Professional Agricultural Workers Journal

Volume 8
Number 1 *Professional Agricultural Workers Journal (PAWJ)*

Article 6

10-12-2021

Air and Soil Temperature Readings, Growing Degree Days, and Chilling Hours Recorded in Two Wiregrass Tunnel Houses Located in East Central Alabama

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AIR AND SOIL TEMPERATURE READINGS, GROWING DEGREE DAYS, AND CHILLING HOURS RECORDED IN TWO WIREGRASS TUNNEL HOUSES LOCATED IN EAST CENTRAL ALABAMA

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Abstract
The study examined air and soil temperature readings, growing degree days, and chilling hours recorded in two Wiregrass tunnel houses during the 2018-2019 season. The monthly average ambient temperature, was 15^{O}F warmer inside the Tunnel House (75/60^{O}F) during the Cool/Cold months, and 17^{O}F warmer inside (90/73^{O}F) during the Warm/Hot seasons of 2018 and 2019. Growing Degree Days heat unit (HU) accumulations were higher inside than outside 4,154 vs. 3,153 HU for the Cool/Cold months and 5,134 vs. 4,800 HU for the Warm/Hot months. Chilling hour accumulations were lower inside the tunnel houses than outside the tunnel houses, 601vs. 671 hr. Utilizing the temperature data from this study, a planting guide consisting of a Cool/Cold (September-February) season and Warm/Hot (March-August) season was developed for a list of crops which producers could plant. The results of this study provides information for growers to better plan their crop choices and planting schedules.
Keywords: Air and Soil Temperature, Growing Degree Days, Chilling Hours, Tunnel House, East Central Alabama

Introduction
Production of vegetables, fruits, flowers, and herbs is carried out in open fields where they are subjected to the uncertainties of temperature, wind, sunlight, water, and nutrients. To reduce production risks, protective measures such as irrigation, wind-breaker, tunnel houses, row covers, and various types of plastic mulches were developed. These advances in production agriculture, modify the natural environment to produce crops, when outdoor conditions make it difficult to raise garden-fresh vegetables. Tunnel houses (THs) are one of the many protective structures developed since the early 1950s to extend the growing season, and is growing in popularity due to governmental support, and its economic benefits (Knewtson et al., 2010; USDA NRCS, 2014; Wittwer and Castilla, 1995).

THs are structures made from wood or metal and covered with clear polyethylene plastic. Following their introduction in the early 1990s (Ghent., 1990; Wells., 1993; Khan et al., 1994;), THs have become popular among small-scale vegetable producers, who see them as an unorthodox alternative of expanding their growing season in the cold, and cool months of the year (Blomgren and Frisch, 2007). The usage of THs is further enhanced by the USDA Natural Resource Conservation Service offering financial assistance to historically underserved producers, and beginning farmers to implement various conservation practices which include THs (USDA NRCS, 2014).

Growing crops in THs is different from growing them in the field, because THs offer some environmental protection from the elements, and they impact the minimum, optimum, and maximum temperatures which influence plant growth and development (Maynard and Hochmuth, 2007). Because crops have different temperature requirements, it is important to determine what the daily average, maximum, and minimum temperatures are in East-Central Alabama so producers can develop planting plans compatible with the seasons. Therefore, the objectives of this study were to: (1) record the average ambient and soil temperatures inside and outside of two Wiregrass THs located in East Central Alabama for four seasons, (2) compute the degree growing days for inside and outside of the THs, (3) calculate the chilling hours for the autumn winter, and spring seasons of the year, and (4) incorporate the temperature data and develop a recommended planting guide for producers and agricultural workers.

Literature Review

Tunnel Houses

THs, also referred to as Hoop Houses, Walk-In-Tunnels, or High Tunnels, are considered an important tool in extending the planting season for many vegetables, small fruits, and cut flower producers in the US. They do not use any artificial heating/cooling or ventilation system, and the only external connection is water for drip or micro-irrigation. THs are very effective in collecting solar energy and using it to increase air and soil temperature to accelerate crop growth. Consequently, in areas with abundant sunlight, THs are very effective for early-season harvest, and lengthening the growing season. They enable intensive crop production of suitable crops on small land areas, and are beneficial to sustainable farming practices. Crops growing within THs protect plants from environmental stresses such as drought, wind, hail, rain and intense sunlight. Also, in the event of heavy rainfall, they prevent soil erosion. The dry environment within the TH keeps the plant canopy dry and reduces diseases and weed growth (Giacomelli, 2009).

THs are either permanent or moveable. Permanent THs are usually built into the ground by embedding the posts in concrete, while the moveable THs are built to be pushed or pulled on skids or rollers. There are two models of THs, Quonset and Gothic. The main advantage of the Quonset model is it is easier and cheaper to construct but the sides are low and will not permit easy cultivation of crops planted close to the sides. The Gothic model is preferred by growers who live in areas where there is substantial snow fall. The reason is that the peek roof reduces snow accumulation; however, the shape of the roof does not allow the plastic to adhere to the rafters, and this causes it to always flap under windy conditions. Additionally, there are several moveable TH models which are popular among growers, such as the skid mounted, the roller, and the lift and tote models. Because these models are moveable there is a limitation on their sizes, which can be 20 ft. wide and shorter than 96 ft. in length (Upson, 2014). One of the advantages of portable TH is that they can be relocated to new sites each season to facilitate crop rotation, avoid nutrient depletion of the soil, and the buildup of soil-borne diseases (Kaiser and Ernst, 2019).

Recently, a wooden model TH referred to as “Wiregrass” Tunnel House was developed in Alabama (Khan et al., 1994; Khan et al., 2013). This type of house encompasses the best parts of the Quonset and the Gothic styles, and is constructed from wood, polyethylene plastic tubes, and covered with 6 mil greenhouse plastic. Polyvinyl chloride (PVC) is used to build lower cost TH, but are vulnerable to destruction in high winds and stormy conditions. PVC TH has a short life expectancy, and is recommended for small hobby type growers. Since PVC pipes are not treated to withstand UV degradation, gray wall electrical conduit pipes are recommended because they are treated to withstand the UV degradation (Upson, 2014).

The selected site for the TH should have access to full sunlight and airflow because a TH is passively ventilated. The length of the TH should be orientated perpendicular to the prevailing wind to ensure proper ventilation (Grubinger, 2016; Giacomelli, 2009). Since Alabama is south of latitude 40^{O}, THs are usually oriented in a north south direction where they can withstand the strong winter winds (Moore, 2008; Khan et al., 1994). In areas which are above 40^{0} latitudes, THs are usually oriented in an east-west direction for maximum light interception particularly during low light months of winter (Giacomelli, 2009). The side walls of TH are rolled up to ensure ventilation, the roll up sides can be made from plastic or other materials such as black canvas. The side walls as well as end doors of the “Wiregrass Model” wooden TH is made from black canvas which can be easily rolled up in multiple segments, or as one complete section. The interior of the “Wiregrass Model” TH can be elevated to prevent flooding due to heavy rainfall, and runoff rain water from the roof. Rodents and wild life can pose a serious problem to TH production; therefore, the “Wiregrass” TH includes, the construction of a fence to keep out wild life. It also has an insect and a varmint proof fence around the bottom perimeter (Biernbaum, 2006; Khan et al., 1994; Khan et al., 2013).

Producing Vegetables in Tunnel Houses

Vegetables produced in TH offer growers certain advantages, such as continuous planting, lower capital costs compared to greenhouses, producing vegetables and fruits which are free from debris requiring less time to clean before marketing them, protection from the elements and reduction in disease pressure, and in some areas, it allows production and sale year round. The main disadvantages are pollinators are usually excluded from the structure and this can be problematic if there are no suitable parthenocarpic or gynecious varieties, temperature within the TH can climb to extremes if attention is not paid to ventilation, and humidity and summer heat can be challenging (Biernbaum, 2006; Moore, 2008).

The growing conditions within a TH are different from field production, which can influence the seasonal selection of what crops can be grown, and managed (Grubinger, 2016). Compatibility among crops should be considered when selecting crops to be grown in the TH because shading can occur when a tall crop is planted next to a short one. Allopathic production of phytochemicals of some plants can affect the growth of another crop. Intra and inter row spacing of vegetable crops within a TH is significant because of the limited space. Early studies (Khan et al., 1994) reported that close intra-row spacing had significantly higher yield for several vegetable crops, compared to farther spacing distances. Soil borne pests can also build up in THs that have been used in several seasons of growth. Soil solarization is a non-chemical method of controlling pests and weeds, and research trials conducted in Southeastern US have shown that this method is effective in controlling weeds and certain soil borne diseases (Stevens, et al. 1991; 1990).

Ghent (1990) and Wells (1993) reported early yield of spring planted tomatoes in Connecticut and New Hampshire, and in Alabama, Khan et al. (1994) reported that a number of Cole crops can be grown during the coldest period of the year without any supplemental heating. Current studies have reported that “cropping” only 50% of the total collard leaves resulted in significantly higher yields, and 117% leaf recovery after harvest compared to plants having a 100% of their leaves harvested (Sparks et al., 2018a; Walton et al., 2018). In another study, Sparks et al. (2018b), compared the traditional method of planting of snapbean seeds spaced 4 inches apart to three seeds planted in “clusters” where each “clusters” were spaced 4 inches apart. The results showed no significant differences in yields based on planting methods; however, they concluded that the “cluster” planting method is more suitable to control weeds within rows.

Drost (2011) reported that summer squash can be successfully grown in TH but recommended parthenocarpic squash varieties to bypass the need for bees to transfer pollen. Kaiser and Ernst (2017) recommended shaded, and well-vented high tunnels can be used to grow cool-season crops like lettuce in early summer, when it would be too hot for production of this crop. Walton et al. (2018) evaluated two sweet potato varieties under conventional and trellised conditions in a TH during the summer months. They reported that the marketable yield of the varieties was different when planted under conventional vs. trellised systems. They concluded that sweet potatoes have the potential of a being suitable crop for TH growers during the hot summer months, provided adequate irrigation is available.

Ambient Temperature and Growing Degree Days in Tunnel Houses

THs are passive heated structures and heat loss from them occurs in three primary ways, namely, escape of the warm air inside to the outside of the TH or by convection, heat loss by conduction through the plastic covering and around the perimeter to the cold soil, and heat loss through radiation to the cold sky. Greenhouses which are artificially heated, lose much of their heat by conduction through the plastic film during the day; whereas, heat loss is through radiation to the cold night air (Biernbaum, 2013). In the TH, on a sunny day, the plastic film traps the incoming sunlight thereby, increasing the internal TH temperature through the creation of the greenhouse effect. Similarly, the incoming radiation heats the soil, changing the soil albedo by the addition of moisture. Thus, the soil becomes warmer and heat is radiated among the plants at night (Khan et al., 2013: Biernbaum, 2013). Clear polyethylene plastic is transparent to long wave radiation, and accounts for most of the heat loss from TH. However, since water reflects radiant energy, the condensation and freezing of the water droplets on the inside of the plastic film on a cold night traps the radiant energy from escaping by creating the” Igloo” effect (Biernbaum, 2013).

There is a need to exchange the air inside a greenhouse or a TH because fresh air is needed to (1) provide carbon dioxide to the growing plants, (2) reduce relative humidity, and (3) cool the structure. On cold clear sunlit winter days’ carbon dioxide can be limited to plants in pots growing in greenhouses. However, in THs, crops are grown directly in soils rich in organic matter, and release of carbon dioxide by the soil microbes may meet the plant carbon dioxide demands. Ventilation during the winter and summer growing seasons in the TH is very important for good crop growth. High relative humidity during the winter months can lead to condensation which reduces light transmission from the sun, and thereby reduces the amount of heat accumulation in the TH. Also, high condensation can stimulate conditions which promote foliar plant diseases. Aerating the TH during the summer growing season is accomplished by rolling up the sides and opening the end doors. Air temperatures in excess of 90-95^{O}F, can reduce growth of certain crops, and affect the pollination, and fruit set of tomatoes, peppers, cucumbers, and eggplants. If regular ventilating practices cannot reduce the temperature within the TH to less than 95^{O}F then the application of shade cloth is recommended (Khan et al., 2013: Biernbaum, 2013).

Temperatures within a closed tunnel can increase rapidly on sunny days even when outside air temperatures are relatively cold, and in the late winter, it is often necessary to ventilate tunnels on sunny days to prevent the temperatures from exceeding the crop's growth optimum limit (Black, and Drost, 2010; Maynard and Hochmuth, 2007). Supplemental heating of TH is an option that some growers explore to reduce crop loss, and increase profits. There are three main ways to heat a high tunnel, namely, in-ground, above-ground, and passive heating. In-ground heating is installed before planting, and is usually set to heat the soil to a certain temperature. There are two common methods of in-ground heating; first, the soil is heated through buried electric heating cables, and second, pumping hot water through buried hoses or pipes. Above ground heating can be accomplished by using heaters powered by electricity or propane gas. Passive heating of the TH can be accomplished by placing barrels of water in the TH during the day and then allow the sun to heat the water. At night as the temperature drops, the heat radiates from the barrels to heat the surrounding air (Maughan et al., 2014).

A study conducted in Minnesota 2003-04 where field production of tomatoes was compared with TH production. The results showed that the first ripe fruits were obtained at 41 and 50, while all of the other parameters studied were higher from plants grown in TH compared to the field (Nennich and Wold-Burkness 2012). Also, during 2003-2004 growing season, the maximum and minimum temperature inside and outside the TH were compared, and the results showed that in 2003 the inside TH temperatures averaged 8.1° F warmer than the outside air temperatures, and in the 2004 growing season, TH temperatures averaged 11.0° F warmer than the outside air, indicating that the TH temperature environment was better for warm season crop production for both growing seasons.

Temperature management in a TH requires an understanding of the three cardinal temperatures (minimum, optimum, and maximum), which defines plant growth within these structures. Different crops have different temperature requirements; for example, cool season crops have lower optimum requirements than warm season crops. Also, plant growth is dependent on temperature or definite amounts of heat to advance from one point in their lifecycle to another such as seedling to first true leaf stage (Miller et al., 2001). Since temperature controls the development of many organisms that do not have a have complex heat regulatory systems, the growth of these organisms can be characterized by using a system called growing degree days (GDD) or heat units (HU) which calculates the accumulated heat units during a growing season (Andrews, 2011; Gibson, 2003). Calendar days are often used to forecast plant growth; however, this method is not reliable because extended cold or warm days can either delay or advance crop growth or harvest dates. By measuring the heat accrued in a given period of time provides a more accurate physiological measurement than just reckoning calendar days. The ability to predict a specific crop stage, relative to insect and weed cycles, permits better management for pesticide and fertilizer applications especially when several crops are grown together (Miller et al., 2001).

A degree growing day is defined as one day when the when the average daily temperature is at least one degree above the lower developmental threshold (the temperature below which development stops). For example, if the low for the day was 33^{O}F and the high was 67^{O}F, then there was an average temperature of 50^{O}F (67 + 33 / 2) = 50). If the crop had a base or a minimum temperature of 32^{O}F where the plant does not or grows slowly, then that day counts as 18^{O}F growing day on the Fahrenheit scale (67 + 33 / 2 - 32 = 18). This growing degree day value of

18^{O}F can be interpreted that the thermal conditions on that date supported a development rate equivalent to 18°F above the lower temperature threshold for the crop in question. Therefore, growing degree days (GDD) is a way of assigning a heat value to each day (Miller et al., 2001). Accumulated GDD is calculated by summing GDDs for each day during a period, and is useful in tracking the development of several important crops and insect pests. There are two ways to compute GDD; specifically, the single sine curve method, and the mean temperature method. The mean temperature method is used in the humid regions of the world where diurnal temperature fluctuations are relatively small during the growing season. The single sine curve method is frequently used in semi-arid and arid regions where there are large diurnal fluctuations in temperature (Gibson, 2003; Zalom et al., 1983).

GDD accumulations inside and outside of a TH were measured for the 2003-2004 seasons in Minnesota, it was found that the GDD inside the TH was 43% higher than the GDD outside; however, the variation was less than 3% in both seasons. Additionally, it was recommended that growers in Northern Minnesota use freeze covers during early spring and fall because there was very little difference between the outside and inside high tunnel minimum temperatures during the study period. Freeze covers offered 8°F to 9°F of protection over outside air and the high tunnel minimum temperatures. The authors concluded that, the use of the freeze covers probably retains the soil heat more efficiently, and prevents its escape to the air, which accounted for 8°F higher temperatures (Nennich and Wold-Burkness, 2012).

Chilling Hours and Bolting in Vegetables

Chilling hours are defined as the number of cold hours or days where the temperature remains around 32-45^{O}F. This chill condition is also known as vernalisation requirement, and is necessary for perennial fruit trees to annually undergo this process to break dormancy and produce fruits (Darren, 2021; Stafne, 2020). Bolting is a term used to describe the situation where annual vegetable plants begins to go to seed, and is manifested by the lengthening of the flower stalk and development of flowers. Prolonged intervals of cool temperatures beginning in the late fall, and extending to early spring, followed by warm temperatures, are conductive to promoting bolting. Some of the crops subjected to bolting are kale, collards, turnips, mustards, tatsoi, bok choy (pac choi), mizuna, radish, carrots, beets, Swiss chard, onions, and spinach (Maynard, 2019).

Chilling hours are calculated using various methods. First, is the F model, which computes the total number of hours when the temperature drops to 45 or below. Second, is 32-45^{O}F F model, which computes the number of hours the temperature was between 32-45^{O}F. Third is the Utah model, which calculates chilling units when the temperature, on an hourly basis, begins to increase from 34-65^{O}F. Lastly, fourth, is the mean temperature model, which uses the average monthly temperature of the coldest months, December and January, to estimate the accumulated chilling units (Byrne and Bacon, 1992).

When vegetable plants begin to bolt, it is an indication that the plant is beginning to produce seeds, and this in turn, initiates and convey plant resources from the production of root, leaves, or fruits, to production of flowers and seeds. Bolting is also an indication of a reduced harvest and a loss of crop quality (Vanderlinden, 2019). The most important factor in determining bolting in early transplanted or directly seed vegetables are periods of cool temperatures, followed by long daylight hours. Other environmental factors such as drought, disease, and nutrient deficiencies can induce plants to bolting. Members of the *Brassicaceae* such as collards, mustards, kale, rutabaga, and turnips, show broad variations in juvenile stage of growth, and temperature levels which would cause them to bolt. Generally, plants, which have attained a certain size, say between 2 to 15 leaves with consistent temperature within their vernalisation range will begin to bolt within 2-8 wks. However, Collards, Brussels sprouts, and cabbage require longer times to vernalize, and are not usually susceptible to early spring cool temperatures before summer weather to keep them vegetative (Phillips and Goldy, 2020).

Materials and Methods

Tunnel House

This study was conducted during the fall of 2018 and winter of 2019 (2018-2019) in a Wiregrass TH. The study had two sites; one located at S&B Farm in Eufaula, Alabama and the other located at Valley, Alabama. The THs used in the study were of the Quonset model. They were from wood and polyethylene pipes, and covered with clear greenhouse plastic film, without any supplemental heat or cooling. All the plantings were done directly in the soil and not in raised beds or containers.

Soil Type and Tunnel House Site Preparation

The soil type at the study sites is characterized as Norfolk sandy loam (fine, siliceous, thermic Typic, Paleudults). Recently, the soil has been reclassified as Kinston fine-sandy loam (fine loamy, siliceous, semiactive, acid, thermic Fluvaquentic Endoaquepts) (USDA, 2004). The sites were rototilled with a mechanical rototiller and were drip irrigated based on the methods described by Khan et al. (1994).

Air Temperature Readings

An AcuRite Pro 5-in-1 Color Weather Station with Wind Direction & Speed and Rain Model 01512 was used to collect the ambient weather data inside and outside of the TH located at Valley, Alabama for the years 2018-2019. This unit was solar powered because there was no electricity available in the THs. This unit logged temperature data inside and outside of the THs every 12 minutes over a twenty-four-hour period, and at the end of every 2-weeks, the data were downloaded to a laptop computer using the manufacturer's software. The Microsoft Excel program was then used to analyze and extract the daily maximum and minimum temperatures, which were then collated to get the monthly figures.

Soil Temperature Readings

Four Lascar EL-USB-1-LCD Temperature Data Loggers with LCD display were used to measure the soil temperatures at the 5cm depth in THs located at Eufaula and Valley, Alabama. The sensors from the data loggers inside and outside the THs were placed at 8 cm depth. These were rotated to different sections inside the THs on a weekly basis in order to get more uniform temperature readings. All of the data loggers were powered by batteries**.** Soil temperature data were recorded every 30 minutes over a 24-hour period. These readings were downloaded loaded at 2-week intervals to a laptop computer, and later analyzed using Microsoft Excel Program.

Growing Degree Day Computation and Chilling Hours

Growing Degree Day (GDD) or heat units is a weather based measurement, which estimates heat accumulation, and is used to predict the development of plants and insects during the growing season. GDD data were recorded at the TH located at Valley, Alabama for the years 2018-2019 (or 2018 and 2019), for collards, cabbage, and potatoes (Cool/Cold Season) at a base temperature of 40^{O}F, and for peppers and tomatoes (Warm/Hot Season) at a base temperature of 60^{O}F (Maynard and Hochmuth, 2007). GDD data were computed using the procedure described by Miller et al. (2001).

Chilling Hours for 2018-2019 were taken at the Valley, Alabama location only and the number of chilling hours accumulated was computed using the procedure described by Byrne and Bacon (1992).

Statistical Analyses

The data collected were: ambient and soil Temperatures, growing degree days (GDD), and chilling hour readings. These were then analyzed using the Coefficient of Variation as described by Snedecor, 1966.

Results and Discussion

Table 1 shows that in 2018 and 2019, the maximum, minimum, and average ambient temperature from inside and outside of the TH at Valley, Alabama, declined from September in 2018 to February 2019. Conversely, the maximum, minimum, and average temperature, increased from March to August. This difference in ambient temperature formed the basis to divide the calendar year into the Cool/Cold season (September-February), and Warm/Hot season (March-August), where the ambient temperature influenced what crops could be planted in each season.

Table 1. The Average Monthly Maximum, Minimum, and Mean Air Temperatures Recorded during the Cool/Cold and Warm/Hot Seasons in 2018 and 2019 from Inside and Outside of a Wiregrass Tunnel House Located at Valley, Alabama

	2018 Cool/Cold Season Air Temperature (^{O}F)							2018 Warm/Hot Season Air Temperature (^{O}F)					
	Maximum		Minimum		Average			Maximum		Minimum		Average	
Mth.	In-door	Out-door	In-door	Out-door	In-door	Out-door	Mth.	In-door	Out-door	In-door	Out-door	In-door	Out-door
Sept.	126	93	71	68	98	81	March	107	69	43	40	75	54
Oct.	108	77	57	56	82	67	April	114	77	51	46	82	62
Nov.	75	59	46	47	64	53	May	113	88	64	61	88	75
Dec.	86	59	41	39	63	49	June	122	94	69	68	96	81
Jan.	95	59	42	39	69	49	July	122	93	71	69	97	81
Feb.	98	69	51	48	74	59	August	124	93	67	64	96	78
Mean	**98**	**69**	**51**	**50**	**75**	**60**	**Mean**	**117**	**86**	**61**	**58**	**89**	**72**
C. V.	**16**	**18**	**20**	**20**	**17**	**19**	**C. V.**	**5**	**11**	**17**	**19**	**9**	**14**

Table 1. Continued The Average Monthly Maximum, Minimum, and Mean Air Temperatures Recorded during the Cool/Cold and Warm/Hot Seasons in 2018 and 2019 from Inside and Outside of a Wiregrass Tunnel House Located at Valley, Alabama

	2019 Cool/Cold Season Air Temperature (^{O}F)							2019 Warm/Hot Season Air Temperature (^{O}F)					
	Maximum		Minimum		Average			Maximum		Minimum		Average	
Mth.	In-door	Out-door	In-door	Out-door	In-door	Out-door	Mth.	In-door	Out-door	In-door	Out-door	In-door	Out-door

Sept.	138	97	67	64	102	80	March	95	69	41	41	68	55
Oct.	113	83	58	57	86	70	April	111	80	51	49	81	64
Nov.	92	64	36	36	64	50	May	130	92	63	61	97	76
Dec.	88	63	39	43	63	53	June	127	92	69	66	98	79
Jan.	93	58	37	34	65	46	July	131	95	71	69	101	82
Feb.	89	68	45	45	67	57	August	133	96	71	68	102	82
Mean	**102**	**72**	**47**	**47**	**75**	**59**	**Mean**	**121**	**89**	**61**	**59**	**91**	**73**
C. V.	**18**	**19**	**25**	**23**	**20**	**20**	**C. V.**	**11**	**11**	**19**	**18**	**14**	**14**

Table 1 also shows that during the Cool/Cold season of 2018 and 2019 the average ambient temperature inside the TH was 75^{O}F compared to 59^{O}F on the outside, thereby establishing warmer conditions within the TH by 16^{O}F, and 89^{O}F compared to 73^{O}F during the Warm/Hot season of the same period, giving an identical difference of 16^{O}F. Nennich and Wold-Burkness (2012) reported a difference of 8 and 11^{O}F, respectively, higher temperature inside the TH compared to the outside, showing a difference of approximately 50% less compared to the results from this study. These results indicate that the TH can be expected to sustain ambient temperature conditions suitable for growing crops which requires a base and upper optimum temperature of 70^{O}F (Maynard and Hochmuth, 2007) during the coldest months of the year. Likewise, during the warmest months of the year, the TH maintained optimum growing conditions for germinating seeds, and the growth of several Warm/Hot season crops (Black and Drost, 2010).

Table 2 shows that the average mean soil temperature within the TH at Valley and Eufaula were similar, 65^{O}F vs. 66^{O}F compared to 60^{O}F vs. 62^{O}F for the outside during the Cool/Cold season

Table 2. The monthly maximum, minimum, and mean soil temperatures recorded from the inside and outside of a Wiregrass Tunnel House at 5cm depth located at Valley and Eufaula AL during the Cool/Cold and Warm/Hot Seasons in 2019

Valley, Alabama													
2019 Cool/Cold Season Soil Temperature (^{O}F)							2019 Warm/Hot Season Soil Temperature (^{O}F)						
	Maximum		Minimum		Average			Maximum		Minimum		Average	
Mths	In-door	Out-door	In-door	Out-door	In-door	Out-door	Mths	In-door	Out-door	In-door	Out-door	In-door	Out-door
Sept.	95	83	82	78	89	81	March	58	60	52	52	55	56
Oct.	82	71	73	67	78	69	April	92	70	51	62	72	66
Nov.	65	55	55	51	60	53	May	133	84	55	72	94	78
Dec.	60	52	53	49	56	51	June	91	85	73	76	82	81
Jan.	61	52	46	45	54	49	July	136	85	60	77	98	81
Feb.	58	58	52	51	55	55	August	139	85	60	77	100	81
Mean	**70**	**62**	**60**	**57**	**65**	**60**	**Mean**	**108**	**78**	**59**	**69**	**84**	**74**
C. V.	**19**	**19**	**21**	**21**	**20**	**19**	**C. V.**	**28**	**12**	**13**	**13**	**19**	**13**

Table 2 Continued. The monthly maximum, minimum, and mean soil temperatures recorded from the inside and outside of a Wiregrass Tunnel House at 5cm depth located at Valley and Eufaula AL during the Cool/Cold and Warm/Hot Seasons in 2019

Eufaula, Alabama													
2019 Cool/Cold Season Soil Temperature (^{O}F)							2019 Warm/Hot Season Soil Temperature (^{O}F)						
	Maximum		Minimum		Average			Maximum		Minimum		Average	
Mths	In-door	Out-door	In-door	Out-door	In-door	Out-door	Mths	In-door	Out-door	In-door	Out-door	In-door	Out-door
Sept.	88	89	75	60	82	75	March	64	64	56	57	60	61
Oct.	84	73	57	68	71	71	April	74	71	64	64	69	68
Nov.	71	62	56	56	64	59	May	84	83	73	74	79	79
Dec.	78	58	57	53	68	56	June	93	88	77	80	85	84
Jan.	58	56	52	50	55	53	July	104	89	73	79	89	84
Feb.	61	61	55	55	58	58	August	92	88	78	77	85	83
Mean	**73**	**67**	**59**	**57**	**66**	**62**	**Mean**	**85**	**81**	**70**	**72**	**78**	**77**
C. V.	**15**	**17**	**13**	**10**	**13**	**13**	**C. V.**	**64**	**64**	**56**	**57**	**60**	**61**

of 2019. However, during the Warm/Hot season, the interior of the TH located at Valley, registered an average soil temperature of 84^{O}F compared to 78^{O}F at Eufaula. This 6^{O}F warmer conditions at Valley could be due to the difference in the soil type at the two locations. The average interior soil temperature within the TH at both locations fell within the ideal range for germinating seeds for a number of Cool/Cold and Warm/Hot season crops as reported by Black and Drost (2010).

Crops growing in a TH have different minimum, maximum, and optimum temperature requirements for germination and growth (Miller, et al., 2001). Consequently, to assist TH growers to extend their growing season during the Cool/Cold and Warm/Hot seasons of the year, Table 3A was developed. This was based on the monthly average TH interior ambient and soil temperatures generated from this study, (Tables 1 and 2), and the recommended temperature guidelines for seed germination, optimum day, and night growing temperatures as reported by Maynard and Hochmuth, (2007) and Black and Drost (2010). Therefore, the planting guide offers a list of recommended cold hardy/frost tolerant vegetables, from which growers can directly seed or transplant, during the Cool/Cold Season of the year. The average ambient temperature for each month in Table 3A was based on the average monthly temperatures recorded for 2018 and 2019.

Table 3B reflects the planting guide for the Warm/Hot Season and the list of recommended crops, which can be planted during that season. Included in this list are selected herbs and cut flowers, which offer TH growers an opportunity to diversify their crop selection and increase farm income. Some producers in the Southeastern US may choose not to plant their TH during the Warm/Hot Season because of the high temperatures. Instead, they could solarize their TH during this period using the methods outlined by Stevens et al. (1991; 1990). Soil solarized should begin in May and extend for a period of 30-90 days; longer periods of solarization usually results in better control of weeds and soil borne pests.

Table 3 A. Recommended Planting Guide for Tunnel House Producer in East Central Alabama

			Temperature Ranges for Tunnel House Crop Growth [1]		
			Germination Temperature	**Optimum Growing Day Temperature**	**Optimum Growing Night Temperature**
			40-80 (^{O}F)	**60-70 (^{O}F)**	**50-60 (^{O}F)**
Cool/Cold Season Months	**Average Tunnel House Temperature (^{O}F)[2]**		**Recommended Cold Hardy/Frost Tolerant Crops for Direct Seeding/Transplanting During the Cool/Cold Season**		
	Ambient	**Soil**			
September	100	86	Collards, Turnips, Mustard, Kale, Cabbage, Broccoli, Brussel		
October	84	75	Sprouts, Cauliflower, Rape, Swiss Chard, Beet, Rutabaga's,		
November	64	62	Lettuce, Arugula, Radish, English Peas, Green Onions,		
December	63	62	Carrots, Radicchio, Spinach, Leeks, Bok Choi, Rhubarbs,		
January	67	55	Parsnips, Shallots, Strawberries, Kohlrabi, Onions Dry Sets,		
February	57	58	Potatoes, Scallions, Celery, Radicchio, Spinach, Endive, Escarole, Garden Cress, Asparagus, Chinese Cabbage, and		

Note: [1] Maynard and Hochmuth; (2007), [2] The ambient and soil temperature data were generated from this study.

Table 3B. Recommended Planting Guide for Tunnel House Producer in East Central Alabama

			Temperature Ranges for Tunnel House Crop Growth [1]		
			Germination Temperature	**Optimum Growing Day Temperature**	**Optimum Growing Night Temperature**
			40-80 (^{O}F)	**60-70 (^{O}F)**	**50-60 (^{O}F)**
			Germination Temperature	**Optimum Growing Day Temperature**	**Optimum Growing Night Temperature**
	Average Tunnel House Temperature (^{O}F) [2]		**40-80 (^{O}F)**	**60-70 (^{O}F)**	**50-60 (^{O}F)**
Warm/Hot Season Months	**Ambient**	**Soil**	**Recommended Tender/Warm Tolerant Crops for Direct Seeding/Transplanting During the Warm/Hot Season**		
March	72	58			
April	83	71	Snapbeans, Tomatoes, Lima Beans, Parthenocarpic Cucumber & Squash, Eggplant, Okra, Sweetpotato, Malabar Spinach,		
May	93	87	Amaranth, New Zeeland Spinach, Hot and sweet Peppers, Rattle Snake Beans, Basil, Onion & Garlic Chives, Cilantro,		
June	97	84	Marjoram, Oregano, Parsley, Rosemary, Sage, Thyme,		
July	99	94	Lavender, Dill, Mint, Marigold, Petunia, Aster, Zinnia, Dahlia, Carnation, Calendula, Periwinkle, Aster, Celosia, Alyssum,		
August	99	93	Spearmint, Savoy, Tarragon, Sesame, Coriander, Caraway, Chervil. Sunflower, Peanuts, Shasta Daisy, and Black -Eye		

Note: [1] Maynard and Hochmuth; (2007), [2] The ambient and soil temperature data were generated from this study.

Even though temperature plays an important part in plant development, they require specific amounts of heat, to advance from one growth stage to the next. Growing Degree Days (GDD) is a method of assigning heat unit (HU) values to each day, which accumulates throughout the growing season. GDD or HU is computed when the average daily temperature exceeds the base temperature, below which growth ceases (Miller et al., 2010; Gibson, 2003; Andrews, 2011).

Table 4 reflects that during the Cool/Cold season of 2018, the inside of the TH accumulated 1,388 or 31% more HU than outside, and dropped to 614 (3,858-3,244), or 16% during the 2019

Table 4. Monthly Average and Cumulative Growing Degree Days (GDD) Inside and Outside of a Wiregrass Tunnel House for the Cool/Cold and Warm/Hot seasons of 2018 and 2019

	Cool/Cold Season 2018 (September-February)			Warm/Hot Season 2018 (March-August)		
	Monthly Average	C.V.	Cumulative	Monthly Average	C.V.	Cumulative
Inside	743	79	4,451	854	18	5,125
Outside	510	57	3,063	793	21	4,757
	Cool/Cold Season 2019 (September-February)			Warm/Hot Season 2019 (March-August)		
Inside	643	25	3,858	857	18	5,144
Outside	541	39	3,244	807	21	4,843

Cool/Cold season. This decline in 2019, could have been due to colder ambient temperatures experienced during this period compared to the mild winter of 2018. Nennich and Wold-Burkness (2012) reported comparable values of 43% more HU accumulation inside than outside a TH, during a two-year period in the spring in Minnesota.

Table 5. Monthly Average and Accumulated Chilling Hours (32^0F-45^0F) Recorded during the 2018 and 2019 Planting Season

	Tunnel House Interior and Exterior Chilling Hours (F^O) for the Cool/Cold Season 2018 and 2019								Tunnel House Interior and Exterior Chilling Hours (F^O) for the Warm/Hot Season 2019				
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Av.	Cumulative	Av.	Mar.	Apr.	Av.	Cumulative	C.V.
In-side	0	22	72	219	189	99	120	601	61	141	61	101	202	40
Out-side	0	30	94	225	225	96	134	671	58	155	75	115	230	21

Conversely, HU accumulation indicated small differences between the inside, and outside the TH, during the Warm/Hot seasons of 2018-19. The recorded differences were 368 or 7% vs. 301 or 6% respectively. This small difference between the inside and outside TH, was probably due to the overall seasonal increase in temperature, and the continuous ventilation of the TH during the Warm/hot season. The higher GDD accumulations inside the Tunnel Houses during the Cool/cold season indicated that TH can be a dependable, and sustainable method of protective agriculture (Blomgren, and Frisch, 2007), which can reduce risks, and increase farm income for small vegetable producers. In Addition, the research findings of Walton et al., (2018); and Sparks et al., (2018) demonstrated that sustainable yield of collards could be harvested during the Cool/Cold seasons under TH conditions during the Cool/in South Central/Eastern AL.
Table 5 shows that chilling hours began to accumulate in October during the Cool/Cold Season,

and reached its highest average during the months of December and January, this was similar to the results as reported by (Byrne and Bacon, 1992), and declined in March and April of the Warm/Hot season. Furthermore, the inside of the TH received a monthly average of 120 chilling hours or 12% less than the outside which received 134 hrs. This trend continued during the months of March and April 2019, where the inside of the TH recorded a monthly average of 101 hrs. or 14% less chilling hours compared to 115 chilling hours on the outside. The monthly accumulation of chilling hours during the Cool/Cold Season from both inside and outside of the TH exceeded the optimum range outlined by Phillips and Goldy (2020) required for the full vernalisation of many members of the *Brassicaceae* family. This suggests that TH producers who plant collards, turnips, cabbages, and broccoli in early fall can expect their crops to be fully vernalized by February of the following year. Therefore, TH producers will have to consider replanting these crops to have them available for sale during the late Cool/Cold season or early in the Warm/hot Season.

Conclusion

The objectives of the study were to record the average ambient and soil temperatures inside and outside of two Wiregrass THs located in East Central Alabama for four seasons; compute the degree growing days for inside and outside of the THs; calculate the chilling hours for the autumn winter, and spring seasons of the year, and incorporate the temperature data and develop a recommended planting guide for producers and agricultural workers. The results showed that the average ambient temperature inside the TH during the Cool/Cold seasons of 2018 and 2019 was 75^{O}F, and that outside the TH was 59^{O}F, a 16^{O}F higher difference. Similarly, the average ambient temperature inside during the warm/hot seasons of 2018 and 2019 was 89^{O}F and that outside the TH was 73^{O}F, also a 16^{O}F higher difference. Soil temperature inside the TH in 2019 in the cool/cold season in Valley was 65^{O}F indoor and 60^{O}F outdoor, a 5^{O}F difference; however, in warm/hot season it was an average of 84^{O}F indoor and 74^{O}F outdoor, a 10^{O}F difference. At Eufaula, corresponding values were 66^{O}F vs. 62^{O}F and 78^{O}F vs. 77^{O}F, respectively. What is more, the HU in the cool/cold season of 2018 was 1,388 more inside the TH than outside, but in the cool/cold season of 2019 was 614 more inside the TH than outside; however, a drop of 16% compared to 2018. Identical figures for warm/hot season for 2018 and 2019 were 368 and 301, respectively. Chilling hours' accumulation was less for inside than outside the TH, with December and January receiving the highest number of chilling hours for inside and outside. Average chilling hours for 2018 were, respectively, 120 and 234 for the inside and outside, and average chilling hours for 2019 were, respectively, 101 and 115 for the inside and outside. Using the temperature data obtained in this study, a planting guide was developed to provide growers with assistance to make important decisions concerning their planting plans and choice of crops to plant.

Acknowledgements

This study was funded by the USDA National Institute of Food and Agriculture (NIFA), Food Research Initiative Competitive Grant, Number 35.31244158; USDA/NIFA/Extension Grant, Number 36.22091431; USDA/NIFA/Evans/Allen Research Grant, and Alabama/ANGA, Grant Number 80.22090210. The authors would also like to thank the Carver Integrative Sustainability Center, Tuskegee University, Alabama, for supporting the study, as well as Russell and Jewel Bean of S&B Farm in Eufaula, Alabama, and Pastor Alzata Florence and the members of the Fellowship of Faith Christian Center, Valley, Alabama, for allowing the researchers to conduct this study in their Tunnel House.

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