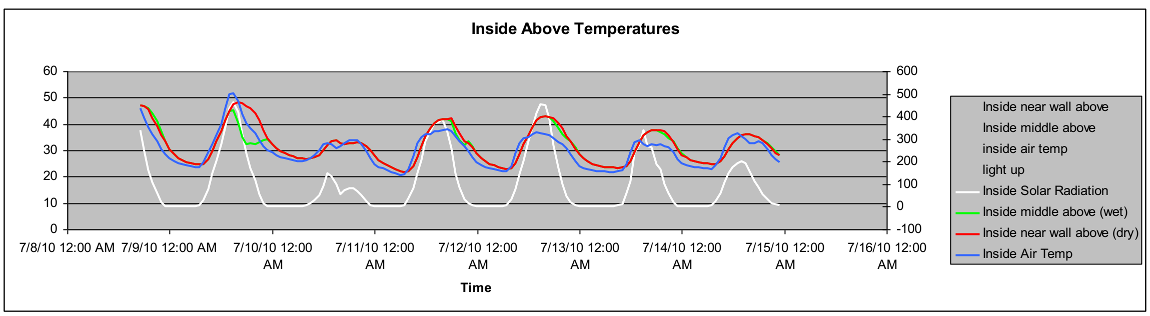


Figure 28: Wet and dry soil temperatures for inside the greenhouse, at the surface locations.

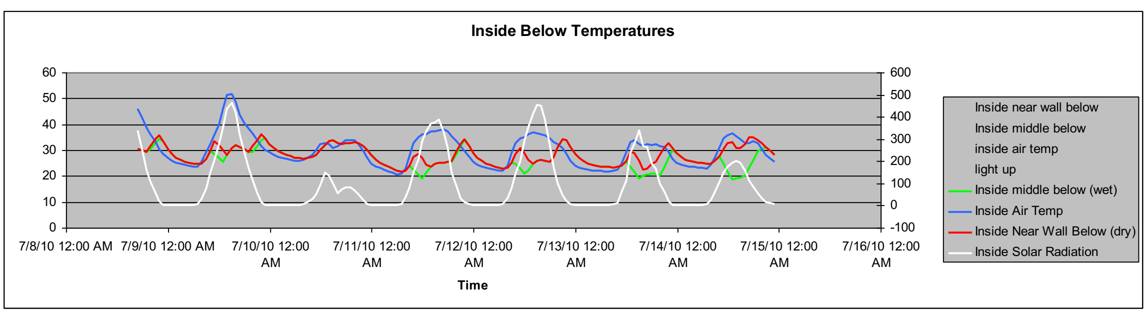


Figure 29: Wet and dry soil temperatures for inside the greenhouse, below the surface locations.

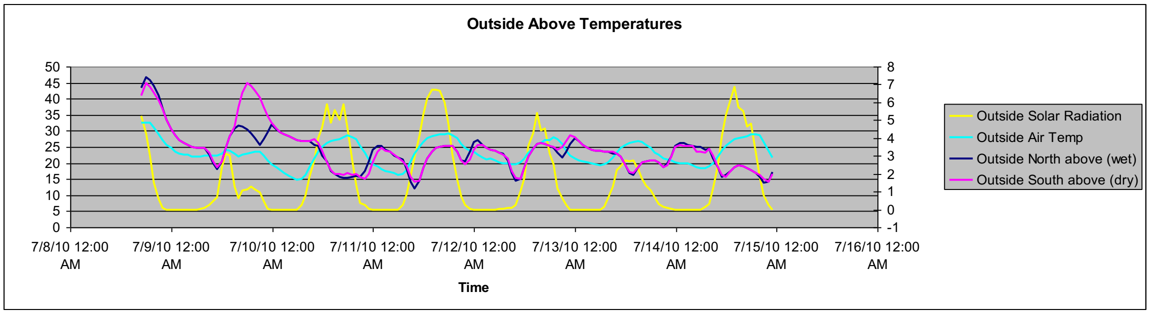


Figure 20: Wet and dry soil temperatures for outside the greenhouse, at the surface locations.

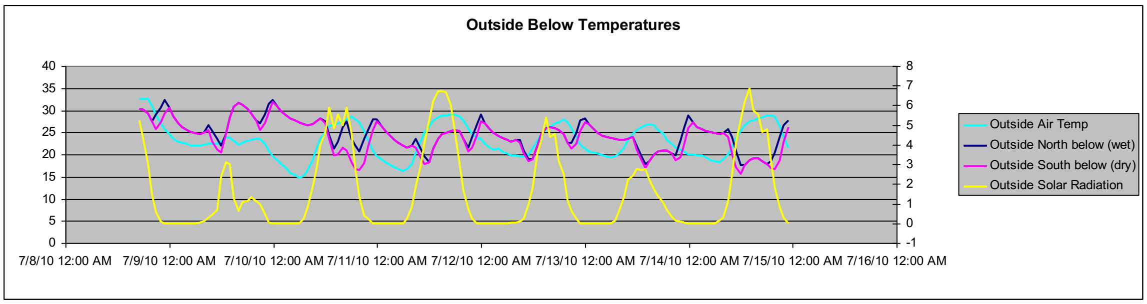


Figure 31: Wet and dry soil temperatures for outside the greenhouse, below the surface locations.

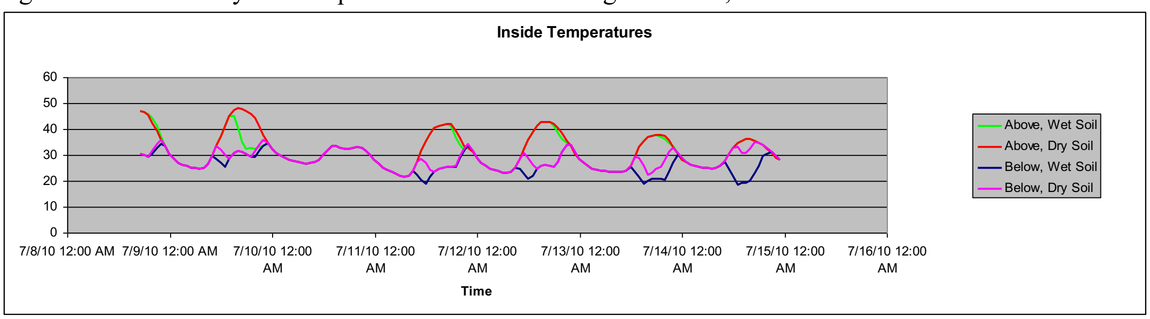


Figure 32: Wet and Dry soil temperatures for at the surface and below the surface locations inside the greenhouse for peak temperature comparison.