CHARACTERIZING THE EFFECTS OF VENTILATION FANS, DOUBLE GLAZING, AND AN AUTOMATED SIDEWALL ROLL-UP SYSTEM ON AN UNHEATED HIGH TUNNEL GREENHOUSE IN THE NORTH CAROLINA HIGH COUNTRY

A Thesis
by
SUMMER GEE

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Abstract

CHARACTERIZING THE EFFECTS OF VENTILATION FANS, DOUBLE GLAZING, AND AN AUTOMATED SIDEWALL ROLL-UP SYSTEM ON AN UNHEATED HIGH TUNNEL GREENHOUSE IN THE NORTH CAROLINA HIGH COUNTRY

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A high tunnel greenhouse allows agricultural producers to extend growing seasons and improve the quality of their crops. High tunnel greenhouses are a viable option for agricultural producers because they are relatively inexpensive, easy to construct, and typically can be moved. These structures are relatively simple and require additional inputs for heating and cooling as seasonal weather variations affect the internal microclimate of the greenhouse. No matter the time of year, there are many methods for increasing a greenhouse's ability to maintain an optimal indoor microclimate. This study quantifies the individual effects of double glazing, ventilation fans, and an automated sidewall roll-up system on temperature, relative humidity levels, and light transmission in a unheated high tunnel greenhouse that is located in the North Carolina High Country. The study will also analyze the combined overall effect of five greenhouse technologies, double glazing, ventilation fans, horizontal airflow fans, an insulated ground skirt, and the automated sidewall roll-up system, working in conjunction. The study found that there was a 16.3% increase in the greenhouse's ability to maintain temperatures above 32°F, and a 20% increase in the greenhouse's ability to maintain temperatures under 90°F after the installation of all five systems. Frequency of freezing and overheating events in the greenhouse were reduced significantly due to the effects of the five systems.

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INTRODUCTION

Addressing the Problem

In regions that experience cold weather, farmers and agricultural producers are forced to rely on greenhouses to extend growing seasons and continue to sell their goods through the winter. Regions that experience temperate climates, such as the High Country region of North Carolina, rely on greenhouses through the winter, fall and spring seasons to provide a regulated environment, as well as to minimize crop loss and freezing. During the summer season, these greenhouses are also used for crop production and must be retrofitted for the warmer weather. No matter the time of year, there are many methods for increasing a greenhouse's ability to maintain an optimal indoor microclimate. These methods can include additions and interventions such as ventilation fans, air circulation fans, gas or electric heaters, solar thermal storage, double glazing and ground skirt insulation, but not all greenhouse owners have the money for or access to these technologies. Focusing on effective, yet inexpensive ways to increase temperature regulation and minimize both freezing and overheating in the greenhouse is the key for creating solutions for small scale farmers.

Providing both insulation and ventilation in a high tunnel greenhouse is crucial to maintaining an optimal growing environment for plants. The installation of ventilation and air circulation fans is a common upgrade in high tunnels because of their relatively low costs and effectiveness in providing ventilation. These fans expel stale air from the high tunnel and keep fresh air circulating through the tunnel. On the other hand, double glazing and insulated ground skirts are common upgrades used for insulation of the greenhouse. Additionally, there are some greenhouse upgrades that tackle the issue of providing both insulation and ventilation in a high tunnel greenhouse, such as an automated sidewall roll-up system.

An automated sidewall roll-up system uses a thermostatic controller to monitor the inside temperature of a greenhouse and controls a motor that is attached to the sidewall curtain of the structure. When the temperature drops below or exceeds a specific set point, the thermostatic controller responds by signaling the motor to roll up or down to provide ventilation or insulation, depending on if the greenhouse needs to be cooled or heated. While purchasing an automated sidewall roll-up system from a manufacturer can become quite costly, building this system as a do-it-yourself project is relatively inexpensive and can be highly effective in controlling one's greenhouse microclimate. When used in conjunction with other technologies, such as ventilation fans and double glazing, a high tunnel microclimate can be maintained and manipulated as desired. Analysis on the ways that these different greenhouse technologies impact the performance of a high tunnel allows farmers and agricultural producers to make a more informed decision when deciding which of these technologies best fits the needs of their greenhouse.

Purpose of Study

This study aims to investigate the effectiveness of multiple different greenhouse technologies in achieving and maintaining an optimal microclimate inside of high tunnel greenhouses located in temperate regions. The aim is to quantify the effects of the individual technologies on a greenhouse microclimate through comparison of temperature, humidity and light transmission levels in the greenhouse from before and after the system's installations. All of the systems being analyzed in this study have been designed with a focus on low-budget, low-tech construction to find solutions that are affordable and approachable for small-scale farmers.

The study will analyze multiple systems, including two ventilation fans with intake shutters installed on a high tunnel end wall. The study will also analyze a double layer air inflation system, which involves a second layer of greenhouse plastic being installed onto the inside frame of the greenhouse paired with air inflators that create an air gap between the two plastic layers. An automated sidewall roll-up system will also be analyzed. These systems can be constructed in a multitude of ways, but a low-tech, low-budget design will be used in this study. For construction of the sidewall roll-up system, a greenhouse motor will be attached to the existing sidewall roll bar. The greenhouse motor will be wired to a livestock-grade thermostatic controller for temperature monitoring and control. The major components used in this system are designed to be easily accessible and feasible to purchase for local, small-scale farmers in the North Carolina High Country. Lastly, the overall effect of five greenhouse technologies, double glazing, ventilation fans, horizontal airflow fans, an insulated ground skirt and an automated sidewall roll-up system, on high tunnel performance will be analyzed.

Significance of Study

The aim of the study is to provide the western North Carolina agricultural community with quantitative information on how these selected greenhouse technologies can help to achieve and maintain optimal microclimate conditions in a high tunnel greenhouse, as well as demonstrate that these systems can be built on a low budget. Reduction of freezing and overheating temperature levels, as well as the reduction of extreme low and high relative humidity levels, will exhibit the difference in greenhouse performance from before and after the installation of each system.

While some of these technologies are well established, the use of an automated sidewall roll-up system on non-commercial greenhouses is a more recent happening in the agricultural field. There is very little published research that quantifies the effects of an automated sidewall roll-up system on a greenhouse microclimate, and the majority of existing literature analyzes the effects of these systems in hot and humid climates. In order to fully understand the effects of this system on greenhouse performance, it is necessary to analyze its impacts in varying climate zones. This study will be especially useful because temperate climate zones, like that of the North Carolina High Country region, experience high temperature fluctuations throughout the year, meaning the farmers in this region could greatly benefit from the increased control that an automated sidewall roll-up system can provide.

There is also very little published information that quantifies the effect of double glazing on the internal temperatures of a high tunnel greenhouse. Analysis on the effects of double glazing will be extremely valuable to farmers in our region that are trying to decide if the performance of this system is worth the installation and materials costs.

Additionally, while this research does focus on characterizing the effects of each system individually, the study will also offer a unique significant opportunity to observe and analyze how the selected systems work together in a high tunnel greenhouse by analyzing the overall effect of all five systems, double glazing, ventilation fans, horizontal air flow fans, an insulated ground skirt and an automated sidewall roll-up system, working in conjunction on greenhouse performance.

Research Hypotheses and Questions

In regions with a temperate climate, such as the mountainous region of western North Carolina, greenhouses can benefit greatly from technical upgrades, or interventions. Temperate climate zones tend to experience low temperatures in the winter months, as well as warm to hot temperatures in the summer. Based on data collected at the Nexus high tunnel greenhouse, which is unheated and owned by Appalachian State, over the past three years, it can be seen that the greenhouse experienced temperatures both below 45°F and over 90°F almost every month of the year, which stresses plants and creates an undesirable greenhouse microclimate. Interventions such as the addition of ventilation fans, double glazing and an automated sidewall roll-up system, can assist growers in maintaining an optimal greenhouse microclimate when outdoor temperatures are too hot or cold.

The hypothesis of this study is that the upgrades made to the high tunnel greenhouse, including ventilation fans, double glazing and an automated sidewall roll-up system, will contribute to decreasing the frequency of overheating and freezing events by providing both insulation and ventilation as needed, as well as allowing for increased or decreased air infiltration and relative humidity in the greenhouse. The study will focus primarily on reducing overheating, as freezing temperatures in the greenhouse cannot be completely avoided without a source of supplemental heating in the High Country area. However, the interventions being analyzed in this study are likely to assist in maintaining temperatures slightly higher than those outdoors when outside temperatures are at or below freezing. Installations of these systems is also likely to result in a reduction of overheating events in the greenhouse, leading to a reduction in potential crop losses. The systems, or interventions, being studied are likely to decrease the overall duration of time that undesirable temperature levels exist in the greenhouse throughout the year. The installed systems are also likely to decrease costs associated with supplemental heating.

The system expected to make the greatest impact on greenhouse temperature and relative humidity is the automated sidewall roll-up system because this system provides both insulation and ventilation in the greenhouse. The ventilation fans are expected to have the second greatest impact on temperature and relative humidity in the greenhouse. The ventilation fans and the automated sidewall roll-up system are connected to thermostatic controllers that allow them to be utilized based on temperature setpoints to bring fresh air into the greenhouse as needed. The double layer air inflation system, or double glazing, is expected to have the third greatest impact on temperature and relative humidity in the greenhouse. By providing insulation and structural support, the greenhouse should be expected to maintain higher temperatures than it did prior to the systems' installation. The overall effect of all three of the interventions, with the addition of horizontal airflow fans and an insulated ground skirt, on the greenhouse is expected to result in greenhouse temperatures and relative humidity staying within our desired range more frequently. It is expected that all five interventions, working in conjunction, will minimize the frequency of overheating and freezing events in the greenhouse, as well as minimizing the frequency of time that relative humidity levels drop below or exceed the desired range (40-80%). Although they vary in their purposes, it is expected that each of the selected systems will be useful tools for maintaining and controlling a high tunnel greenhouse microclimate.

In order to analyze and quantify the effectiveness of these upgrades, or interventions, on greenhouse microclimate optimization, an experimental study must be conducted. This study aims to prove the effectiveness of the system by considering:

- How does the installation of an automated sidewall roll-up system affect temperature and relative humidity levels in a high tunnel greenhouse?
- How does the installation of two ventilation fans and two horizontal airflow fans (HAF) affect temperature and relative humidity levels in a high tunnel greenhouse?
- How does double glazing affect temperature and light transmission levels in a high tunnel greenhouse?
- What is the overall effect of all five interventions (double glazing, ventilation fans, horizontal airflow fans, an insulated ground skirt and the automated sidewall roll-up system) on temperature and relative humidity levels in a high tunnel greenhouse?

Limitations of Study

This study will take place at the Nexus Facility owned by Appalachian State University and will be limited by geographical location, as well as existing greenhouse systems and uses. The Nexus facility is equipped with a 20 foot by 30 foot high tunnel greenhouse that does not have supplemental heating. The Nexus facility has gone through a series of 'retro-fit' upgrades between 2021 and 2022, including the addition of a second layer of polyethylene greenhouse film (double glazing), two ventilation fans, two horizontal air flow circulation fans, an insulated ground skirt, and an automated sidewall roll-up system, installed in the order listed above. The table below shows the timeline for the installation of these systems.

Table 1

List of Interventions and Dates of Installation

Intervention/Feature	**Installation Date**
Double Glazing	February 12th, 2021
(2) Ventilation Fans & (2) Horizontal Air Flow fans	March 4th, 2021
Insulated Ground Skirt	March - September, 2021
Automated Sidewall Roll-up System	April 17th, 2022

Studies done on the effects of each of the selected systems will likely be affected by interactions with other existing systems in the greenhouse, as the impacts of each system cannot be completely isolated from the others. This is the largest limitation of this study. Certain interventions were periodically and intentionally turned off during the data collection period in order to minimize these interactions between the interventions. Maximum effort has been put forth to analyze the data in a way that differentiates between the effects of each system.

The Nexus greenhouse has two small buildings connected to either end wall, which could impact temperature and relative humidity levels in the greenhouse. There is a pond located inside of the Nexus greenhouse which is used for hydroponics research and acts as a large thermal mass contributing to heating and cooling inside of the greenhouse. This pond is approximately 15.6 by 5.3 feet with an average depth of 14 to

20 inches deep. The depth of the pond varies based on evaporation rates in the greenhouse. The surface area is approximately 82.6 feet, with a volume of approximately 96.4 to 138 cubic feet, which was multiplied by a conversion factor of 7.4805 to find that the pond contains roughly 720 to 1,030 gallons of water. The pond's maximum capacity is approximately 1,200 gallons. The pond could affect the results of this study, and it is assumed that the results would differ slightly if this study was performed in a greenhouse that did not have this thermal mass present. This greenhouse is used as a research facility and learning lab for Appalachian State University. Days with high foot traffic in the greenhouse will be excluded from the study to account for changes in temperature or relative humidity that could be caused by people coming in and out of the greenhouse, doors getting left open to the outside, etc.

The study will also be limited by time constraints of the data collection period. Data used in this study was collected between January 1st, 2020 and October 25th, 2022. The automated sidewall roll-up system being analyzed in this study was installed at Nexus on April 17th, 2022, which means there was no data collected on the performance of this system during the winter season. Crops are only grown seasonally at the Nexus greenhouse which means that transpiration levels vary throughout the year.

There will not be a control greenhouse in this study due to lack of funds, resources, and space. Due to the lack of a control, results will be drawn by comparing temperature and relative humidity in the same greenhouse before and after interventions.

LITERATURE REVIEW

High Tunnel Greenhouse Overview

Temperature, relative humidity, and solar radiation influence how crops grow and develop. In a high tunnel greenhouse, growers can influence these conditions but do not have precise control. High tunnel greenhouses are polyethylene, plastic or fabric covered hoop structures that protect crops from insects, sun, wind, excessive rainfall, or cold, to extend the growing season in an environmentally safe manner (USDA, 2015). These structures can range from just a few feet tall, to being commercial sized walk-in greenhouses, and usually consist of crops planted in the ground or in raised beds. Typical high tunnel structures are constructed of metal, wood, and/or durable plastic frames that are anchored to the ground and then covered with a material sufficiently thick enough to withstand seasonal temperature changes, typically polyethylene (“Conservation Practice Fact Sheet”, 2015). Polyethylene covers are a minimum 6-mil greenhouse grade, UV-resistant material, that are installed onto the greenhouse frame in a single or double layer. End wall coverings for high tunnel greenhouses can be constructed of greenhouse-grade plastic such as polyethylene, poly-carbonate, wood, or other suitable materials (“Conservation Practice Fact Sheet”, 2015). To achieve adequate ventilation, the high tunnel greenhouse must have side covers that can be rolled up and/or completely removed to control internal temperature and humidity. End wall coverings are typically framed-in to enclose the structure, and often include doors and additional ventilation openings ("Conservation Practice Fact Sheet", 2015).

High tunnel greenhouses provide many unique benefits over traditional greenhouses, including reduced costs and easier installation. They provide weather, wind, frost, and insect protection, and when managed correctly, can lead to growing season extension, increased crop production, and improved crop quality (Cogger et al., n.d.). While there are many applications for these structures, high tunnel greenhouses are primarily used for growing season extension, as the greenhouse cover material, typically polyethylene, allows the farmer to combine indoor and outdoor growing by rolling up or removing the cover layer during warm seasons and sealing the greenhouse by rolling down or replacing the cover layer during cold seasons. This allows crops to be protected from early spring or late fall frosts without the burden or costs associated with a fully equipped traditional greenhouse (Rimol Greenhouse Systems, 2019).

To achieve the desired benefit of season extension, a high tunnel greenhouse must be properly managed. The most common mistake made in managing a high tunnel is allowing the greenhouse to overheat or freeze, which can stress plants and reduce crop production. In order to avoid overheating and freezing in the high tunnel, the greenhouse microclimate needs to be closely monitored and adjusted. Another frequent mistake made when managing a high tunnel greenhouse is allowing relative humidity levels to get too high or too low. When relative humidity levels in a greenhouse fall below 40% or rise above 80%, crops become susceptible to drying out or becoming oversaturated (Schiller & Plinke, 2016). Excessive moisture in a greenhouse can lead to mold, mildew and plant disease, which should be avoided if possible. Closely monitoring relative humidity levels in a greenhouse and adjusting them as needed is key to growing healthy and bountiful plants (Cogger et al., n.d.).

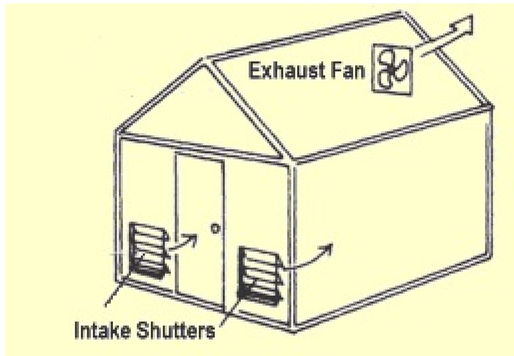
High tunnel greenhouses were initially designed and installed to be simple covered growing spaces for crops, but they can be upgraded significantly through outfitting with environmental controls, electricity, heating and cooling, insulation and ventilation. While not standard to the original high tunnel design, these additions can greatly increase energy efficiency and allow high tunnels to be powerful growing tools for farmers for much of the year. The possibilities are nearly limitless when it comes to upgrading and customizing one's high tunnel greenhouse to best fit their needs and location, but some improvements are more common and effective than others.

Ventilation and Horizontal Airflow Fans

One of the most common upgrades made to a high tunnel greenhouse, often before installation is completed, is the addition of ventilation and horizontal airflow fans (HAF), or air circulation fans. These fans help to reduce overheating and maintain desirable relative humidity levels in a high tunnel greenhouse. One or more exhaust fans are installed on the end wall or in the roof of the greenhouse structure. On the opposite end wall or side of the greenhouse, intake shutters are installed, so that when the exhaust fan is turned on, it forces the intake shutters open, which allows air to be moved from one side of the greenhouse to the other. Figure 1 below offers a better understanding of this process.

Figure 1

Ventilation Fan Diagram



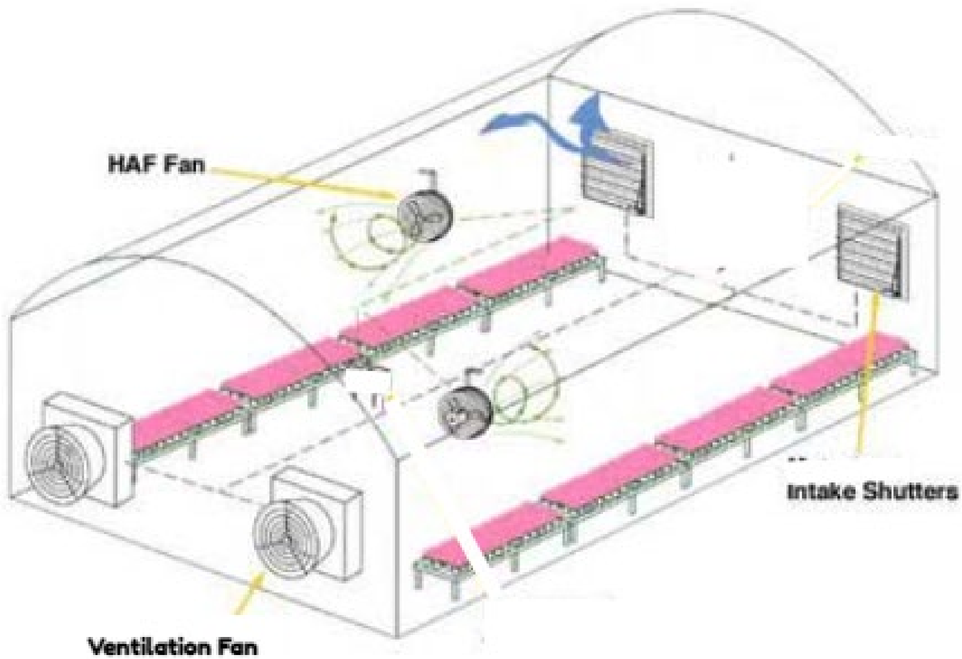
Note. As the fan exhausts the depleted air, a slight vacuum is created that draws in fresh outside air through the intake shutters, ventilating the greenhouse ("What are the Types of Greenhouse Ventilation?", n.d.).

To provide adequate air for the exhaust fan(s), the intake shutter area should be at least 1.25 times the fan area, especially in polyethylene covered greenhouses. This keeps airflow patterns steady and balances the negative pressure that can be caused by the exhaust fan (Bartok & Grubinger, 2019a). Ventilation fans can drastically improve greenhouse microclimate control and provide a method for decreasing the temperature and relative humidity in the greenhouse. Also, because photosynthesis depletes carbon dioxide within the greenhouse boundary layer during daylight hours, ventilation fans allow for fresh air with a higher carbon dioxide content to move into the greenhouse to replace the depleted air (Bartok & Grubinger, 2019a). A study performed by Jayasinghe and Weerakkody (2005) found that the use of ventilation fans in a greenhouse was effective in reducing maximum temperatures by up to 4°C.

In addition to ventilation fans, horizontal air flow (HAF) fans are also a common high tunnel upgrade to provide a more uniform temperature distribution throughout the greenhouse. Figure 2 below shows a diagram of a greenhouse with both HAF and ventilation fans.

Figure 2

HAF Fan Diagram



Note. The greenhouse in this diagram has two horizontal air flow (HAF) fans installed near the center of the structure blowing in opposite directions. The greenhouse also has ventilation fans with intake shutters installed on opposite walls (Factory Fans Direct, n.d.).

Horizontal air flow fans, or air circulation fans, can be installed anywhere throughout the greenhouse, but are typically placed near the center of the structure. The HAF concept states that air that moves in a coherent horizontal pattern in a building like a greenhouse needs only enough energy to overcome turbulence and friction loss to keep it moving. Therefore, HAF fans are installed to ensure air moves consistently throughout the greenhouse (Bartok & Grubinger, 2019b). HAF fans are often installed in groups of two or more fans, installed at a set distance apart, in order to keep air moving throughout the structure. HAF fans also can reduce foliage disease associated with humidity by removing moisture from the plant canopy (Bartok & Grubinger, 2019b). Ventilation and HAF fans are some of the most commonly used ways to keep fresh air flowing in, out of, and around the greenhouse.

Double Glazing

While ventilation and HAF fans work to cool temperatures and decrease humidity in the greenhouse, some high tunnel upgrades aim for the opposite effect, which is insulation. One of the most common insulation related upgrades is a double layer air inflation system (Alexander, 2018). On its own, greenhouse plastic, commonly polyethylene, has very little insulation value. In order to increase greenhouse insulation, a second layer of greenhouse plastic can be installed underneath the outer layer onto the inside frame of the greenhouse, essentially creating a double glazing for the greenhouse. An inflation blower fan(s) is installed between the two plastic layers on the inside of the greenhouse. The inflation blower fan pulls air in from the inside of the greenhouse and blows it out in between the two greenhouse plastic layers, creating an air bubble effect where the volume between the two layers is inflated (Alexander, 2018). The double layer air inflation system provides additional insulation to the greenhouse and improves the structure's ability to retain temperatures on cold nights. Additionally, the system provides structural benefits as it helps the greenhouse to absorb strong winds and shed snow more effectively (Alexander, 2018).

This system can be further improved upon by utilizing an infrared anti-drip (IRAD) greenhouse plastic. Water condensation build up on greenhouse plastics can significantly reduce light transmission. The IRAD plastic prevents condensation build-up between the two layers which can lead to unwanted moisture dripping down onto plants, and has an increased thermicity, which can retain heat better than standard greenhouse polyethylene glazing (Alexander, 2018).

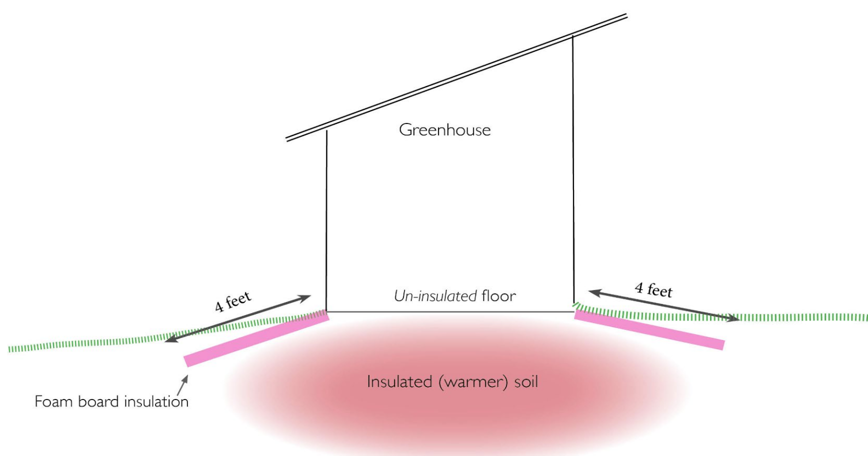
However, double glazing on a greenhouse reduces the amount of photosynthetically active radiation, or PAR, that plants in the greenhouse receive, which is a downside to the double glazing upgrade. According to Maynard & O'Donnell, 2018, a single layer of greenhouse plastic typically transmits 88% to 92% of PAR under ideal conditions, whereas a double layer will likely only transmit 77% to 85% under ideal conditions. As greenhouse plastic ages, PAR transmission decreases, meaning that actual PAR transmission may be as low as 67% when not under ideal conditions (Maynard & O'Donnell, 2018). Greenhouse plastic should be replaced approximately every 5 years (Maynard & O'Donnell, 2018).

Insulated Ground Skirt

Another upgrade that can help increase heat retention in a high tunnel greenhouse is an insulated ground skirt, or a Swedish skirt, as it is commonly referred to in some places. An average home loses approximately 15% of its total heat loss through the floors ("Solar Greenhouse Basics: Insulating Your Foundation", 2015). This is because the ground freezes just like the air does in the winter if it is not insulated. An insulated ground skirt, or Swedish skirt, is an effective, inexpensive option for insulating the ground surrounding a high tunnel greenhouse. To install an insulated ground skirt, rigid foam board is laid horizontally, starting at the base of the greenhouse, and extending an average of 4' away from the greenhouse. The foam boards need to slope gently away from the greenhouse for drainage, which requires digging or raking during the installation process. The foam boards can be wrapped in polyethylene or other greenhouse plastics before being buried in order to further deflect moisture away from the greenhouse foundation. While not required, it is best to cover the foam boards with gravel or soil, as direct UV rays will damage the insulation and can cause the boards to shift from their intended locations. This system prevents wet and frozen soil from creeping under the structure, while keeping the warm, dry soil directly under one's greenhouse. A visual representation of how the insulated ground skirt system works is shown below in Figure 3.

Figure 3

Insulated Ground Skirt Diagram



Note. Rigid foam board insulation is installed horizontally along the sides of the greenhouse, sloping slightly downward to deflect moisture away. The insulated ground skirt allows for warmer, dryer soil underneath the greenhouse ("Solar Greenhouse Basics: Insulating Your Foundation", 2015).

An insulated ground skirt can also be installed vertically, which requires the rigid foam board to be installed 4' vertically underground surrounding the greenhouse's footprint on all sides, although a vertical installation is not technically considered a Swedish skirt (Dawling, 2018). Whether one uses a vertical or horizontal insulated ground skirt, the benefits of this system are undeniable.

Similar to water, stone, or concrete, soil is a thermal mass that stores thermal energy, or heat, and slowly releases it later. By preventing heat loss to the surrounding topsoil, the soil underneath the greenhouse can now trap and store heat, creating a pocket of warmer soil underground ("Solar Greenhouse Basics: Insulating Your Foundation", 2015).

The ground skirt connects the greenhouse to the thermal mass (soil), allowing for warmer, more stable greenhouse microclimate year-around. The reason for installing a ground skirt, or insulating the area around the greenhouse, rather than just insulating the greenhouse floor, is to tap into the Earth's generous source of heat. Soil below the frost line maintains a stable temperature year-around due to geothermal activity, and leaving the floor of the greenhouse uninsulated allows heat exchange to occur between the ground and the greenhouse ("Solar Greenhouse Basics: Insulating Your Foundation", 2015).

There are many other methods used to insulate a high tunnel greenhouse, including bubble plastic and thermal insulation foil that can be installed on the walls of the greenhouse. Greenhouses can also be insulated and heated using solar thermal mass, in ground heating, heating pads, and portable heaters. Improving a greenhouse's insulation and ability to retain heat is a key factor for growing season extension. While season extension is very important, insulation in the greenhouse must be balanced with ventilation in order to avoid overheating and burning of crops.

Sidewall Roll-Up System

In temperate climates, such as Western North Carolina, even during the colder months that span through late fall to early spring where temperatures often reach below freezing, it is not uncommon to have warm spells. For example, the Nexus high tunnel greenhouse, owned by Appalachian State University and located in Boone, NC, historically reaches temperatures over 90 degrees Fahrenheit every month of the year, even during cold winter months. Variations in temperature and solar radiation levels mean that even during the winter, greenhouse owners need to be prepared to both insulate and ventilate their greenhouses.

One effective way to reduce greenhouse overheating and maintain optimal greenhouse microclimate is through a sidewall roll-up system. This system is made up of a long piece of plastic or metal conduit attached along the loose bottom end of the greenhouse glazing along the length of the sidewalls. The conduit is rotated manually or with a motor and wraps the sidewall greenhouse plastic tightly around the conduit as it is rotated. The sidewall can be rolled up or down to help keep rain and wind out of the tunnel, and to provide passive ventilation (Butler & Bauer, 2013). The sidewall roll-up system operates on the principle that heat is removed from the greenhouse when a pressure difference from wind gradients is created, therefore no supplemental energy is required to operate fans to move air from outside to inside of the greenhouse (Bartok & Grubinger, 2019a). The wind speed required to force cool air in the windward sidewall is 2-3 miles per hour (Bartok & Grubinger, 2019a). When the sidewall is open and the wind is blowing, the air traveling over and through the high tunnel creates a vacuum on the leeward side to pull out and replace the heated air (Bartok & Grubinger, 2019a). Figure 4 below shows a greenhouse with a sidewall curtain ventilation system that is in the rolled up position.

Figure 4

Sidewall Roll-Up System Example

Note. This image shows two commercial greenhouses that are equipped with sidewall roll-up systems. The sidewall curtains in this photo are in the rolled up position, allowing for ventilation in the greenhouse (Bartok, 2021).

Sidewall roll-up systems can be motorized or operated manually. Manual operation options for a high tunnel sidewall roll-up system include hand crank systems and gearbox roll-up assemblies. Sidewall roll-up systems can also be powered with motors that require control inputs to roll up or down, or can be automated through timers or thermostatic controllers. While motorized and automated roll-up systems tend to be much more expensive than a manual system, they are typically much more effective in maintaining an ideal greenhouse microclimate. An automated sidewall roll-up system operates in conjunction with a thermostatic control system. The use of a thermostatic controller allows the operator to choose set point temperature or humidity ranges for their greenhouse. The thermostatic controller then works with a temperature or humidity sensor and the greenhouse motor, so that once temperature or humidity falls below or rises above the operator's desired set point, the thermostatic controller signals to the motor to roll up or down in order to readjust to the desired set points. An automated sidewall roll-up system can be a highly effective tool for greenhouse microclimate control, but these systems tend to be fairly expensive. Designing and building these systems independently as opposed to purchasing preprogrammed kits from greenhouse suppliers can make implementation of these systems considerably less costly.

As mentioned in the introduction, there is very little research on the effectiveness of an automated roll-up system for controlling a greenhouse microclimate in temperate weather climates. However, there have been some studies on how these systems perform in more hot and humid environments. A study performed by the University of Maryland and funded by SARE, the Sustainable Agriculture Research and Education program, was carried out from 2005 to 2007. This project focused on high tunnel production by performing a case study on three separate farms in the Mid-Atlantic region with high tunnel greenhouses (Butler & Bauer, 2013). This study validates the ability of the sidewall roll-up system to maintain desirable greenhouse temperatures. As previously explained, the sidewall roll-up system plays a role in maintaining greenhouse temperatures by lowering the sides in the afternoon to hold heat during periods of cold weather, and then raising the sides in the morning to vent before temperatures inside get too high (Butler & Bauer, 2013). This study showed that closing the sidewalls in the afternoons, between 2 and 4 p.m., allows daytime heat to gather overnight (Butler &

Bauer, 2013). As opposed to waiting until nightfall or until temperatures drop to critical lows, closing the sidewalls earlier in the afternoon can be much more effective in maintaining desired temperatures in the high tunnel. However, in the morning, temperatures can quickly reach 100+ degrees Fahrenheit in the high tunnel if it is in the line of direct morning sunlight (Butler & Bauer, 2013).

Heat can easily overwhelm plants as early as 8 or 9 in the morning, meaning that close monitoring and early morning ventilation is key to avoid overheating. Results from the study showed that if greens were planted in February, direct morning sunlight in late-March or April could stunt growth if the sidewalls are not opened to allow heat to escape in the mornings (Butler & Bauer, 2013). During sunny days, temperatures in a high tunnel greenhouse can reach 30 to 40 degrees Fahrenheit higher than outside temperatures, meaning that high tunnels must be adequately vented (Kaiser & Ernst, 2021). Ventilation not only cools the structure's interior, but also lowers humidity and dries foliage which can help reduce plant and insect related diseases.

Another study performed in Shanghai in 2014 used computational fluid dynamics (CFD) to investigate greenhouse seasonal climate variations during the cooling and dehumidification processes with natural ventilation. This study analyzed the effect of vent configuration and vent size opening on high tunnel greenhouse dehumidification time, air temperature and relative humidity (He et al., 2015). During the summer months when the greenhouse is being cooled, the external colder airflow enters into the greenhouse and pushes out the depleted warm internal air. The study concluded that the greater the airflow velocity was from the ventilation openings, the lower the air temperature dropped (He et al., 2015). During the dehumidification process in the winter months, dry airflow from outside penetrates into the greenhouse and replaces the wetter internal air. Airflow velocity affected the difference in humidity between the leeward and windward areas (He et al., 2015). A high airflow velocity in a greenhouse correlates directly with a higher level of turbulence, which leads to more homogeneous distributions of temperature and humidity in the greenhouse (He et al., 2015).

A study done in Ithaca, NY in 2008 characterized the spatial variations of high tunnel temperature during both the growing season and in the winter off-season. The study found that in the summer months, when the sidewall is left open, daytime air temperatures inside of the greenhouse exceeded those outside by 10 degrees Celsius or more on sunny days, and that crop beds located near the open sidewall had temperatures 2 to 3 degrees Celsius cooler than beds approximately 5 meters from the open side (Wien & Pritts, 2009). Similar but opposite effects were observed in the winter, where air temperatures at the center of the tunnel were –6 degrees Celsius, and 1 to 2 degrees cooler at the edge (Wien & Pritts, 2009). By taking advantage of the sun's heat in the daytime and trapping it by closing off ventilation in the afternoons, temperatures inside of the greenhouse were maintained at least 5 °C higher than outdoor temperatures for a majority of the cold season (Wien & Pritts, 2009).

Sidewall ventilation also affected plant growth and development in the study. Plants on the outside row were more susceptible to wind and insect damage, but still had better yields than plants in the center rows because of the increase in lighting. The improved light conditions in the outside rows of greenhouses improved yield of trellised tomatoes from six fruits per cluster for plants in the center of the house, to eight fruits per cluster for the edge plants (Wien & Pritts, 2009). Overall, sidewall ventilation was effective in maintaining desired temperatures and increased crop production.

Although an automated sidewall roll-up system gives the operator additional control over the greenhouse microclimate, it is not always possible to maintain desired temperatures. A study on high tunnel crop yield performed in Eastern North Carolina in 2012 involved a multi-span high tunnel greenhouse with an automated sidewall roll-up system. In this study, increases in nighttime temperatures in the high tunnel compared with field temperatures were small (O'Connell et al., 2012). The study states that on the coldest evenings, a difference of just a few degrees appeared to provide frost protection to the high tunnel transplants even when temperatures dropped below 0 degrees Celsius in the field. The study found that in North Carolina, high tunnel greenhouses could allow tomato production to start as early as 3-4 weeks before normal growing times (O'Connell et al., 2012).

Temperature in the High Tunnel

As mentioned previously, case studies and research on the effect of sidewall ventilation on high tunnel microclimate are very limited, but it is important to understand these topics in order to improve greenhouse management techniques and increase high tunnel energy efficiency. Designing a high tunnel greenhouse with temperature and relative humidity in one's climate in mind is important for best management practices, and management approaches must change with the seasons. The temperature in a high tunnel greenhouse is a balance between energy entering the tunnel, energy stored in the tunnel, and energy leaving the tunnel (Maynard & O'Donnell, 2018). Sunlight is the main source of energy in a passive high tunnel greenhouse. In early fall, the main reason to manage temperatures in the high tunnel is to prevent crop damage from both excessive high and low temperatures. In a warmer fall season, it is not uncommon for the sidewall to be left in the rolled up position. When night temperatures in the fall drop below 35 to 40 °F, the tunnel will need to be closed to avoid near-freezing temperatures in the greenhouse (Maynard & O'Donnell, 2018). As temperatures rise with daybreak, the sidewalls need to be reopened to keep temperatures in the high tunnel below 70 to 75 degrees Fahrenheit. Similarly, during the spring season, it is usually cold enough to keep the tunnel closed at night, whereas sunny warm days are when the tunnel often requires venting (Maynard & O'Donnell, 2018).

Managing the greenhouse through the use of an automated sidewall roll-up system is most beneficial during the spring and fall season because of these high fluctuations in temperature. The automated sidewall roll-up system allows air temperatures inside of the greenhouse to be monitored and controlled through ventilation. During these seasons of high temperature fluctuations, the automated system maintains desired air temperatures in the high tunnel by reacting to these fluctuations and rolling the sidewall up or down as needed. Summer and winter seasons require less input from the automated sidewall roll-up system, because steadily warm or cold outside temperatures typically require the sidewall to be left in the rolled up or rolled down position (Maynard & O'Donnell, 2018). The automated sidewall roll-up system eliminates the need to anticipate out of season temperatures, so that when a rare warm day begins to overheat the greenhouse in the winter, the system can react by rolling the sidewalls up for the duration of time necessary to bring the greenhouse back to one's desired temperature range.

Ventilation fans are also a helpful tool for cooling down a greenhouse when needed and can be used in conjunction with a thermostatic controller to turn on and off as temperature levels inside of the greenhouse vary throughout the day. On the other hand, double glazing is a method that can be used to provide additional insulation in a greenhouse and can increase the structure's ability to retain heat. When temperatures in the greenhouse get too high, relative humidity can drop significantly, and vice versa for very low temperatures that can cause excess of relative humidity (Maynard & O'Donnell, 2018). Maintaining desired temperatures and relative humidity levels in the greenhouse is imperative for healthy and bountiful crop production.

Relative Humidity in the High Tunnel

Monitoring relative humidity (RH) in high tunnel greenhouses helps to determine when venting should occur to reduce moisture buildup, or when additional moisture inputs are needed if the greenhouse is getting too dry. Monitoring RH also helps with understanding the daily and seasonal dynamics of humidity in the greenhouse over time (Maynard & O'Donnell, 2018). This information can then be used to alter management practices to avoid RH-related plant diseases and growth issues, as well as mold and mildew. Respiration of crops at night increases the greenhouse's RH as the air cools down in the evenings (Maynard & O'Donnell, 2018). Air circulation fans are commonly installed in high tunnel greenhouses to reduce moisture buildup and keep the air inside of the greenhouse from becoming stagnant. There are some greenhouse technologies that help to control relative humidity levels in a high tunnel greenhouse. For example, programming one's automated sidewall roll-up system to ventilate the greenhouse in the mornings for 10 to 20 minutes can help to relieve the moisture build up caused by respiration and dry the plants (Butler & Bauer, 2013). Because high tunnels prevent natural rainfall, it is important to find a balance between irrigation and maintaining desirable RH levels in the greenhouse. Precise control of relative humidity is not achievable, and many high tunnel owners choose to prioritize temperature control.

Ventilation through the use of an automated sidewall roll-up system is an effective way to help control temperature and relative humidity levels in a greenhouse (Maynard & O'Donnell, 2018). Ventilation rates from the sidewall openings vary with the size and shape of a high tunnel greenhouse. The more sidewall surface area a high tunnel has in comparison with its volume, the faster it will cool down. Therefore, a long and narrow high tunnel will cool down quicker than a short and wide high tunnel covering the same area (Maynard & O'Donnell, 2018). Orienting the high tunnel so that the roll-up sides face prevailing winds can improve the passive ventilation provided by the rollup sidewalls (Maynard & O'Donnell, 2018).

High tunnel greenhouses are a great option for growing season extension, and the farmers and crop producers that use them are typically rewarded with more and higher quality harvests than those grown in fields (Adams & Todd, 2015). High tunnels can also allow producers to extend the time period over which cash flows are generated from certain crops resulting from extended growing seasons. Location specific conditions, such as available sunlight, average temperatures, winds, neighboring land uses, and government regulations, will impact the success of a high tunnel, which is why it is important to analyze how these structures perform in different zones (Adams & Todd, 2015). With careful planning, site preparation, and the use of quality components and systems, such as an automated sidewall roll-up system, ventilation fans and double glazing, a high tunnel greenhouse can be taken from being a simple covered structure to being a highly effective tool for producing healthy crops and bountiful harvests.

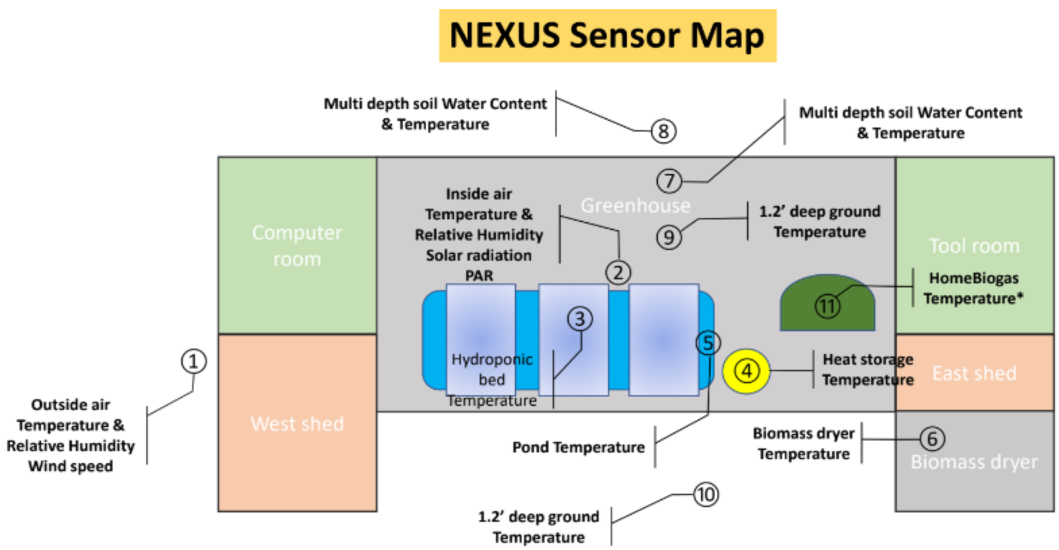
RESEARCH METHODOLOGY

This project will analyze the effects of an automated sidewall roll-up system, ventilation and horizontal airflow fans, and double glazing on high tunnel greenhouse air temperature, relative humidity, and light transmission. The study will also analyze the overall effects on greenhouse temperature and relative humidity of five interventions, the automated sidewall roll-up system, ventilation and horizontal airflow fans, double glazing and an insulated ground skirt, working in conjunction. The facility this study will be performed at is the Nexus Facility owned by Appalachian State University that is located in Boone, NC. This property features a 20’x30’ high tunnel greenhouse that is outfitted with an automated sidewall roll-up system, two ventilation fans, two horizontal air flow circulation fans, two layers of polyethylene greenhouse plastic, and an insulated ground skirt. The structures’ volume is 6,800 cubic feet.

As mentioned previously, data that was gathered includes inside and outside air temperature and relative humidity, ground temperature and moisture content, as well as solar irradiance, PAR, dew point, wind speed, gust speed and wind direction. The data will be acquired using the existing ONSET RX3000 remote logging system at the Nexus facility. These additional data points will be collected in order to provide a more thorough data analysis and comparison between greenhouse microclimate before and after the additions of the systems, but temperature, humidity and light transmission are the main data points being focused on. Data will be collected through the use of existing and additional sensors and data loggers that are installed in various points around the greenhouse, as well as in the ground surrounding the ground skirt and sidewall roll-up system. Currently, the sensors and data loggers at the Nexus facility are collected in 5-minute intervals. Additional sensors and loggers installed for this project will follow this same interval to simplify the data analysis process. The locations of the sensors installed at the Nexus facility are detailed in the map shown below in Figure 5.

Figure 5

Nexus Sensor Map



Note. This image shows the sensor map for the Nexus facility.

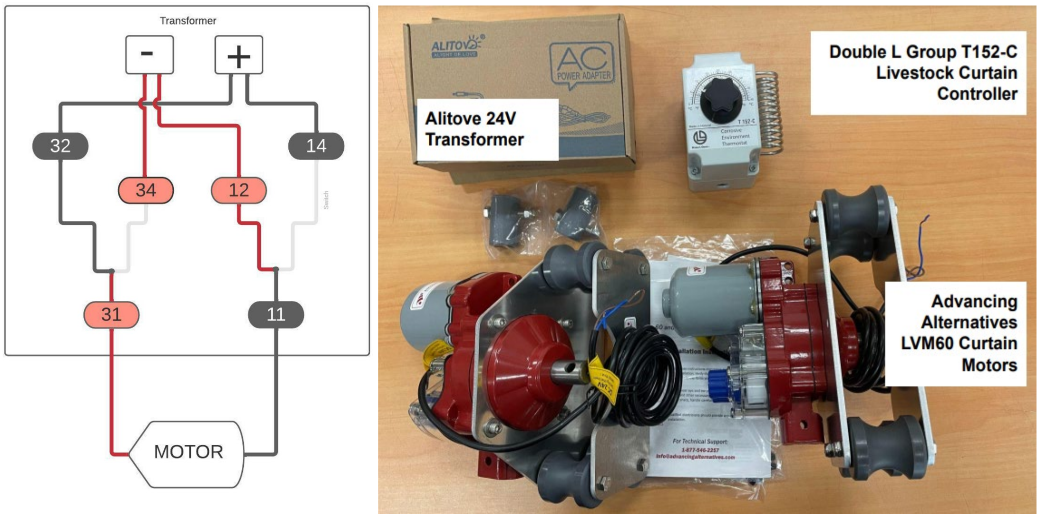
Data will be collected on the effect of the systems on greenhouse microclimate and analyzed using Excel. Ongoing efforts associated with the Nexus Project simplified funding for this study. Materials for the installation of the two ventilation fans, two air circulation fans, and the ground skirt at the Nexus facility were purchased under the Nexus projects' AEC 2020 internal grant. Costs associated with the sidewall roll-up system will be covered by an ASUREI student engagement grant that was approved in April 2021. This grant will allow materials for the system to be purchased costing up to $1,500, which was the approximate total cost for the installation of the automated sidewall roll-up system on both sides of the Nexus greenhouse.

Research Question #1

In order to address the research question, “How does the installation of an automated sidewall roll-up system affect temperature and relative humidity levels in a high tunnel greenhouse?” data points will be taken from before and after the system’s installation and compared to determine the numerical and percent differences. The automated sidewall roll-up system installed at the Nexus facility will consist of two (2) Advancing Alternatives LVM60 greenhouse curtain motors, two (2) Double L Group T152-C livestock curtain controller thermostats, and two (2) Alitove 24V transformers. The installation of this system began by securing a 1.315” galvanized metal pipe to the sidewall curtain of the greenhouse, which is secured onto the motor. The motor was then connected to the Double L Group thermostat controller, which is connected to the transformer, and then the power supply. Figure 6 below shows a diagram that displays the different components of the automated sidewall roll-up system and the wiring of the system.

Figure 6

Automated Sidewall Roll-up Components and Wiring



Note. The left side of the image shows a wiring diagram representing the inside of the T152-C curtain controller. The right side of this image shows the components used to build the automated sidewall roll-up system, not including the (2) 30’ 1.315” galvanized metal pipes that were attached to the sidewall curtain and motor.

The thermostatic controller will be set at a temperature range of 60°F-68°F. Once the greenhouse reaches an indoor temperature outside of the set range, the system will work to roll the sidewall up or down in order to adjust the indoor temperature as needed.

The automated sidewall roll-up system was installed at Nexus on April 17th, 2022, and its effect on greenhouse temperatures and relative humidity were analyzed. In order to isolate the effects of the automated sidewall roll-up system from the ventilation fans, the ventilation fans were unplugged and turned off for a two week time period, from October 11th to October 25th, 2022. A majority of the data used to analyze the effect of the automated sidewall roll-up system will be drawn from this time period. To measure the impact of this system, an in-depth excel analysis was performed on data collected from both before and after the installation of the automated sidewall roll-up system.

Conditional formatting will be used to simplify the data organization on Excel, and from there, we will identify 20-30 groups of days with similar outside weather conditions from before and after the systems installation. Pairs and groups of days were selected by evaluating outdoor temperatures, relative humidity (RH), dew point, wind speed and irradiance levels to find days from before and after the installation of the automated sidewall roll-up system with near identical outdoor weather conditions. Days that were selected for comparison had a difference of less than 2°F and relative humidity levels that differed by no more than 5%. Once we have identified pairs and groups of days with similar outdoor weather conditions, we will compare indoor temperature and relative humidity data points from inside of the greenhouse to see how the system's performance affects the greenhouse microclimate. Daily, monthly, and annual data will also be compared to characterize the effect of this system.

The number of hours and days that the greenhouse was outside of the desirable relative humidity and temperature range was also calculated in order to determine the percentage of time that greenhouse was inside of the desired range when outdoor weather conditions exceeded the desirable range. For example, one of the calculations performed was to pinpoint the percentage of time that relative humidity in the greenhouse was maintained below 80%, when outside RH levels were above 80%. The equation used for this calculation is as follows:

$$\%\, of\ time\ = (1 - (\, (\#\, of\ hours\ GH\ RH\ is\ above\ 80\%) \div (\#\, of\ hours\ outdoor\ RH\ is\ above\ 80\%)) \times 100)$$

Determining the percentage of time that desirable temperature and RH levels exist in the greenhouse allows us to evaluate the way that the interventions have altered the greenhouse microclimate. This process will be repeated to answer the following research questions as well. The ONSET RX3000 remote logging system at the Nexus facility collects data in 5 minute intervals, so we will be able to pinpoint the time of day with the most similar outdoor weather conditions and compare indoor data points from those specific time intervals, in order to carry out the most accurate data analysis possible. Results will be recorded in the form of percent (%) increase or decrease in temperature and relative humidity inside of the greenhouse.

Research Question #2

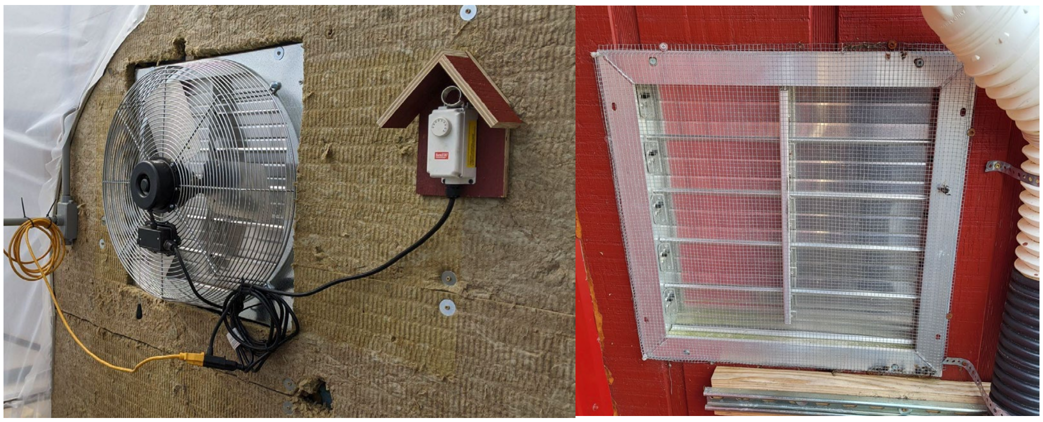
In order to address the research question, "How does the installation of two ventilation fans and two horizontal airflow fans affect temperature and relative humidity levels in a high tunnel greenhouse?", a similar approach will be used as for question one. Data points will be taken from before and after the system's installation and compared to determine the numerical and percent differences. The Nexus greenhouse is equipped with two (2) heavy duty two-stage exhaust fans mounted on the east end wall, with two (2) 2.4 sq. ft. intake shutters that are mounted into the west end wall of the greenhouse. The 115V, 4.8A ventilation fans were sourced from J&D Manufacturing and have a surface area of 5.4 square feet. These fans provide one air exchange per minute in the greenhouse when they are turned on (Kim, 2021).

The fans are connected to a thermostat controller that is set at 70°F, meaning that the fans are set to turn on automatically once temperatures in the greenhouse exceed

70°F. These ventilation fans were installed on March 4th, 2021. Figure 7 below shows an image of one of the ventilation fans and an intake shutter at the Nexus greenhouse.

Figure 7

Ventilation Fans at Nexus



Note. This image shows one of the two ventilation fans that are mounted on the east end wall of the Nexus high tunnel greenhouse, as well as the intake shutter that is installed opposite of the fan on the west end wall.

On the same day, March 4th, 2021, two horizontal airflow fans (HAF) were also installed in the greenhouse. These 120V, 0.58A HAF fans are manufactured by Powermax Electric Co. and run 24 hours a day to keep air circulating throughout the greenhouse. The HAF fans are expected to reduce excess moisture and create a more uniform temperature throughout the greenhouse. Figure 8 below shows an image of the horizontal airflow fans that are installed inside of the Nexus greenhouse.

Figure 8

HAF Fans at Nexus

For this research question, an in-depth excel analysis will be performed on data from the year both before and after the installation of the HAF and ventilation fans. The results will focus specifically on greenhouse temperature and relative humidity, but data will also be collected on solar radiation, PAR, dew point, wind speed, and wind direction to ensure the most accurate results for the study, using the ONSET RX3000 remote logging system. Procedures used for data analysis within Excel will be the same as those used to answer research question #1, as well as to quantify the effects of the other systems being analyzed in this study. Daily, monthly, and annual data will also be compared to characterize the effect of these systems.

Research Question #3

In order to address the research question, "How does double glazing affect temperature and light transmission levels in a high tunnel greenhouse?", a similar approach will be used as was for questions one and two. Data points will be taken from before and after the system’s installation and compared to quantify the effect of double glazing on light transmission and temperature inside of the greenhouse.

A second layer of greenhouse polyethylene was installed onto the inside of the Nexus greenhouse at the end of February 2021. Figures 9 and 10 below show photos during and after the installation of the double glazing at the Nexus greenhouse.

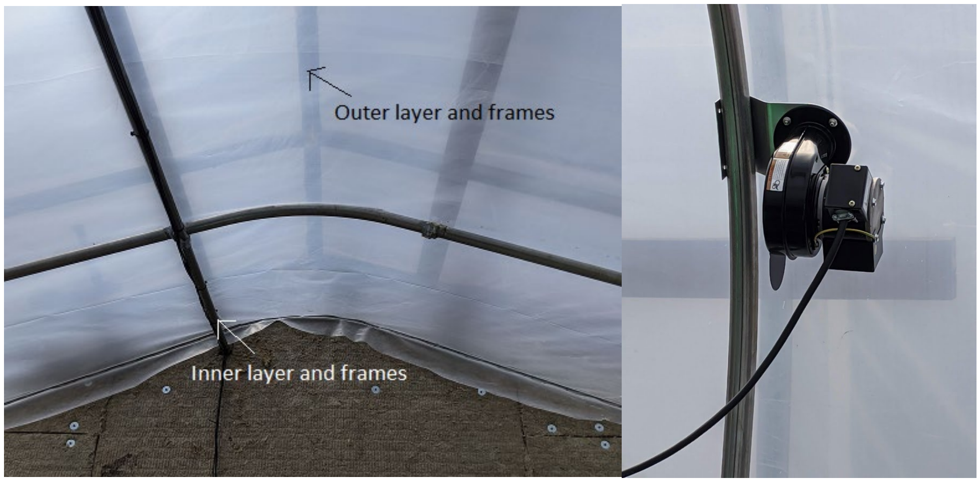
Figure 9

Double Glazing Installation at Nexus

Note. This image shows the second layer of polyethylene film being installed on the inside framing of the greenhouse. The film was spread across the inner frame and secured in place along the bottom of the frame using wiggle wire.

Figure 10

Double Glazing at Nexus



Note. These images show the separation between the inner and outer layers of polyethylene film on the greenhouse after the double glazing installation was completed. Two air inflation fans were installed and run continuously to separate the layers and create a bubble effect on the top of the greenhouse. This helps with insulation, wind protection, and snow shedding.

Double glazing was the first intervention from this study installed at the Nexus greenhouse on February 12th, 2021, and there were no other greenhouse microclimate control technologies installed until March 4th, 2021 when the ventilation and horizontal airflow fans were put in. The time period between February 12th, 2021 and March 4th, 2021 can be used to best represent the effects of double glazing on light transmission and indoor temperatures since there were no other systems manipulating the greenhouse's natural microclimate at this time. Data from this time period will be primarily used for the double glazing analysis. The ONSET RX3000 remote logging system will be used to collect data from the year before and after the systems installation in order to quantify the effect of double glazing on greenhouse temperature and light transmission. As with all of the research questions, conditional formatting will be used to simplify the data organization on Excel, and from there, we will identify 20-30* groups of days with similar outside weather conditions from before and after the systems installation. Once we have identified pairs or groups of days with similar outdoor weather conditions, we will compare indoor temperature and light transmission data points from inside of the greenhouse to see how the system's performance affects the greenhouse microclimate. Light transmission through the greenhouse was calculated by converting irradiance data to sun-hours. Indoor and outdoor irradiance values were used to calculate average daily indoor and outdoor sun hours values using the following calculation.

$$Daily\ Sun\ Hours = Irradiance \times 24 \div 1000$$

Average daily sun hour values from inside and outside of the greenhouse were then used to find the percent of light transmitted through the greenhouse using the following calculation.

$$Light\ Transmission\ (\%) = Indoor\ Sun\ Hours \div Outdoor\ Sun\ Hours$$

Light transmission values were then averaged to daily and monthly values for data analysis purposes. Annual data will also be compared to characterize the effect of this system.

Research Question #4

In order to address the research question, "What is the overall effect of all five interventions (double glazing, ventilation fans, horizontal airflow fans, an insulated ground skirt and the automated sidewall roll-up system) on temperature and relative humidity levels in a high tunnel greenhouse?", data points will be compared from before and after the five system's installations to determine the numerical and percent differences.

As with the other research questions, the RX3000 remote logging system will collect data on inside and outside ground and air temperature, relative humidity, solar radiation, PAR and dew point, as well wind direction, wind speed, and gust speed. These data points will be organized on Excel using conditional formatting to identify pairs and groups of days with similar weather conditions. Once we have identified days with similar outdoor weather conditions, we will compare indoor and ground temperature and relative humidity data points from inside of the greenhouse to see how the system's performance has affected the greenhouse microclimate. We will also identify the number of days and hours that greenhouse temperature and relative are outside and inside of our desired range. This will help us determine the overall effect of the five systems on greenhouse performance, and quantify their ability to reduce freezing, overheating, excessive dryness, and excessive moisture in the greenhouse. Daily, monthly, and annual data will also be compared to characterize the effects of this system.

RESULTS

Research Question #1: How does the installation of an automated sidewall roll-up system affect temperature and relative humidity levels in a high tunnel greenhouse?

Effect of the Sidewall Roll-up System on Greenhouse Relative Humidity

The effect of the sidewall roll-up system on greenhouse relative humidity was analyzed first. The first step in analyzing the effect of the sidewall roll-up system on greenhouse relative humidity was to perform a day by day comparison. Pairs and groups of days were selected by evaluating outdoor temperatures, relative humidity, dew point, wind speed and irradiance levels to find days from before and after the installation of the automated sidewall roll-up system with near identical outdoor weather conditions. Once these similar days were identified and matched up, indoor relative humidity levels were compared. Table 2 displays a chart showing these pairs and sets of days with near identical outdoor conditions.

Table 2

Sidewall Roll-up Relative Humidity Analysis #1

DATE	AVG RH GH	DATE	AVG RH GH
10/18/2020	68.0	10/15/2020	72.7
10/4/2020	73.1	10/22/2020	77.0
10/3/2020	71.3	10/21/2020	76.2
10/21/2022	63.1	10/27/2020	78.8
10/23/2022	68.6	10/16/2022	75.2
10/14/2020	60.2	10/17/2020	65.6
10/15/2022	64.7	10/21/2022	63.1
10/15/2020	72.7	10/18/2020	68.0
10/13/2022	76.0	10/23/2022	77.8
10/17/2020	65.6	10/4/2020	73.1
10/20/2022	64.6	10/11/2022	76.6

Note. This chart shows pairs and sets of days with similar outdoor weather conditions selected from before and after the installation of the automated sidewall roll-up system. Gray shading in this chart differentiates between the groups of days that were compared. 2022 values are highlighted in red text.

The data presented in Table 2 did not indicate any noticeable trend in the effect of the automated sidewall roll-up system on greenhouse humidity levels. As can be seen in the chart, greenhouse relative humidity levels in 2022 were sometimes higher, and sometimes lower, than the RH levels recorded in 2020 prior to the sidewall roll-up systems' installation. Another analysis method was attempted in order to identify the effect of the system on greenhouse relative humidity levels.

Data was selected from the time period between April 17th through October 17th for the years 2020 and 2022. Analysis was performed to determine the number of days that relative humidity levels exceeded 80% inside of the greenhouse and outdoors to determine the effect of the automated sidewall roll-up system on relative humidity. Table 3 below shows the number of days that GH and outdoor RH levels were over 80%, as well as the percentage of time that greenhouse RH levels were over 80% when outdoor RH levels were over 80%.

Table 3

Sidewall Roll-up Relative Humidity Analysis #2

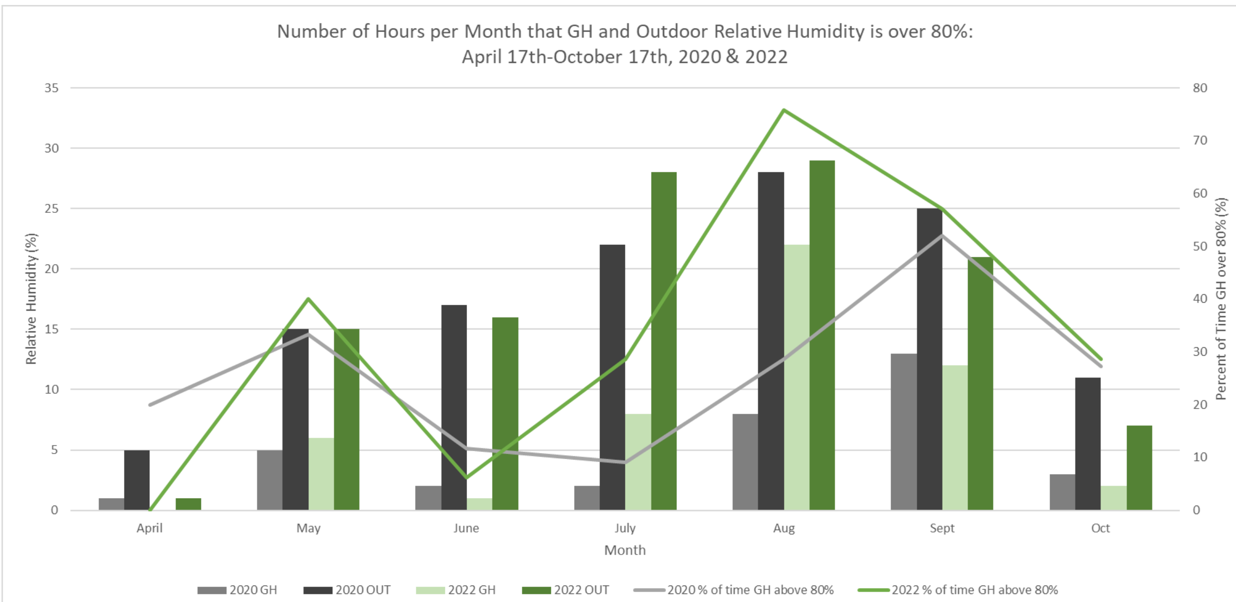
	# of Days that RH exceeds 80%: April 17th - Oct. 17th, 2020 vs. 2022						
	Year	2020	**2020**	2020	2022	**2022**	2022
	Location	GH	OUT	% of time GH above 80%	GH	OUT	% of time GH above 80%
17-31st	April	1	5	20	0	1	0
	May	5	15	33.3	6	15	40
	June	2	17	11.8	1	16	6.3
	July	2	22	9.1	8	28	28.6
	Aug	8	28	28.6	22	29	75.9
	Sept	13	25	52	12	21	57.1
1-17th	Oct	3	11	27.3	2	7	28.6
	Sum	34	123	**28%**	51	117	**44%**

Note. The number of days that relative humidity levels exceed 80% in the greenhouse and outside between April 17th and October 17th for the years 2020 and 2022. This chart also shows the percentage of time that GH RH exceeded 80% when outdoor RH levels exceeded 80%.

In 2020, prior to the installation of the automated sidewall roll-up system, when outdoor relative humidity levels were over 80%, greenhouse relative humidity levels exceeded 80% for only 28% of the time. In 2022, following the installation of the system, when outdoor relative humidity levels were over 80%, greenhouse relative humidity levels exceeded 80% for 44% of the time. Figure 11 below shows a graph based on the data presented above in Table 3.

Figure 11

Sidewall Roll-up Relative Humidity Analysis #3



Note. The number of days and percentage of time that relative humidity levels exceed 80% in the greenhouse and outside between April 17th and October 17th for the years 2020 and 2022.

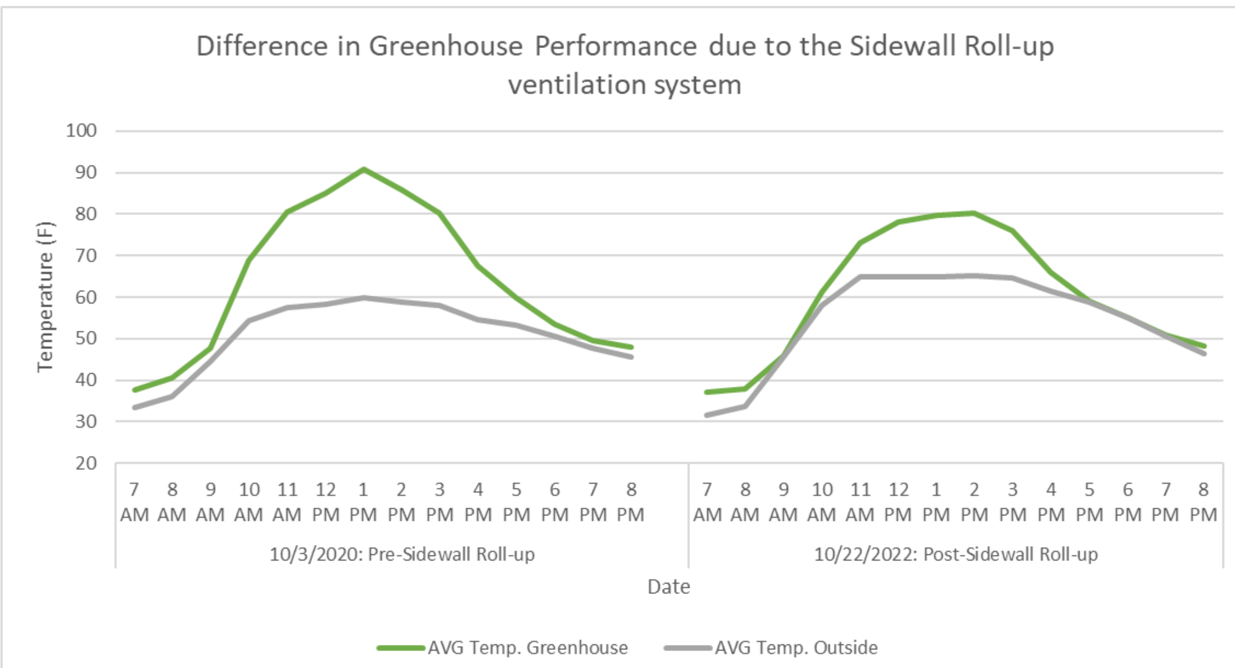
Based on the results presented in Table 3 and Figure 11, it can be concluded that there was a 16% decrease in the greenhouse's ability to maintain relative humidity levels under 80% following the installation of the automated sidewall roll-up system.

Effect of the Sidewall Roll-up System on Greenhouse Temperature

The main purpose of the automated sidewall roll-up system is to decrease events of overheating and freezing in the greenhouse. Several different methods were used to analyze the effect of the automated sidewall roll-up system on indoor greenhouse temperatures. This first approach to analyzing the system's effect on greenhouse temperature was to look at day by day comparisons. Figure 12 below presents a comparison between two days with nearly identical weather, October 3rd, 2020 and October 22, 2022. The graph shows hourly data for temperatures measured inside and outside of the greenhouse for the two days.

Figure 12

Sidewall Roll-up Temperature Analysis #1



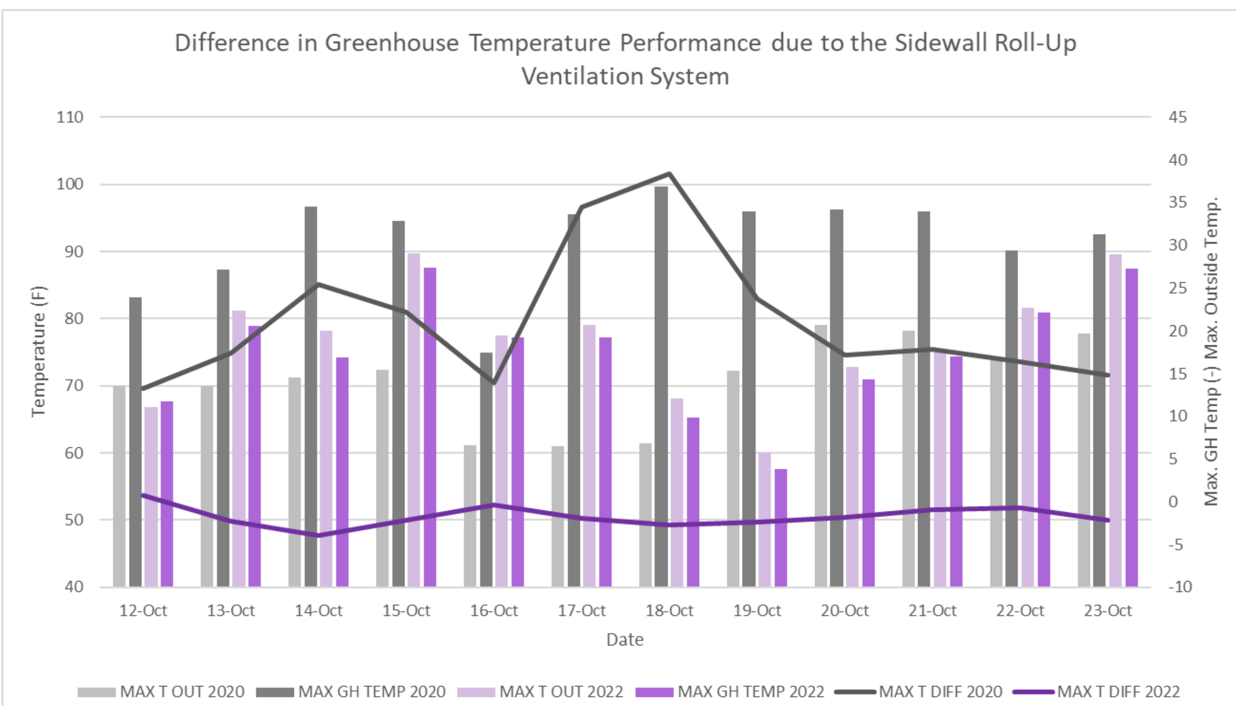
Note. This graph shows hourly average greenhouse and outdoor temperatures for October 3rd, 2020 and October 22, 2022.

As can be seen in Fig. 12, prior to the installation of the automated sidewall roll-up system, on October 3rd, 2020, outdoor temperatures peaked at 60°F, while greenhouse temperatures peaked at 90°F. However, on October 22nd, 2022, after the installation of the system, outdoor temperatures peaked at 65.2°F, while greenhouse temperatures peaked at only 80°F. In 2020 there was an average 30.9°F difference between outdoor and indoor temperatures, while in 2022, the average difference between inside and outside temperatures was only 15.1°F. This data supports the hypothesis that the sidewall roll-up system is reducing overheating episodes in the greenhouse.

For the next analysis method, we zoomed out on a larger time period to better understand the effects of this system on greenhouse temperature. For both the years of 2020 and 2022, data from October 12th through October 23rd was selected and analyzed. Figure 13 below presents daily maximum greenhouse and outdoor temperatures for this time period, as well as temperature differences between in and outdoor at the Nexus facility.

Figure 13

Sidewall Roll-up Temperature Analysis #2



Note. This graph represents the differences in greenhouse temperatures from 2020 to 2022 during the selected time period. Maximum daily greenhouse and outdoor temperatures, as well as the temperature difference between maximum daily GH and outdoor temperatures.

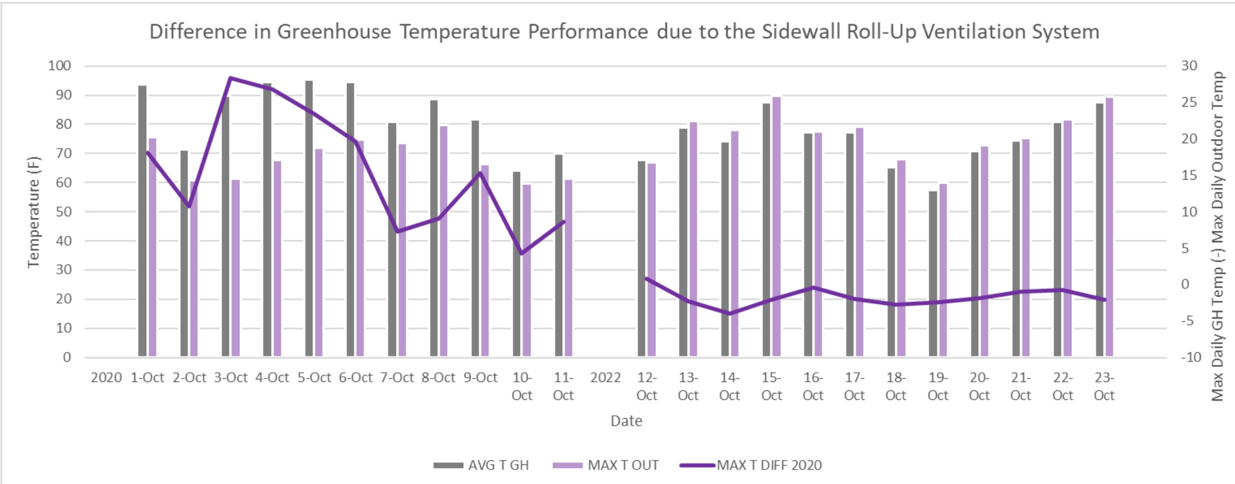
In Fig. 13, it can be seen that the greenhouse was frequently overheating in 2020, reaching temperatures above 90°F during nine out of the twelve days represented in this graph. Prior to the installation of the automated sidewall roll-up system, the greenhouse was consistently experiencing large upward swings in temperature around midday. On October 18th, 2020, the temperature difference, during the peak of the day, between inside and outside of the greenhouse was 37.9°F, with the greenhouse reaching 99.8°F around 2pm.

In 2022, after the installation of the automated sidewall roll-up system, the greenhouse experienced far fewer overheating events, regardless of the fact that outdoor temperatures were generally warmer in 2022 than in 2020. The greenhouse is now relatively stable in relation to outside temperatures throughout the day following the installation of this system. During the time period between October 12th and October 23rd, in 2020, prior to the installation of the sidewall system, the average temperature difference between inside and outside of the greenhouse was 20.3°F. In 2022, after the systems' installation, the average temperature difference between inside and outside was only 1.6°F. This means that the automated sidewall rollup is capable of decreasing greenhouse temperatures by up to 18.7°F to avoid overheating.

The same methodology used in Figure 13 was also used to compare data from October 12th through 23rd, 2022, with a different time period, October 1st through 11th, 2020, in Figure 14. Figure 14 below shows this comparison.

Figure 14

Sidewall Roll-up Temperature Analysis #3



Note. This graph presents average daily greenhouse and outdoor temperatures from the selected time periods. The left side of the graph represents data from 2020, while the right side represents 2022.

The graph shown in Fig. 14 is broken up into two halves, with the left side representing Oct. 1-11th, 2020, and the right side representing Oct. 12-23rd, 2022. It can be clearly seen that the difference between greenhouse and outdoor temperatures is significantly larger in 2020, prior to the installation of the automated sidewall roll-up system. During the time period between October 1st and October 11th, 2020, prior to the installation of the sidewall system, the average temperature difference between inside and outside of the greenhouse was 15.6°F. In 2022, after the systems' installation, the average temperature difference between inside and outside was only 1.6°F. Based on the data presented in Fig. 14, the automated sidewall rollup system decreased the difference between indoor and outdoor temperatures by 14°F, which leads to less frequent overheating events in the greenhouse.

The average daily differences found between indoor and outdoor temperatures from 2020 and 2022 were 15.8°F in Fig. 12, 18.7°F in Fig. 13 and 14°F in Fig. 14. In efforts to quantify one value for the effect of the automated sidewall rollup system on greenhouse temperatures, the values concluded from Figures 12, 13, and 14 were averaged. It was concluded that the average greenhouse to outdoors temperature difference from before and after the installation of the automated sidewall roll-up was 16.2°F.

Prior to wrapping up the analysis of the sidewall roll-up system, I wanted to lastly look at the number of hours that the greenhouse was outside of our desired temperature range during a specific time period. Again, October 12th through October 23rd, for the years 2020 and 2022, was the time period selected. The number of hours that greenhouse temperatures exceeded 80°F was recorded, as well as the number of hours that outdoor temperatures exceeded 70°F. This information was used to calculate the percentage of time that greenhouse temperatures were maintained below 80°F when outdoor temperatures were above 80°F. Table 4 below shows that chart containing this data.

Table 4

Sidewall Roll-up Temperature Analysis #4

	2020			2022		
DATE	Hours Over 80F GH	Hours Over 70F Outside	% of time GH is <80F when OUT T <70F	Hours Over 80F GH	Hours Over 70F Outside	% of time GH is <80F when OUT T <70F
12-Oct	4	0	100	0	0	n/a
13-Oct	5	0	100	1	0	100
14-Oct	6	5	100	0	0	n/a
15-Oct	6	4	100	4	6	0.667
16-Oct	0	0	n/a	0	1	0
17-Oct	6	0	100	0	0	n/a
18-Oct	6	0	100	0	0	n/a
19-Oct	6	3	100	0	0	n/a
20-Oct	6	6	100	0	0	n/a
21-Oct	6	8	0.75	0	0	n/a
22-Oct	6	6	100	2	0	100
23-Oct	6	6	100	4	5	0.8
AVG	5.3	3.2	91.0	0.9	1.0	40.3

Note. This chart presents data on the number of hours that greenhouse temperatures reach above 80°F and outdoor temperatures reach above 70°F for the selected time period, in 2020 and 2022. The right column in the chart shows the percentage of time that greenhouse temperatures are over 80°F when outdoor temperatures are over 70°F.

The data presented Table 4 allows us to conclude that the percentage of time that greenhouse temperatures are maintained below 80°F when outdoor temperatures are above 70°F was 9% in 2020 and 59.7% in 2022. Results presented in the past four figures support the hypothesis that the automated sidewall roll-up system does positively affect indoor temperatures and reduces the number of overheating events in the greenhouse.

Research Question #2: How does the installation of two ventilation fans affect temperature and relative humidity levels in a high tunnel greenhouse?

Effect of the Ventilation Fans on Greenhouse Relative Humidity

Maintaining an optimal range of relative humidity between 40-80% in a greenhouse is imperative to avoid moisture buildup or excessive dryness that could harm crops. Finding a proper balance for the ventilation of a greenhouse is key to maintaining relative humidity levels in a desired range. The effect of the ventilation fans on greenhouse relative humidity and temperature was analyzed. The effect of the ventilation fans on relative humidity was evaluated first using multiple approaches. The first approach was identifying days with extremely similar outdoor weather conditions in order to find comparable time periods. Once these pairs of days and time periods were identified, data points collected on indoor relative humidity were analyzed and compared to determine the effect of the ventilation fans. The following chart shown in Table 5 presents a small selection of the many days with similar weather conditions that were compared.

Table 5

Ventilation & HAF Fans Relative Humidity Analysis #1

DATE	T OUT	RH OUT	IRR OUT	WIND SPD	RH GH NW	RH GH SW
8/27/2020	71.9	84.5	225.1	1.9	76.5	72.8
6/21/2021	71.3	83.8	248.0	2.8	78.9	77.3
10/6/2020	56.2	86.2	196.3	0.9	73.8	67.8
5/17/2021	56.0	85.6	185.5	1.2	72.4	68.8
10/21/2020	59.5	86.3	167.7	1.2	76.8	70.8
6/2/2021	60.1	85.5	166.4	0.9	75.2	75.4
6/23/2020	67.1	84.7	204.5	1.6	67.4	63.9
6/29/2022	68.3	84.4	201.6	0.7	74.9	75.9
8/26/2020	71.8	84.8	231.9	0.9	76.1	71.6
7/24/2022	71.4	85.4	241.4	0.5	77.6	76.5
1/15/2020	53.2	98.3	41.2	2.0	87.4	86.4
9/10/2022	60.0	98.8	51.9	1.4	93.0	91.7
11/10/2020	58.4	98.4	47.2	3.2	78.6	74.5
9/10/2022	60.0	98.8	51.9	1.4	93.0	91.7
8/3/2020	63.7	98.7	68.3	0.5	77.7	75.7
9/5/2022	65.5	99.6	72.0	0.7	92.8	93.0
11/12/2020	59.5	98.8	61.5	1.4	88.9	87.7
9/22/2021	58.9	97.8	66.9	2.7	91.0	91.7
9/10/2022	60.0	98.8	51.9	1.4	93.0	91.7
11/11/2020	63.4	99.2	48.0	2.1	86.5	85.1
9/21/2021	61.1	99.9	55.8	1.5	93.0	91.9
5/27/2020	59.4	99.9	52.1	1.9	87.9	85.2
10/8/2021	59.6	100.0	52.7	0.9	93.9	94.0
10/25/2020	55.6	100.0	46.0	0.7	87.6	83.3
10/8/2021	59.6	100.0	52.7	0.9	93.9	94.0

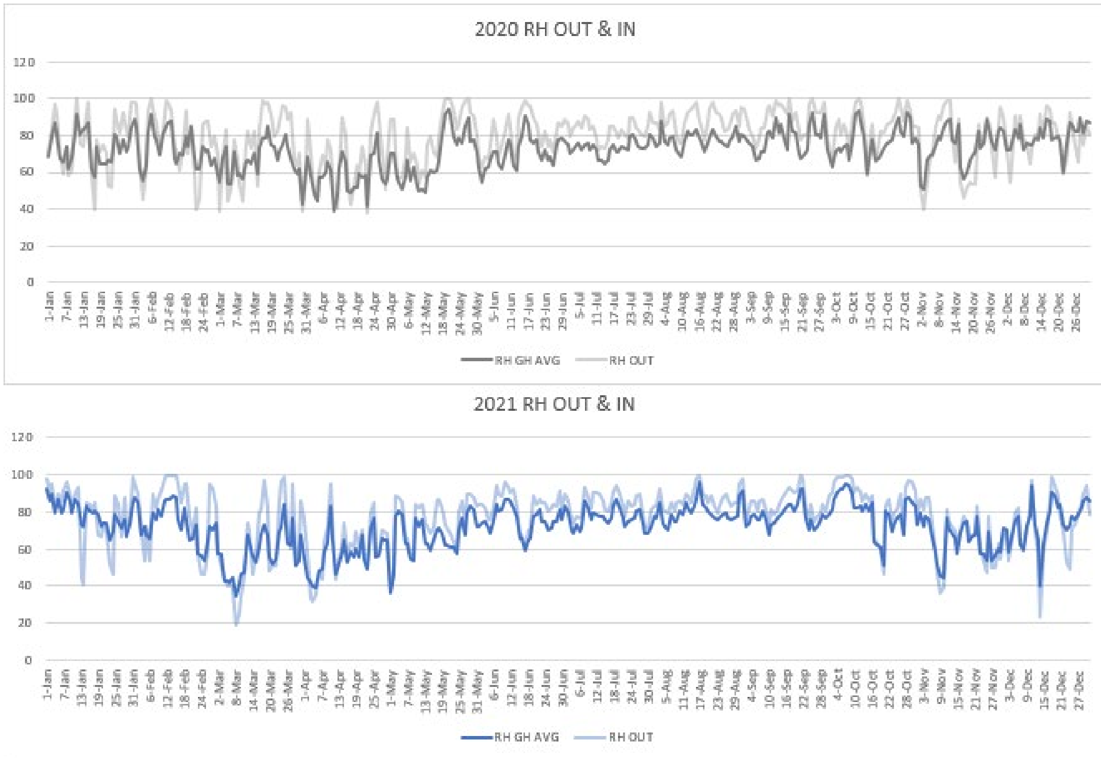
Note. This chart shows pairs and sets of days with similar weather conditions selected from before and after the installation of the ventilation fans. The left side of the chart shows daily averages for outdoor weather values (outdoor temperature, relative humidity, irradiance, and wind speed), while the right side represents indoor relative humidity (RH) levels measured at the north wall (NW) and south wall (SW) of the greenhouse.

The values that are highlighted in red in the far right column of Table 5 show the days where greenhouse relative humidity was higher after the installation of the ventilation fans when compared with days from before the installation. Looking at only the data represented in Table 5, it can be seen that greenhouse relative humidity levels are actually higher post interventions 92% of the days represented in this chart. Using only this analysis method, we cannot determine if greenhouse relative humidity is generally increased or decreased due to the ventilation fans. For that reason, another analysis approach was tested.

In efforts to identify the effect of the ventilation fans on greenhouse relative humidity, we next calculated the sum of days that greenhouse and outdoor relative humidity levels were over 80%. That data was then used to determine the percentage of time that greenhouse relative humidity levels were maintained below 80% when outdoor humidity levels were above 80% in 2020, before the ventilation fans were installed, and 2021, post-installation. Figure 15 and Table 6 below show relative humidity levels, and the number of days relative humidity was over 80% for those two years.

Figure 15

Ventilation & HAF Fans Relative Humidity Analysis #2



Note. These graphs show indoor and outdoor relative humidity levels for the years 2020 and 2021.

Table 6

Ventilation & HAF Fans Relative Humidity Analysis #3

# of Days that Relative Humidity levels exceed 80%: Pre & Post-HAF and Ventilation Fans			
2020	2020	2021	2021
OUT	GH	OUT	GH
210	83	200	93

Note. This chart shows the number of days that relative humidity (RH) levels reached above 80% outdoors and inside of the greenhouse (GH) in 2020 and 2021.

The data represented in Table 6 was used to determine the percentage of time the greenhouse relative humidity levels were maintained below 80% when outdoor RH levels were above 80%. The study found that relative humidity levels were maintained under eighty percent in greenhouse 60% of the time in 2020, but only 53% of the time in 2021 post-ventilation fans. The analysis method, once again, did not show us that relative humidity levels are reduced in the greenhouse due to the ventilation fans, which was the desired result of this study. To be sure that the utilization of daily averages in the previous two analyses wasn't causing an error in the results, we zoomed in to look at hourly relative humidity levels.

The sum of hours that greenhouse and outdoor relative humidity levels were over 80% were calculated for 2020 and 2021. Table 7 below shows the number of hours over 80% for those two years. Due to the fact that the ventilation fans were installed on the morning of March 5th, 2021, data points from March 1st through 4th were omitted from both the 2020 and 2021 datasets.

Table 7

Ventilation & HAF Fans Relative Humidity Analysis #4

	# of Hours over 80%							
	Year	2020	2020	2021	2021		2020	2021
	Month	GH	OUT	GH	OUT		% time over 80%	% time over 80%
5th-31st	Mar	250	339	111	225		73.7	49.3
	Apr	172	241	103	139		71.4	74.1
	May	319	412	275	371		77.4	74.1
	Jun	340	451	371	444		75.4	83.6
	Jul	375	464	406	474		80.8	85.7
	Aug	435	564	471	526		77.1	89.5
	Sep	465	564	455	223		82.4	204.0
	Oct	451	495	466	532		91.1	87.6
	Nov	383	332	177	205		115.4	86.3
	Dec	499	442	385	316		112.9	121.8
	SUM	3689	4304	3220	3455	AVG	85.8%	95.6%

Note. This chart shows the number of hours that outdoor and greenhouse relative humidity levels reached above 80% in 2020 and 2021. It also shows the percentage of time that greenhouse RH levels exceeded 80% when outdoor RH levels were also above 80%

Results concluded from Table 7 show that, when outdoor relative humidity levels were over 80%, relative humidity exceeded 80% in the greenhouse 85.8% of the time in 2020 and 95.6% of the time in 2021. Data presented in Tables 6 and 7 were averaged to conclude that the was an 8.4% increase in the frequency of RH levels over 80% following the installation of the ventilation and HAF fans. Data used to quantify the effect of the ventilation fans on greenhouse relative humidity was analyzed with day-to-day comparisons, as well as finding the number of days and hours that the greenhouse exceeded 80% during the year before and after the installation of the fans. Results from all three of these analysis methods conclude that the ventilation fans are not improving the greenhouse's ability to maintain desirable relative humidity levels.

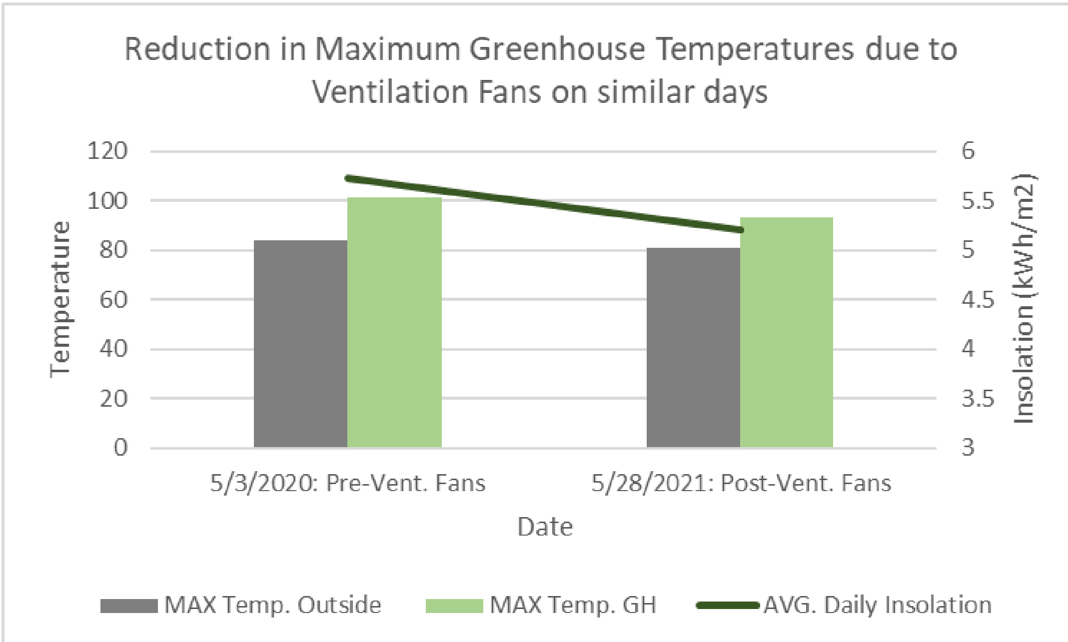
Effect of the Ventilation Fans on Greenhouse Temperature

The primary purpose of ventilation fans in a greenhouse is to reduce overheating. The effect of the ventilation fans on greenhouse temperature levels was analyzed to determine if they improve the greenhouse's ability to shed excess heat. Comparing indoor temperature values is tricky due to variance in outdoor weather conditions, so for this portion of the study, two methodologies were used to perform day-by-day comparisons of indoor temperature values from before and after the installation of the ventilation fans.

The first methodology used was a day by day temperature comparison with the addition of comparing average daily insolation levels. Figures 16 and 17 represent maximum daily indoor and outdoor temperature taken from days with extremely similar outdoor weather conditions, as well as the average daily insolation, or sun hours, value from those dates. Days with near-identical outdoor weather conditions from before and after the systems' installation were identified, and average daily indoor temperatures were compared.

Figure 16

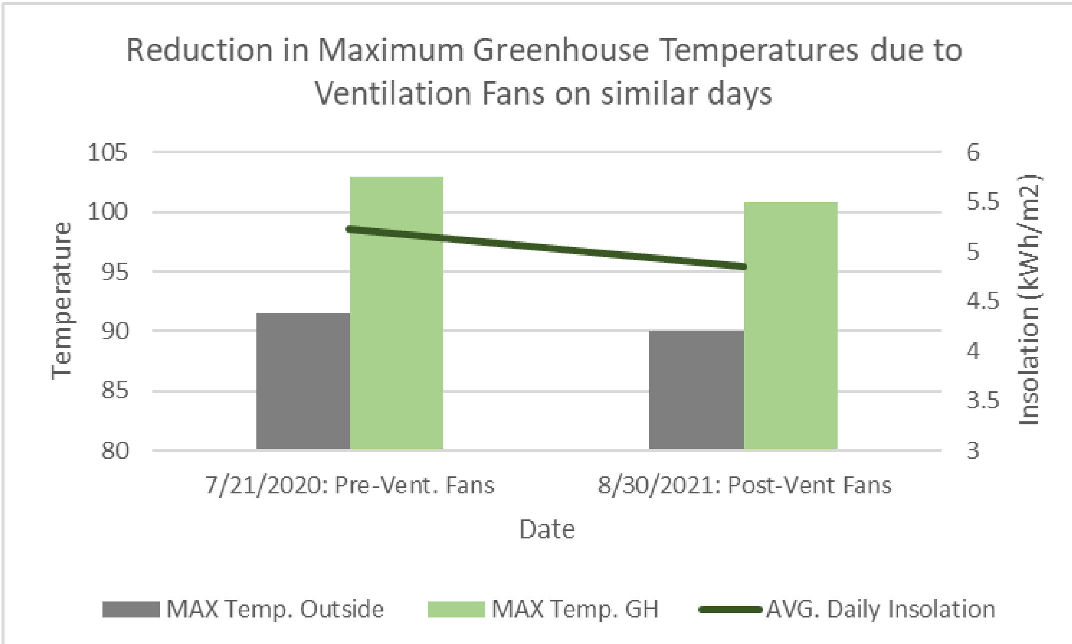
Ventilation & HAF Fans Temperature Analysis #1



Note. These graphs show daily temperature averages for days with similar weather conditions pre and post installation of the ventilation fans.

Figure 17

Ventilation & HAF Fans Temperature Analysis #2



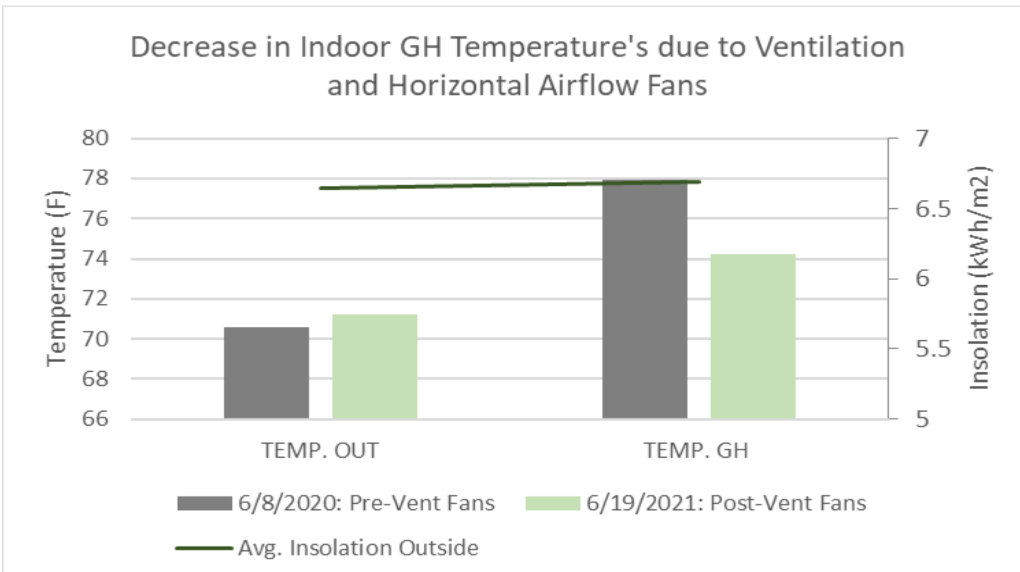
Note. These graphs show daily temperature averages for days with similar weather conditions pre and post installation of the ventilation fans. It can be seen that even though outdoor temperatures were near identical on both days, indoor temperatures were decreased following the installation of the ventilation and horizontal airflow fans.

Results drawn from the data represented in Figures 16 and 17 tell us that the greenhouse was maintained at lower temperatures, regardless of outdoor weather conditions, after the installation of the ventilation fans. In Fig. 16, when comparing May 3rd, 2020 with May 28th, 2021, a 5°F reduction in greenhouse temperatures was observed. A 2.2°F reduction in greenhouse temperatures was identified when comparing July 21st, 2020 with August 30th, 2021 in Fig. 17. This data supports the hypothesis that ventilation fans reduce greenhouse temperatures and prevent overheating. However, further analysis was required to acquire more information on the effect of the ventilation fans on greenhouse temperatures.

The second approach taken to analyze the effects of the ventilation fans was similar to the first methodology used, although the temperature difference per degree day value was omitted. Figures 18, 19 and 20 show greenhouse temperatures, outdoor temperatures, and outdoor solar irradiance conditions from three pairs of days that were compared.

Figure 18

Ventilation & HAF Fans Temperature Analysis #3

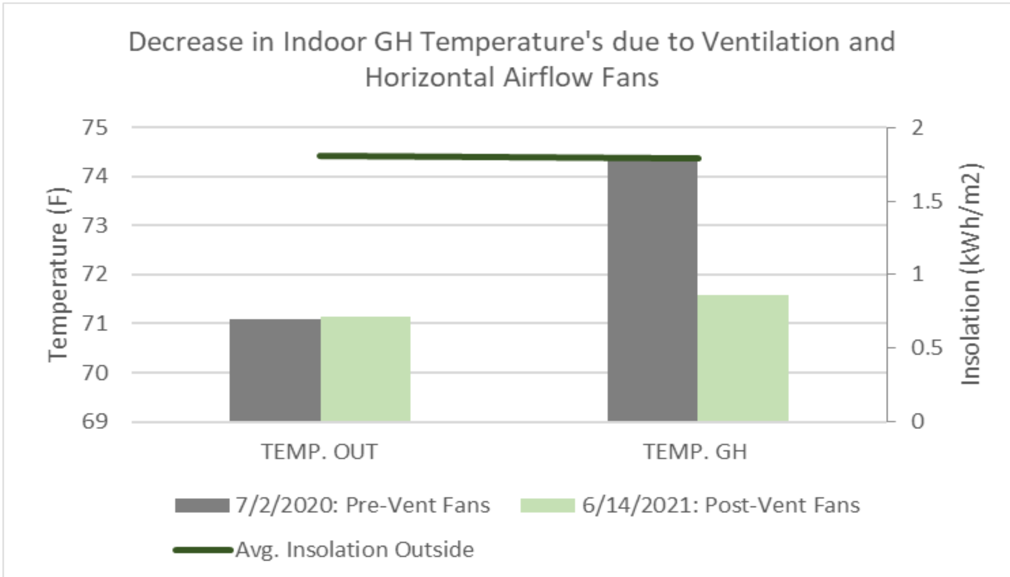


Note. These graphs show daily temperature averages for days with similar weather conditions pre and post installation of the ventilation fans.

In Figure 18, there is only a 0.7°F difference between outdoor temperatures on these days, but the greenhouse temperature was 3.7°F cooler on the day post-installation of the ventilation and horizontal airflow fans.

Figure 19

Ventilation & HAF Fans Temperature Analysis #4

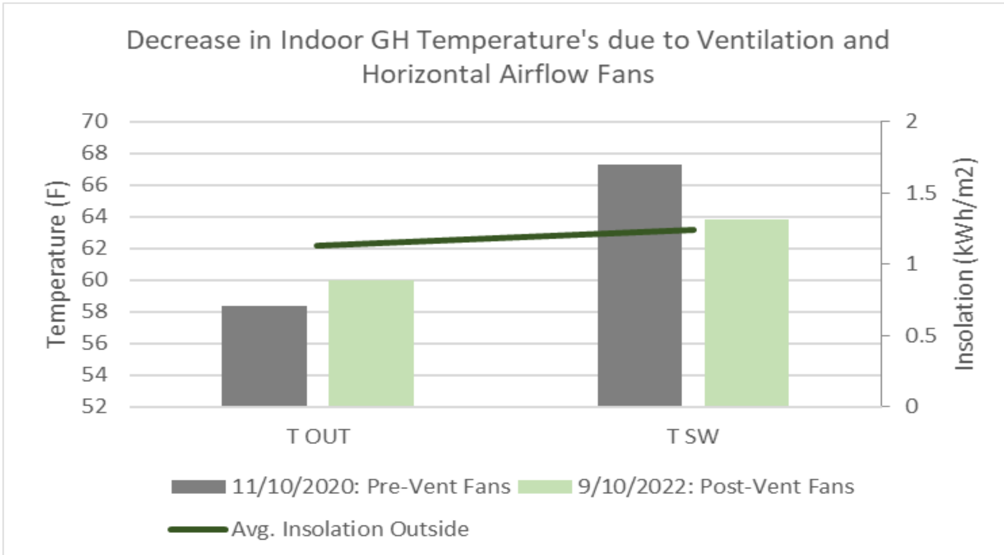


Note. These graphs show daily temperature averages for days with similar weather conditions pre and post installation of the ventilation fans.

In Figure 19, there is only a 0.06°F difference between outdoor temperatures on these days, but the greenhouse temperature was 2.8°F cooler on the day post-installation of the ventilation and horizontal airflow fans.

Figure 20

Ventilation & HAF Fans Temperature Analysis #5



Note. These graphs show daily temperature averages for days with similar weather conditions pre and post installation of the ventilation fans. It can be seen that indoor temperatures are lower post-ventilation fans even when outdoor temperatures are almost identical.

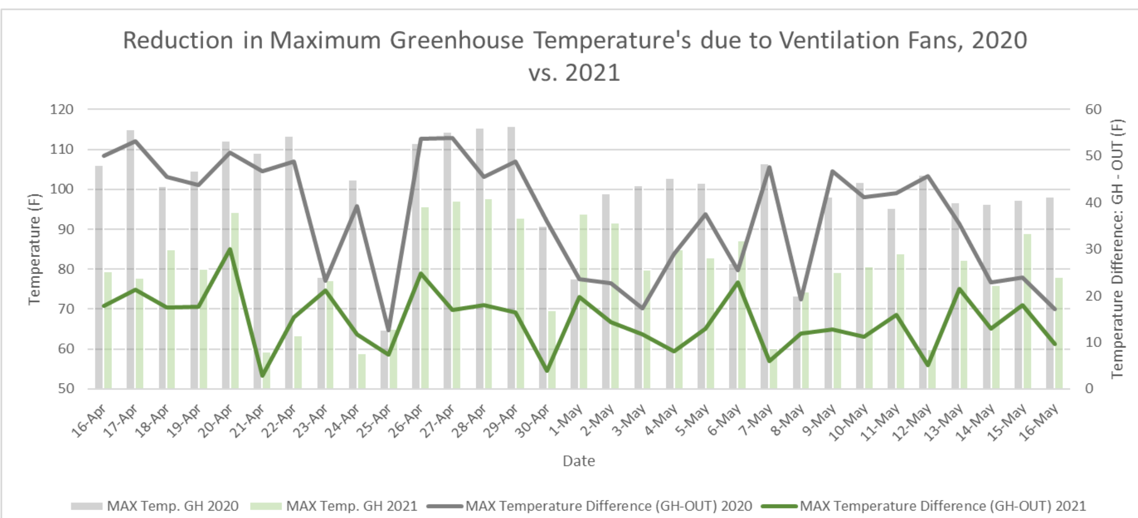
In Figure 20, there is only a 1.6°F difference between outdoor temperatures on these days, but the greenhouse temperature was 3.5°F cooler on the day post-installation of the ventilation and horizontal airflow fans.

As mentioned previously, Figures 18, 19 and 20 represent the analysis of three separate pairs of days with near identical weather conditions. When comparing June 8th, 2020 with June 19th, 2021, a 3.7°F decrease in temperature was observed due to the ventilation fans. When comparing July 2nd, 2020 with June 14th, 2021, a 2.8°F decrease in temperature was observed due to the ventilation fans. Lastly, when comparing November 10th, 2020 with September 10th, 2021, a 3.5°F decrease in temperature was observed due to the ventilation fans. The degree decrease (°F) observed in the five graphs from Figures 16, 17, 18, 19 and 20 were summed to find a value for the average reduction in greenhouse temperatures due to the ventilation fans. An average greenhouse temperature decrease of 3.5°F was concluded after summing and averaging these values.

To further evaluate the effect of the ventilation fans on greenhouse temperatures, we zoomed out from the day-to-day comparisons and selected a month-long time period from which we compared the difference between greenhouse and outdoor temperatures. While variations in outdoor weather conditions do affect the internal microclimate of a greenhouse, looking strictly at the difference between indoor and outdoor temperatures allows us to eliminate the variance of outdoor data and simply quantify the differences in greenhouse performance from before and after the installation of the vent fans. Figure 21 shows maximum daily indoor and outdoor temperature data from April 16th through May 16th of 2020 and 2021.

Figure 21

Ventilation & HAF Fans Temperature Analysis #6



Note. The graph shows the maximum daily outdoor and greenhouse temperatures, as well as the temperature difference from inside to outside of the greenhouse, from April 16th through May 16th for the years 2020 and 2021.

The difference between indoor greenhouse temperature and outdoor temperature was calculated for each day represented in Figure 21. Maximum avg. daily greenhouse temperatures are, for the most part, lower in 2021 after the ventilation fan installation. In the graph shown in Fig. 21, every instance where 2021 greenhouse temperature values are higher than 2020 values are due to extreme low outdoor temperatures in 2020. Prior to the installation of the ventilation fans, between April 16th and May 16th, 2020, the average difference between maximum daily indoor temperature and maximum daily outdoor temperature was 29.7°F. Between April 16th and May 16th, 2021, after the installation of the vent fans, the average difference between maximum daily indoor temperature and maximum daily outdoor temperature was 13.9°F.

The data presented in Figure 21 was also used to identify the number of hours the greenhouse reached above 100°F for each year in this dataset. In 2020, between April 16th and May 16th, eighteen out of thirty-one days were identified in which indoor greenhouse temperatures exceeded 100°F. In 2021, between April 16th and May 16th, zero days were identified in which indoor greenhouse temperatures exceeded 100°F, despite maximum daily outdoor temperatures being higher in 2021 for 27 out of the 31 days shown in Figure 21. This data further supports the conclusion that ventilation fans help to maintain greenhouse temperatures within a desirable range and contribute to minimizing overheating in a greenhouse.

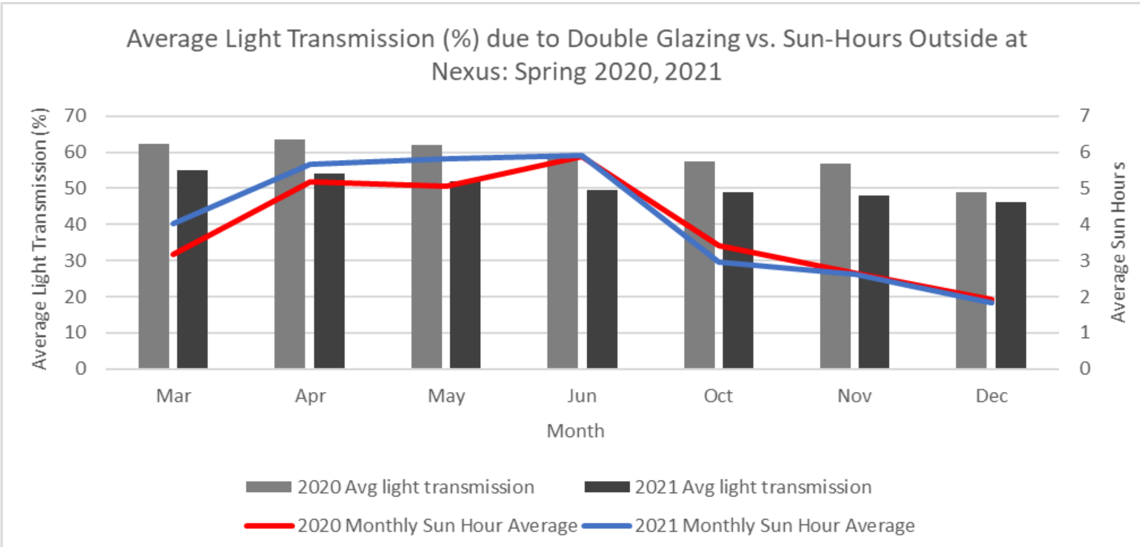
Research Question #3: How does double glazing affect temperature and light transmission levels in a high tunnel greenhouse?

Effect of Double Glazing on Greenhouse Light Transmission

The downside to the double layer air inflation system is that the second layer of polyethylene film reduces the amount of light that is transmitted through the greenhouse. Light transmission was calculated through the use of irradiance data captured by the RX3000 remote logging system at the Nexus facility and was averaged to daily and monthly values for data analysis purposes. The study found that the double glazing layer installed on the Nexus greenhouse decreased light transmission by an average of 7.95% annually. Figure 22 below shows a graph representing monthly reduction in light transmission compared with outdoor sun hours. Outdoor sun hour values are represented in this graph to show the effect that varying solar irradiance conditions have on light transmission values.

Figure 22

Double Glazing Light Transmission Analysis #1

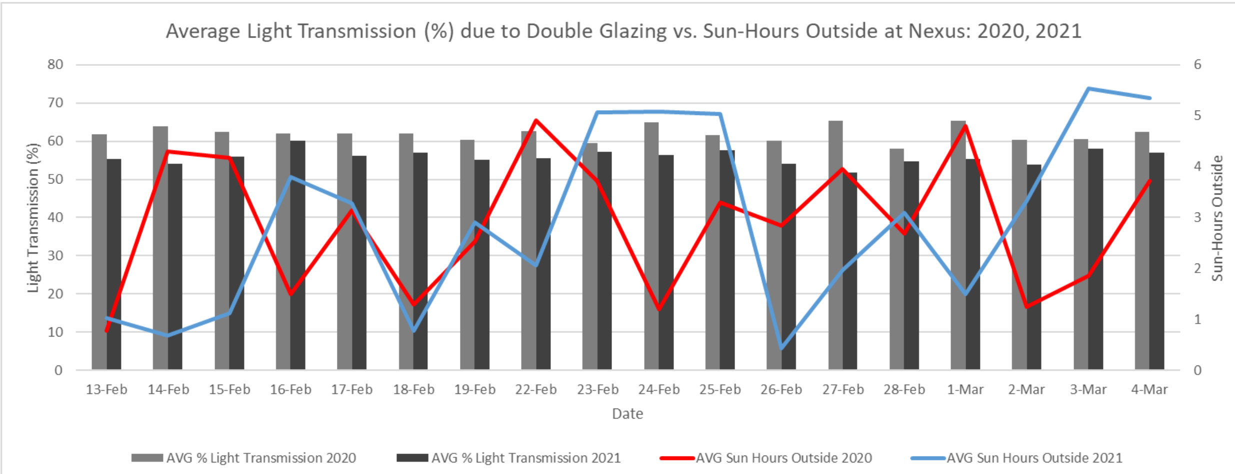


Note. This graph compares average monthly values for percent of light transmitted through the greenhouse and outdoor sun hours from before and after the installation of double glazing at the Nexus greenhouse. It can be seen here that regardless of outdoor sun hour values, light transmission in the greenhouse is significantly lower after the double glazing was installed. 2020 values represent the time period before the installation and 2021 values represent the time period after the installation. Some months are omitted because of sensor errors and the intervention timeline (double glazing was installed in February.)

To further represent reduction in light transmission due to double glazing, we also looked at daily values to ensure that monthly averages were not generalizing the results. In Figure 23 below, average daily light transmission and outdoor sun hour values are compared for the time period between February 12th and March 4th from 2020 and 2021. This figure further represents the reduction in light transmission through the greenhouse caused by double glazing at the Nexus facility.

Figure 23

Double Glazing Light Transmission Analysis #2



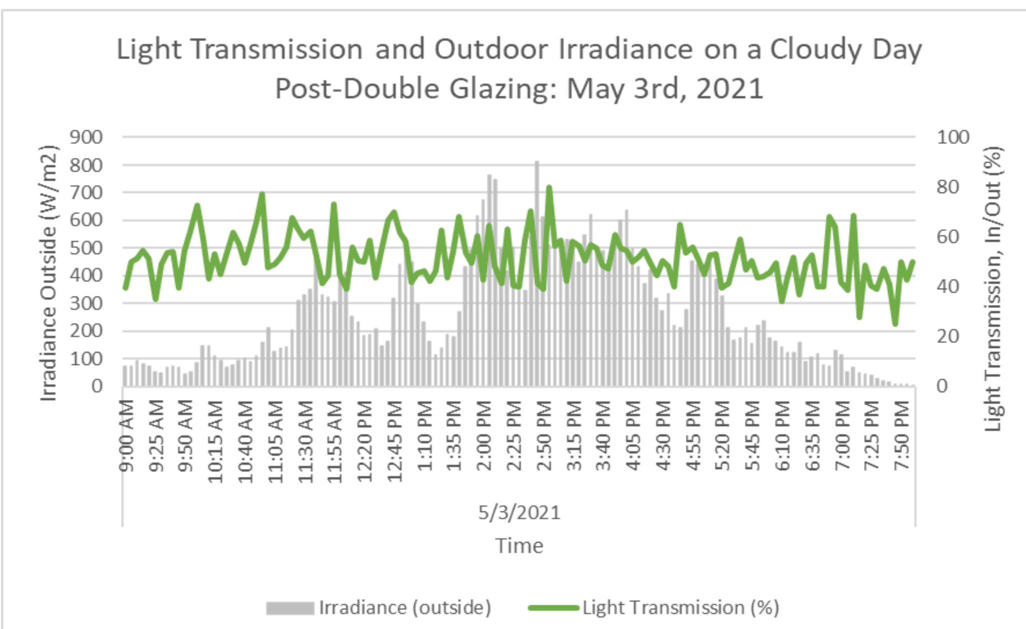
Note. This graph compares daily values for light transmission and outdoor sun hours. Similar to Figure 22, this graph shows that, regardless of outdoor sun hour values (insolation), percent of light transmitted through the greenhouse is consistently lower after the installation of double glazing. 2020 values represent the time period before the installation of double glazing, and 2021 values represent the time period after the installation.

When comparing the time period between February 12th and March 4th from 2020 and 2021, the average percent reduction in light transmitted through the greenhouse was 6.1%. Multiple other time periods from before and after the installation of double glazing at the Nexus greenhouse were also analyzed to further prove the relationship between double glazing and reduction in greenhouse light transmission. Comparing the months of January 2021 with January 2022, it was found that the average light daily light transmission through the greenhouse was 51% in January 2021 and 41% in January 2022, which shows a 10% average monthly decrease in light transmission. Similar results were found when comparing June 2020 before the installation with June 2021, after the installation of the double layer air inflation system. Average daily light transmission through the greenhouse was 58.58% in June 2021 and 49.38 % in 2022, which shows a 9.2% average monthly decrease in light transmission.

Additionally, the effect of varying outdoor solar irradiance conditions on the reduction of light transmission due to double glazing was analyzed. Data pulled from an overcast and a sunny day were selected and compared. Both of the days represented were from after the installation of double glazing on the greenhouse. Figure 24 and 25 below shows average daily light transmission and outdoor sun hour values being compared on a day with low solar irradiance and a day with high solar irradiance. The overcast day represented is May 3rd, 2021 in Fig. 24. The sunny day represented is May 21st, 2021 in Fig. 25.

Figure 24

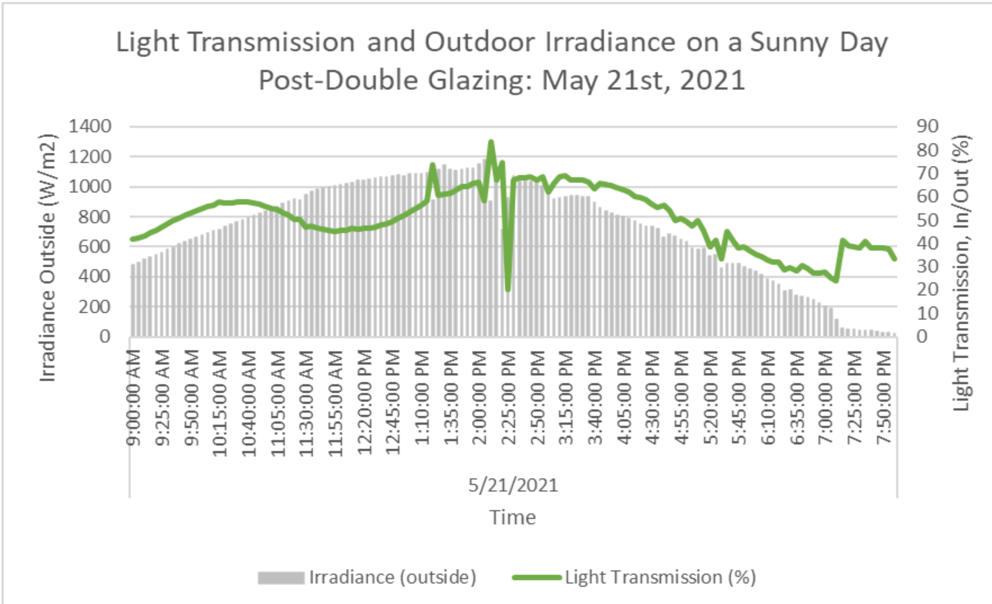
Double Glazing Light Transmission Analysis #3



Note. This graph shows light transmission and outdoor sun hour values from a cloudy day (5/3/21).

Figure 25

Double Glazing Light Transmission Analysis #4



Note. This graph shows light transmission and outdoor sun hour values from a sunny day (5/21/21).

In Figure 24, it can be seen that light transmission and outdoor sun hour values varied greatly on the overcast day due to varying solar irradiance conditions caused by clouds passing over the greenhouse. However, on the sunny day represented in Fig. 25, light transmission and outdoor sun hour values were relatively smooth with little variation due to the lack of cloud coverage. Average light transmission on the cloudy day, May 3rd, 2021, was 57.5%. Average light transmission on the sunny day, May 21st, 2021, was 52.5%. A 5% difference in light transmission between the cloudy and sunny days can be concluded from these graphs.

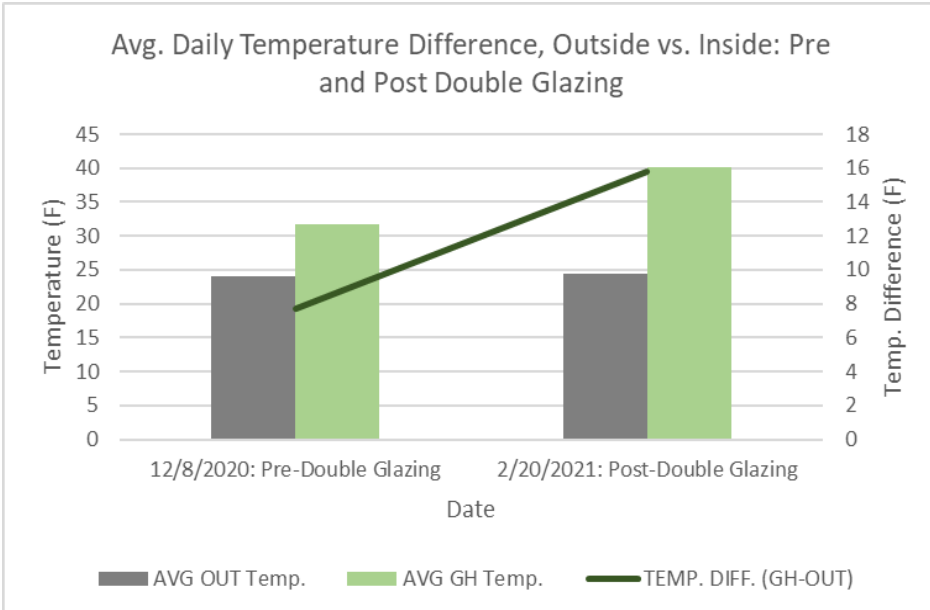
Regardless of the difference between light transmission on a sunny versus cloudy day, it can be seen throughout all of our data that percent of light transmitted through the greenhouse is consistently lower post-double glazing, regardless of outdoor weather conditions. Reduction in light transmission is not desirable for a greenhouse microclimate but can be justified by the increase in insulation that the double glazing provides. The decrease in light transmission due to double glazing is merely a tradeoff for increasing the greenhouse's ability to retain heat.

Effect of Double Glazing on Greenhouse Temperature

Analyzing the effect of double glazing, or any of the other interventions, on indoor greenhouse temperatures is challenging due to the variance in outdoor weather conditions. In order to avoid false results due to these variances, days and time periods were selected where outdoor weather conditions were extremely similar. The study found that, on average, the greenhouse was able to maintain temperatures 4.1°F higher after the installation of double glazing on the greenhouse. Figures 26, 27, 28 and 29 show multiple graphs where days with similar outdoor weather conditions were compared in order to analyze the difference in indoor greenhouse temperatures.

Figure 26

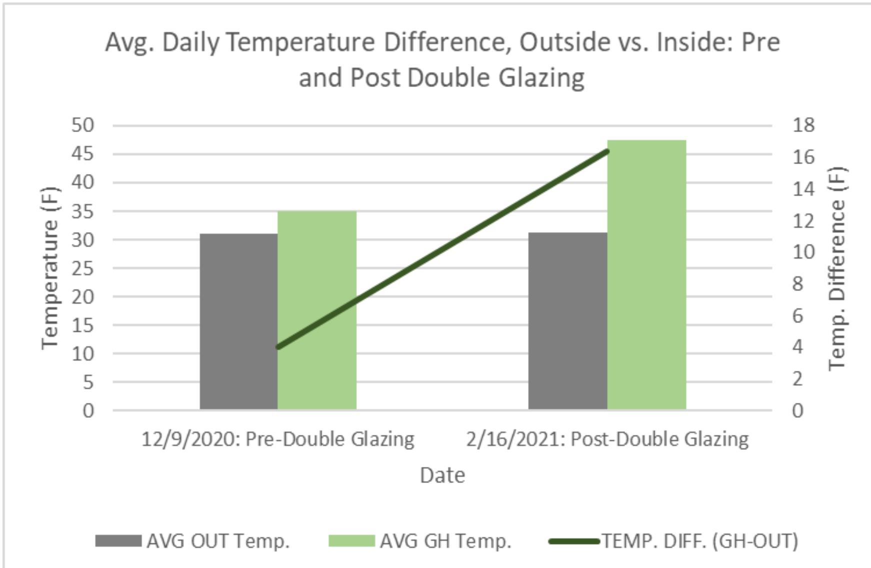
Double Glazing Temperature Analysis #1



Note. This graph compares two days with extremely similar outdoor weather conditions from before and after the installation of double glazing to determine the effect of double glazing on indoor greenhouse temperatures. An 8.1°F increase in greenhouse temperatures was observed when comparing December 8th, 2020 with February 20th, 2021.

Figure 27

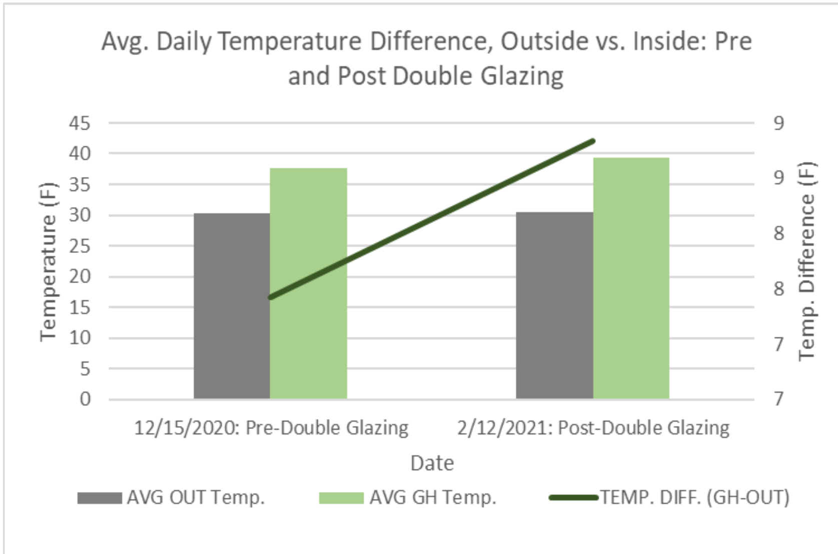
Double Glazing Temperature Analysis #2



Note. This graph compares two days with extremely similar outdoor weather conditions from before and after the installation of double glazing to determine the effect of double glazing on indoor greenhouse temperatures. A 12.3°F increase in greenhouse temperatures was observed when comparing December 9th, 2020 with February 16th, 2021.

Figure 28

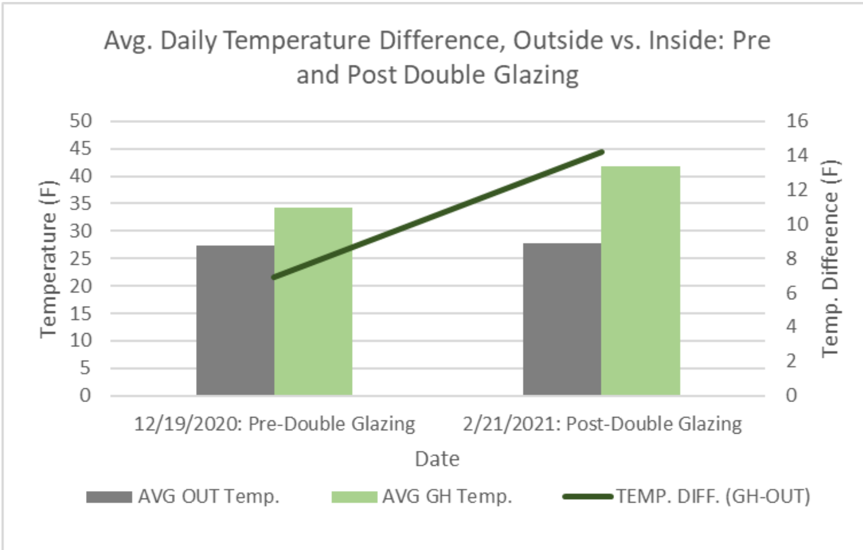
Double Glazing Temperature Analysis #3



Note. This graph compares two days with extremely similar outdoor weather conditions from before and after the installation of double glazing to determine the effect of double glazing on indoor greenhouse temperatures. A 1.4°F increase in greenhouse temperatures was observed when comparing December 15th, 2020 with February 12th, 2021.

Figure 29

Double Glazing Temperature Analysis #4



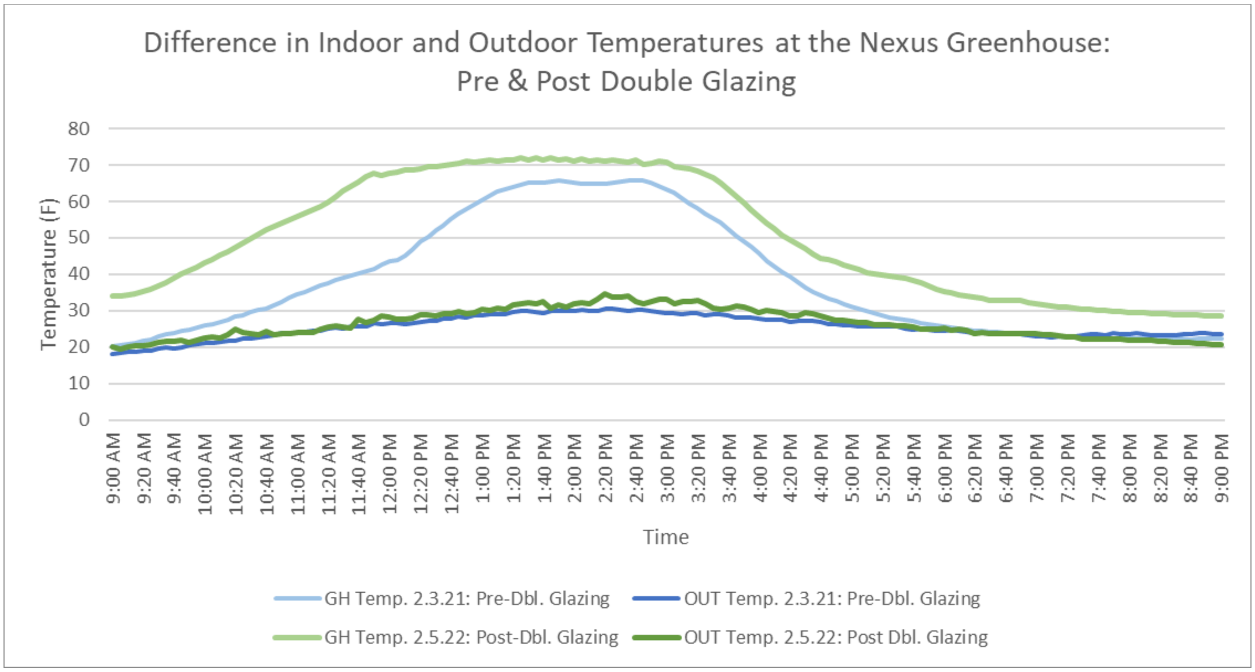
Note. This graph compares two days with extremely similar outdoor weather conditions from before and after the installation of double glazing to determine the effect of double glazing on indoor greenhouse temperatures. A 7.29°F increase in greenhouse temperatures was observed when comparing December 19th, 2020 with February 21th, 2021.

In Figures 26, 27, 28 and 29, when zooming in closer to look specifically at days where temperatures were below freezing (under 32°F), it can be seen that greenhouse temperatures can be maintained on average 6.63°F higher indoors after the installation of the double glazing when compared to days below freezing when there were no interventions in the greenhouse. Figures 26, 27, 28 and 29 represent four different comparisons between days under 32°F with similar outdoor weather conditions, but further analysis was needed to quantify to effects of double glazing on greenhouse temperature.

To zoom in even further on the data and determine the effect double glazing has on the greenhouse through a single day, two days were selected and analyzed using 5-minute interval data. Figure 30 shows this comparison.

Figure 30

Double Glazing Temperature Analysis #5



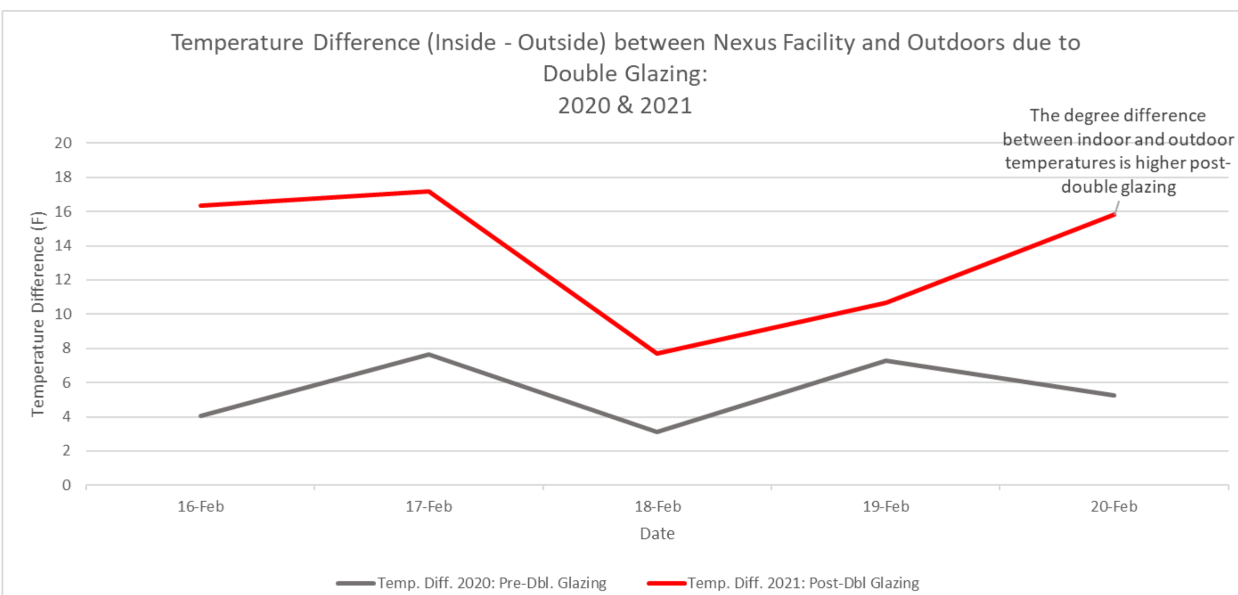
Note. The graph compares two days from before and after the installation of double glazing on the Nexus greenhouse to determine how the intervention affects greenhouse temperatures over the course of a day.

Figure 30 zooms in on February 3rd, 2021 to represent a day pre-double glazing, and February 5th, 2022 to represent a day post-double glazing. On February 3rd, 2021, the average temperature difference between inside and outside of the greenhouse was 7.4°F, with a minimum temperature difference of -0.05°F and a maximum temperature difference of 35.9°F. On February 5th, 2022, after the installation of double glazing, the average temperature difference is 15.1°F, with a minimum difference of 3.4°F and a maximum difference of 41.9°F. These temperature difference values can be used to draw conclusions about the effect of double glazing on the greenhouse's ability to retain heat. Based on the data presented in Fig. 30, Indoor greenhouse temperatures are maintained on average 6.85°F higher after the installation of double glazing in the greenhouse. Even when focusing on the minimum temperature difference values, we can determine that the greenhouse is maintained at least 3.45°F warmer post-double glazing than it was before the intervention.

Figures 26 through 30 focused on daily comparisons, so to continue the analysis, a larger time frame was selected to further evaluate the effect of double glazing on indoor greenhouse temperatures. Figure 31 shows the comparison between temperature difference (inside minus outside) for 2020 and 2021 during the selected five-day period.

Figure 31

Double Glazing Temperature Analysis #6



Note. This graph shows a comparison of temperature difference between inside and outside of the greenhouse in 2020 and 2021 during a selected five day time period.

As mentioned previously, the effects of double glazing on greenhouse temperature fluctuate day to day due to variation in outdoor weather conditions. Data presented in Figure 31 was analyzed to determine that the increase in temperature difference from 2020 to 2021 during the selected time period was, on average, 2.2°F. This value was determined by calculating the gap between 2020 and 2021 temperature difference for each of the five days, then averaging those values to find the average increase in temperature difference.

Data collected on the effect of double glazing was analyzed multiple ways. To quantify a final value for the effect of double glazing on greenhouse temperature, the results presented in Figures 26 through 31 were averaged together. The study found that the greenhouse was able to maintain temperatures, on average, 4.1°F higher after the installation of double glazing on the greenhouse.

Research Question #4: What is the overall effect of all five interventions (double glazing, ventilation fans, horizontal airflow fans, an insulated ground skirt and the automated sidewall roll-up system) on temperature and relative humidity levels in a high tunnel greenhouse?

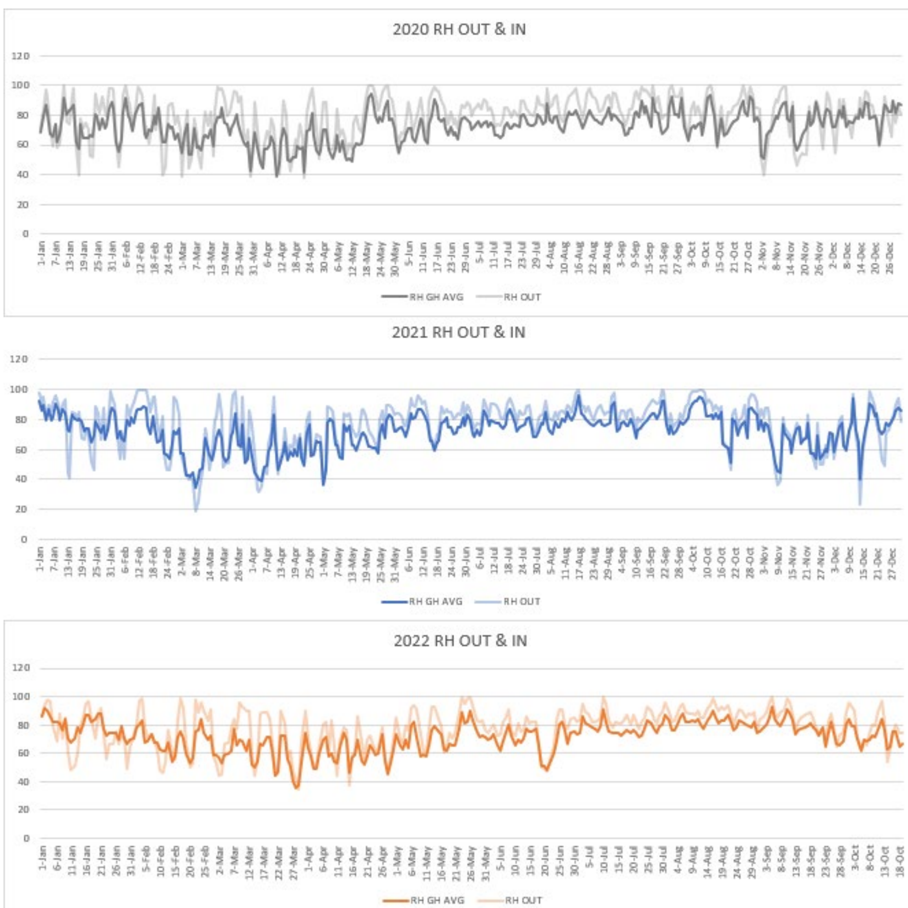
Effect of all Five Interventions on Greenhouse Relative Humidity

While each individual intervention had its own unique effect on the greenhouse microclimate that is important to quantify, it would be remiss to not also quantify the effects of all five systems, the double glazing, ventilation fans, horizontal airflow fans, the insulated ground skirt, and the automated sidewall roll-up, as a whole. The goal of the overall analysis on all five systems is to identify and quantify the differences between greenhouse temperature and relative humidity levels from before and after the greenhouse retro-fit.

The overall analysis began with looking at the effects all five systems had on greenhouse relative humidity. This first step was to graph out the indoor and outdoor relative humidity levels for the years 2020, 2021 and 2022 to identify any noticeable trends. Figure 32 displays these graphs.

Figure 32

Overall Effect Relative Humidity Analysis #1



Note. These graphs show average daily indoor and outdoor relative humidity level at the Nexus greenhouse during 2020, 2021 and 2022.

As shown in Fig. 32, there were no visually noticeable trends in the average daily relative humidity levels from the three years, so instead, we decided to focus on the percentage of time that greenhouse relative humidity levels were maintained in our desired range (40-80%) for the three years. We first looked at the number of days per year that indoor and outdoor relative humidity levels were over 80%. All days that experienced at least one hour where RH levels were over 80% were counted towards the table in Table 8. Table 8 below shows the total number of days over 80% for each year.

Table 8

Overall Effect Relative Humidity Analysis #2

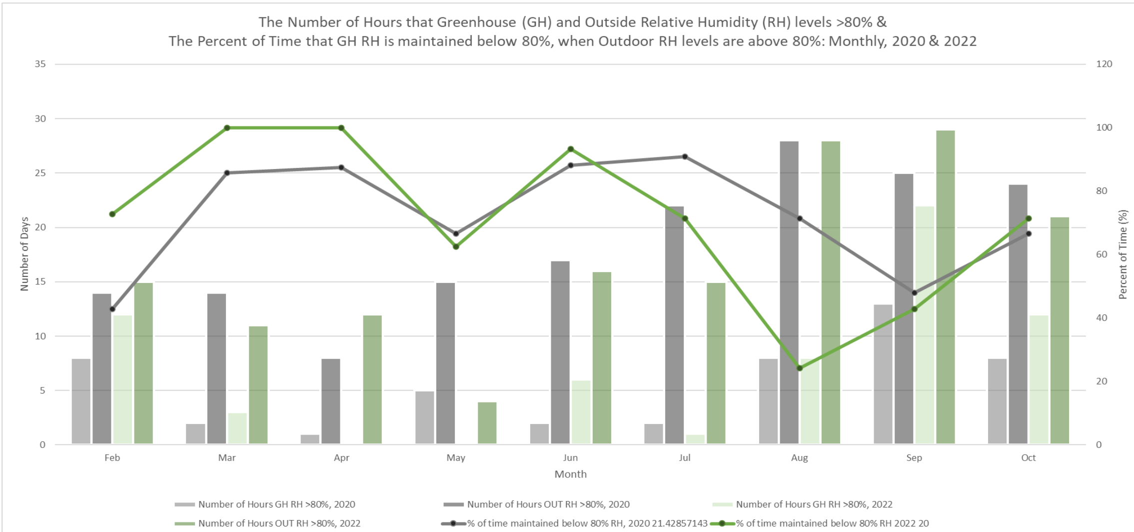
Sum's: Days per year, Relative Humidity						
Year	2020	2020	2021	2021	2022	2022
Location	GH	OUT	GH	OUT	GH	OUT
<40	1	6	5	11	2	2
>80	83	210	93	199	69	155

Note. This chart shows the number of days that greenhouse and outdoor relative humidity levels exceeded 80% or dropped below 40% for the years 2020, 2021 and 2022.

Using the data displayed in Table 8, it was found that the percentage of time that greenhouse relative humidity is maintained below 80% when outdoor relative humidity is above 80% was 60% in 2020, 53% in 2021, and 55% in 2022. This means that greenhouse relative humidity levels were better maintained in 2020, prior to our interventions, than in 2021 or 2022. In Figure 33 below, this percentage of time under 80% was graphed per month for the years 2020 and 2022.

Figure 33

Overall Effect Relative Humidity Analysis #3



Note. The graph represents the percentage of time per month that greenhouse relative humidity levels were maintained under 80% when outdoor RH level were over 80%, for the years 2020 and 2022

As can be seen in Fig. 33, it is hard to discern and quantify the difference between relative humidity levels from before and after the interventions. In the graph, the percentage of time maintained under 80% was higher in 2022 for the months of January through April, although 2020 levels beat out 2022 levels for most of the remainder of the year. Due to the fact that average greenhouse RH levels from 2020 were only 5-8% more ideal than in 2021 and 2022, it cannot be completely assumed that the interventions are negatively affecting greenhouse RH levels.

In order to fully analyze the effects of the interventions on greenhouse relative humidity, we also looked at the number of days the greenhouse reached relative humidity levels below 40%. There were less than six days where the greenhouse dropped below

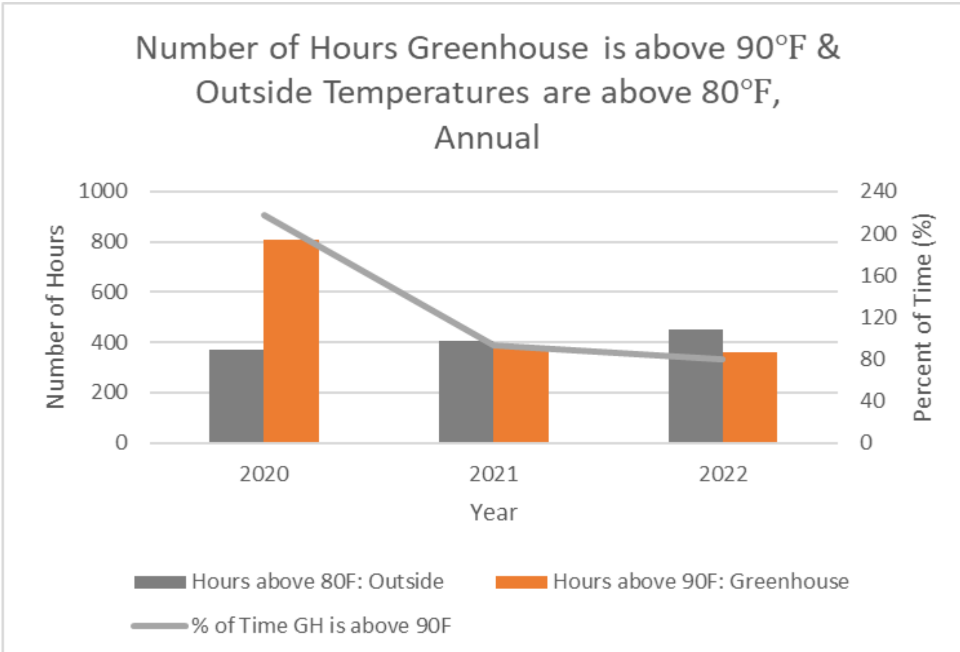
40% relative humidity in 2020, 2021 or 2022. Because there were so few days below 40%, this data is not significant to our final results.

Effect of All Five Interventions on Greenhouse Temperature

In the analysis of the overall effect of all five interventions, double glazing, ventilation fans, HAF fans, an insulated ground skirt and an automated sidewall roll-up system, we also looked at changes in indoor greenhouse temperatures. Similar to the overall analysis performed on greenhouse relative humidity, we wanted to focus on the percentage of time the greenhouse temperatures were outside of the desired range (below 32°F and above 90°F). We first focused on overheating in the greenhouse. The number of hours that greenhouse temperatures reached above 90°F and outdoor temperatures reached above 80°F were recorded for 2020, 2021 and 2022. The following chart in Table 9 and the graph shown in Figure 34 represents the number hours per year that greenhouse and outside temperatures exceed 90°F and 80°F, respectively.

Figure 34

Overall Effect Temperature Analysis #1



Note. The graph displayed above represent the number hours per year that greenhouse and outside temperatures exceeded 90°F and 80°F, respectively. The percentage of time that greenhouse temperatures are maintained below 90°F when outdoor temperatures are above 80°F is also displayed.

Table 9

Overall Effect Temperature Analysis #2

YEAR	# of Hours Outdoor temp.'s exceed 80F	# of Hour GH temp.'s exceed 90F	% of time GH is above 90F, when Outdoor temp.'s are above 80F
2020	371	808	217.8%
2021	405	375	93%
2022	450	360	80%

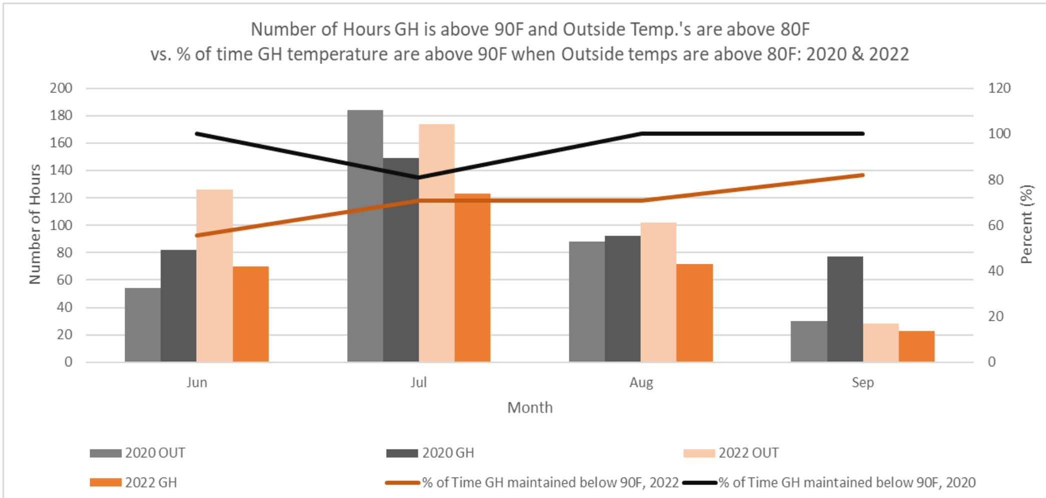
Note. The chart displayed above represent the number hours per year that greenhouse and outside temperatures exceeded 90°F and 80°F, respectively. The percentage of time that greenhouse temperatures are maintained below 90°F when outdoor temperatures are above 80°F is also displayed.

It can be seen in Table 9 and Fig. 34 that prior to the interventions installed at the Nexus greenhouse, the number of hours where GH temperatures exceeded 90°F was more than twice the number of hours that outdoor temperatures exceed 80°F. The greenhouse was not at all able to maintain temperatures in our desired range once outdoor temperatures rose above 80°F. On the contrary, in both 2021 and 2022, the number of hours that greenhouse temperatures were recorded above 90°F was less than the number of hours that outdoor temperatures exceeded 80°F. The percentage of time that greenhouse temperatures were 90°F while outside temperatures were above 80°F was a 217.8% of the time in 2020. This means that the greenhouse was frequently overheating, even when outdoor temperatures were below 80°F. In comparison, greenhouse temperatures were 90°F when outdoor temperatures were above 80°F, for 93% of the time in 2021 and 80% of the time in 2022. In 2020, the greenhouse was overheating even when outdoor temperatures were mild. In 2021 and 2022, the greenhouse only reached overheating temperatures when outdoor temperatures rose above 80°F. Even when outdoor temperatures were above 80°F, the greenhouse was able to maintain temperatures below 90°F for 7% of the time in 2021, and 20% of the time in 2022. This shows a significant increase in the greenhouse's ability to decrease overheating events due to the interventions made over the past two years.

This same analysis method was performed to find the number of hours per month that greenhouse and outside temperatures exceeded 90°F and 80°F, respectively. Figure 35 below shows these values, in addition to showing the monthly percentage of time that greenhouse temperatures were above 90°F when outdoor temperatures were above 80°F.

Figure 35

Overall Effect Temperature Analysis #3



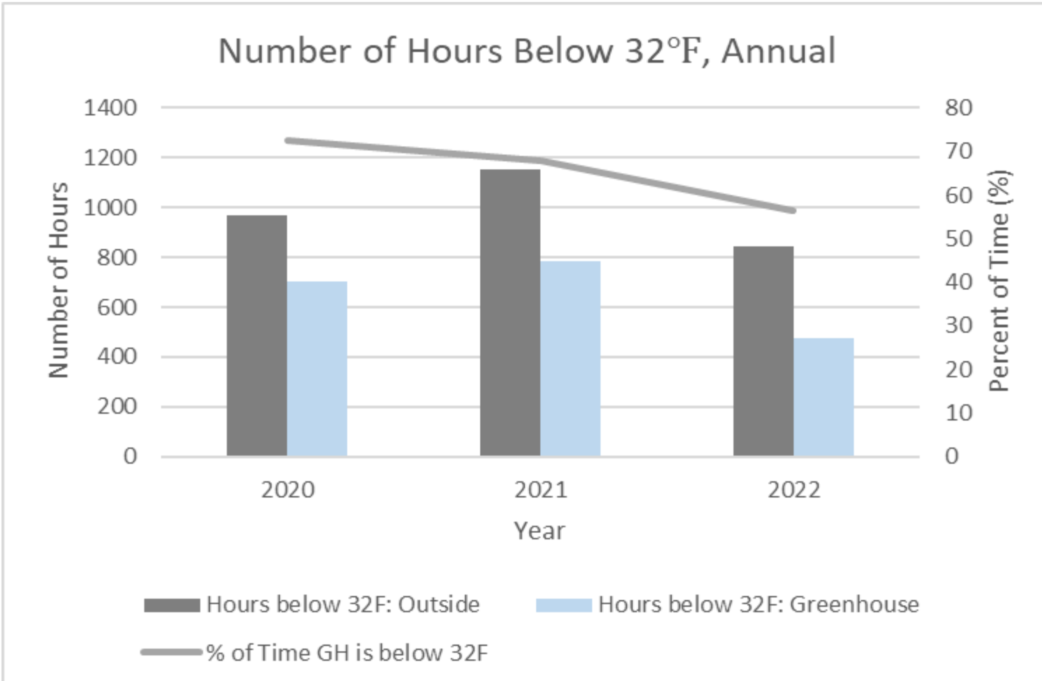
Note. This graph shows the number of hours per month that greenhouse and outside temperatures exceeded 90°F and 80°F, respectively, in addition to showing the monthly percentage of time that greenhouse temperatures were above 90°F when outdoor temperatures were above 80°F.

Fig. 35 is a further reflection of the results concluded from Fig. 34, which demonstrates the greenhouse's increased ability to avoid overheating events following the installation of our interventions.

In addition to looking at data pertaining to overheating, it is also important to zoom in on time periods where the greenhouse is experiencing temperatures below freezing (32°F). The number of hours that greenhouse and outdoor temperatures reached below 32°F were recorded for 2020, 2021 and 2022. The following chart shown in Table 10 and the graph shown in Figure 36 represents the number of hours per year that greenhouse and outside temperatures dropped below 32°F.

Figure 36

Overall Effect Temperature Analysis #4



Note. The chart and graph displayed above represent the number hours per year that greenhouse and outside temperatures dropped below 32°F. The percentage of time that greenhouse temperatures are below 32°F when outdoor temperatures are below 32°F is also displayed.

Table 10

Overall Effect Temperature Analysis #5

YEAR	# of Hours Outdoor temp.'s are below 32F	# of Hour GH temp.'s are below 32F	% of time GH is below 32F, when Outdoor temp.'s < 32F
2020	971	705	72.6%
2021	1155	783	67.8%
2022	844	475	56%

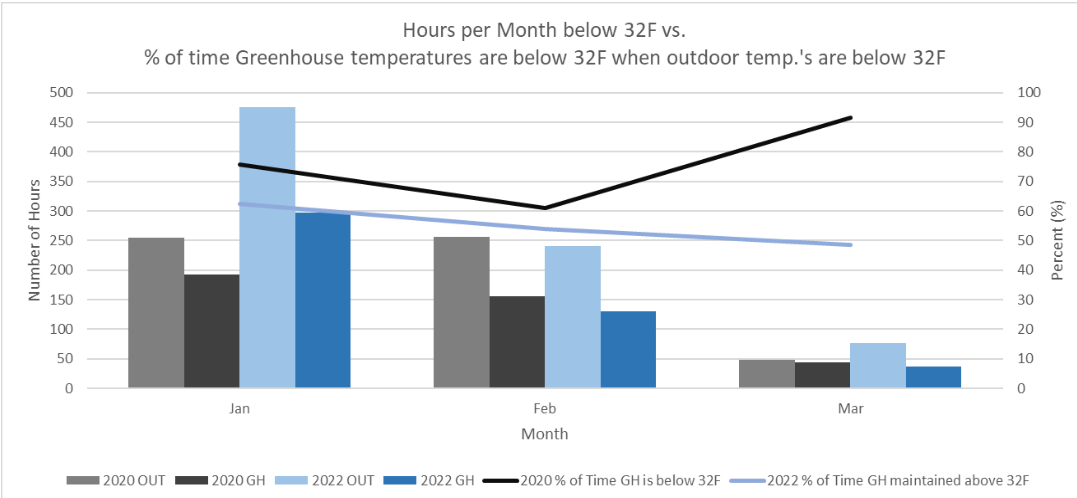
Note. The chart displayed above represents the number hours per year that greenhouse and outside temperatures dropped below 32°F. The percentage of time that greenhouse temperatures were below 32°F when outdoor temperatures were below 32°F is also displayed.

According to Table 10, when outdoor temperatures were below 32°F, greenhouse temperatures were also below 32°F for 72.6% of time in 2020, 67.8% of time in 2021 and 56% of time in 2022. This means that there was a 4.8% increase in the greenhouse's ability to maintain heat between 2020 and 2021, and a 11.8% increase between 2021 and 2022. When comparing 2020 values from before the greenhouse interventions, with 2022 values from after the interventions, we can see an overall 16.6% increase in the greenhouses ability to maintain temperatures above 32°F, when outdoor temperatures were below 32°F. This demonstrates the greenhouse's increased capability to retain heat and minimize freezing events following the installation of our interventions.

Once again, this same analysis method was performed to find the number of hours per month that greenhouse and outside temperatures exceeded 32°F. Figure 37 below shows these values, in addition to showing the monthly percentage of time that greenhouse temperatures were below 32°F when outdoor temperatures were below 32°F.

Figure 37

Overall Effect Temperature Analysis #6



Note. This graph shows the number of hours that per month that greenhouse and outside temperatures were below 32°F, in addition to showing the monthly percentage of time that greenhouse temperatures were below 32°F when outdoor temperatures are below 32°F.

Fig. 37 is a further representation of the results drawn from Fig. 36. It is important to zoom in on monthly greenhouse performance in order to analyze the effect that seasonal variations have on the performance of the interventions installed at the greenhouse. Overall, it can be concluded that there was a 5-8% increased frequency of undesirable relative humidity levels in the greenhouse following the installation of all five interventions. However, this study proved that the interventions installed at the Nexus greenhouse have greatly improved the structures' ability to retain heat during the winter and ventilate excess heat during the summer.

DISCUSSION OF RESULTS

Due to the fact that this study aimed to answer four different research questions, and therefore had many results, the discussion of the results section will be broken down by research question for organizational purposes and to avoid confusion. The section will begin with the discussion of results related to the automated sidewall roll-up system, followed by the ventilation fans, double glazing, and lastly the overall impact.

Automated Sidewall Roll-Up System

Analysis of the sidewall roll-up system began by analyzing its effect on greenhouse relative humidity levels. Analysis began by performing day-by-day comparisons of indoor relative humidity levels on pairs or sets of day with nearly identical outdoor weather conditions, as shown in Fig. 8. Performing day-by-day comparisons did not produce any significant results for the effect of the system on greenhouse RH. The lack of results from the analysis method is likely due to the fact that cold temperatures in the 2022 data set used for this analysis meant that the sidewall was rolled down for the majority of the time, potentially trapping moisture inside of the greenhouse. Another reason for the lack of results drawn here could be that the Nexus facility is not equipped with a rain gauge, meaning that day-by-day comparisons did not account for differences in precipitation levels, which, of course, could have affected relative humidity levels in the greenhouse. We then moved away from day-by-day comparisons and instead, analyzed the percentage of time that greenhouse relative humidity levels were maintained below 80%, when outdoor RH levels were above 80%, as shown in Fig. 9 and 10. Based on these results, it was found that there was an 11.9% increase in the greenhouse's ability to maintain RH under 80% when outdoor RH levels are above 80%. Zooming out to a larger time period, as opposed to day-by-day comparisons, we were able to average the percent of time that the greenhouse maintained a desirable RH range over the course of multiple days. It can be concluded from these results that the greenhouse is able to better maintain desirable relative humidity levels after the installation of the sidewall roll-up system.

The effect of the automated sidewall roll-up system on indoor greenhouse temperatures was also analyzed using several different methods, beginning with day-by-day comparisons as shown in Fig. 11. In Fig. 11, it can be seen that regardless of the fact that outdoor temperatures were higher in the day selected from 2022 versus 2020, greenhouse temperatures in 2020 reached 15.8°F higher in 2020. This is due to the lack of ventilation in the greenhouse prior to the interventions. Before the ventilation fans or the automated sidewall roll-up system were installed at the Nexus facility, the only method used to ventilate the greenhouse was to manually roll-up the sides or to leave the doors open. These actions require someone to be physically present at the greenhouse, both to open the greenhouse sidewalls or doors, and also to close them in the evening before cool, nighttime temperatures penetrate the greenhouse. The Nexus greenhouse is visited frequently, but not every day. It is likely that the overheating event that occurred on October 3rd, 2020, as shown in Fig. 11, was due to the fact that the greenhouse was not ventilated at all that day, likely because no one was available to visit the facility to manually roll the sidewall curtain up and secure it. The beauty of the automated sidewall roll-up system is that it diminishes the demand for labor that was previously required to roll the sidewall up or down. For greenhouse owners that do not live on the same property as their greenhouse, this automated system can drastically reduce the labor involved with driving back and forth to the greenhouse each day to manually roll the sidewall up and down.

For the next analysis method, we zoomed out on a larger time period to better understand the effects of the automated sidewall roll-up system on greenhouse temperature. Maximum indoor and outdoor temperatures were graphed and compared, as shown in Figures 12 and 13. The study found that there was a 50.7% increase in the greenhouse's ability to maintain temperatures under 80°F when outdoor temperatures are over 70°F. It was also concluded that the average temperature difference between the inside and outside of the greenhouse, from before and after the installation of the automated sidewall roll-up system, was 16.2°F. These results display a significant increase in the greenhouse's ability to shed excess heat. Although, it is believed that the results of this study could have been further improved. The automated sidewall roll-up system at the Nexus greenhouse is not properly sealed where the roll bar meets the ground, which will be discussed further in the suggestions section. It is likely that if the roll bar was better sealed with the ground when in the 'rolled down', overheating and freezing events would be further reduced. Unfortunately, data was not able to be collected or presented on the performance of this system during the winter months. The system was installed in May of 2022, and data collection for this study ended on October 24th, 2022., which is why our analysis primarily focuses on the reduction of overheating.

Theoretically, with improved sealing, the automated sidewall roll-up would also decrease freezing events in the greenhouse. Overall, the analysis of the automated sidewall roll-up system was largely successful, concluding that the system did increase the ability of the greenhouse to shed excess heat and maintain a desirable relative humidity range.

Ventilation & HAF Fans

Multiple analysis methods were used to determine the effect of the ventilation and HAF fans on greenhouse temperatures and relative humidity. Effects on relative humidity were evaluated first. We began evaluating the effect on RH by performing day-by-day comparisons, as shown in Table 5. It was concluded that greenhouse relative humidity levels were actually higher after the installation of the ventilation and HAF fans (2021) for 92% of the days represented in Table 5. Theoretically, relative humidity should be decreased by the ventilation fans as they exchange stale, heavy air from the exhaust fans and suck in fresh air from the intake shutters, as well as from the HAF fans because they keep air circulating throughout the greenhouse. We next took the approach of analyzing the percentage of time that GH RH is maintained within a desirable range, as shown in Figure 15, and Tables 6 and 7. Unfortunately, similar to the results drawn from Table 5, it seemed that RH ranges in the greenhouse were better maintained prior to the installation of the ventilation and HAF fans. It was concluded that there was an 8.4% increase in the prevalence of undesirable relative humidity levels in the greenhouse following the installation of the ventilation fans at the Nexus greenhouse. This increase is difficult to account for, but there are a few hypotheses as to why this result may have been found. Ventilations fans move air through the greenhouse, which in theory, should decrease relative humidity levels by ventilating the space. However, ventilation fans do cool down the greenhouse, and because cold air holds more moisture than warm air, it makes sense that a decrease in relative humidity was observed as a result of decreased temperatures due to the fans. Additionally, it is important to note that the relative humidity data collected in 2020 was heavily influenced by the lack of ventilation in the greenhouse. The lack of ventilation in the greenhouse in 2020 directly correlated with the high greenhouse temperatures observed during that year. Those higher temperatures lead to relatively lower relative humidity levels. Higher relative humidity levels, and increased frequency of RH levels over 80%, following the installation of the ventilation fans and sidewall roll-up systems were likely due to the subsequently lower temperatures caused by those systems.

While it is unfortunate that the frequency of RH levels over 80% in the greenhouse was increased following the installation of the ventilation and HAF fans, which could lead to mold and mildew problems in the greenhouse, the primary purpose of the ventilation fans is to reduce overheating. Day-by-day comparisons were performed, as well as an analysis on the reduction of overheating GH temperatures for a 45-day time period. An average 3.5°F difference in temperatures was concluded from Figures 16 through 20. As mentioned previously, prior to the interventions installed at the Nexus greenhouse, the only way to ventilate the greenhouse was to manually roll-up the sides or open doors. This decrease in greenhouse temperatures is due simply to the addition of ventilation at the site. Also, the shutters that cover the ventilation fans are not airtight, so even if the fans were not turned on and running, they still create and provide gaps in the building envelope which increases outside air infiltration and allows hot air to escape out of the greenhouse. Further analysis was also done to determine the reduction in maximum daily greenhouse temperatures due to the ventilation fans, as shown in Fig. 21. It was concluded that there was a 65% reduction in overheating events after the installation of the ventilation fans, which is once again, namely due to the increase in outside air infiltration that they provide. Overall, regardless of their effect on relative humidity, it can be seen that the ventilation fans greatly increase the user's control of the greenhouse microclimate, especially regarding temperature control, and help the structure to shed excess heat.

Double Glazing

In order to determine the effect of the double glazing on greenhouse light transmission and temperature, a number of analysis methods were performed. The effect on light transmission was evaluated first. The study found that the double glazing layer installed on the Nexus greenhouse decreased light transmission by an average of 7.95% annually, as can be shown in Figures 22 and 23. Further analysis was performed to conclude if there was a difference in light transmission based on outdoor weather conditions by comparing a sunny and cloudy day, as shown in Figures 24 and 25. It was concluded that there was a 5% difference between light transmission level on the cloudy day versus the sunny day. Higher overall solar irradiance and light transmission values on the cloudy, overcast day (May 3rd, 2021) are likely due to the combination of refraction and reflection between varying clouds, which results in a significantly greater UV strength on cloudy days versus sunny days.

Overall, during every time period analyzed, light transmission through greenhouse was decreased following the installation of the double glazing. Light transmission in a greenhouse is an important factor that impacts plant growth as well as greenhouse temperatures. Decreased light transmission during the summer season could decrease the frequency of overheating events, due to the decrease in solar irradiation penetrating the greenhouse. However, during the winter months, decreased light transmission could decrease the potential of one's greenhouse structure to maintain desirable temperature ranges. In summary, decreased light transmission leads to cooler greenhouse temperatures, which is only advantageous during the warmer parts of the year. While reduction in light transmission is not always desirable, it can be justified by the increase in greenhouse insulation that the double glazing layer provides.

Multiple analysis methods were used to quantify the effect of the double glazing on greenhouse temperatures, as shown in Figures 26 through 31. It was concluded that the double glazing increase GH temperatures by an average of 4.1°F, but this value can range from 3.5°F to 6.9°F. It can be concluded from the results that the double glazing increases insulation and heat retention in the greenhouse.

Overall Analysis

While the analysis of each system individually was important to determine which had the greatest effect, it is also necessary to evaluate the impact of all five systems on the greenhouse microclimate. The five systems analyzed were the double glazing, ventilation fans, HAF fans, an insulated ground skirt and an automated sidewall roll-up system. The effect of these systems, functioning all at once, on greenhouse relative humidity was analyzed first. It was concluded from Figures 32, 33 and Table 8 that the greenhouse experienced an 8% decrease in its ability to maintain RH levels between 40-80% from 2020 to 2022. This means that relative humidity levels in the greenhouse were more often over 80% or under 40% following the installation of all five of our interventions. This could be attributed to many factors. The decrease in desirable RH levels could be due to the increase in moisture rich air penetrating the greenhouse through the ventilation fans and the automated sidewall roll-up system. This could also likely be attributed to the former ventilation practices at the greenhouse. Prior to our interventions, the greenhouse sidewall was typically left in the rolled down position for a majority of the fall and winter and rolled up during the spring and summer. At the Nexus greenhouse, overheating temperatures are experienced more often than freezing temperatures, so it is likely that the sidewall was rolled up for 7-8 months out of the year. This constant source of ventilation likely allowed the greenhouse to stay within desirable RH levels for a larger percentage of the year.

Although our overall results pertaining to greenhouse relative humidity levels were not in line with the original hypothesis, the effect of these systems on greenhouse temperatures exceeded our expectations. It was concluded from the study that there was a 16.3% increase in the greenhouse ability to maintain temperatures above 32°F, and a 20% increase in the greenhouse's ability to maintain temperatures under 90°F. The double glazing layer installed at the greenhouse significantly reduced freezing events, and the ventilation fans, in partnership with the automated sidewall roll-up system, significantly reduced overheating events.

SUGGESTIONS FOR FURTHER RESEARCH

Greenhouses have played an important role in scientific research for centuries, and they will continue to do so for years to come. This study examined multiple greenhouse microclimate control technologies and their ability to impact greenhouse performance. The research performed on these technologies and the supporting literature review will serve as a resource for agricultural professionals looking to improve the performance of their greenhouses or carry out further research on the interventions studied.

This study could have been improved in many ways. The most important limiting factor in this study was the lack of a control greenhouse due to limited funds and physical space. A control greenhouse would greatly reduce the amount of time needed to perform this study, and could provide the opportunity for more thorough and accurate results. A control greenhouse could also reduce the complication of interactions between the different interventions. The interventions that were studied were installed at the greenhouse one after another. This caused a major hiccup in the study, because the individual effects of each system had to be isolated from one another. Having a control greenhouse could have prevented this issue. Also, as mentioned in the limitations section, the nexus greenhouse is equipped with many interventions and features that were not included in this study. One of the most significant out of those features is the pond that is located inside of the Nexus greenhouse and used for aquaponics research, which has a

1,200 gallon capacity. The thermal mass provided by this pond undoubtedly contributed to heating and cooling of the greenhouse throughout the time period from which data used in this study was collected. There is also an insulated ground skirt underground installed along the north and south walls of the Nexus greenhouse that was installed throughout the duration of this study. The installation time period lasted from March 2021, when the south side ground skirt was installed, to September 2021, when the north side ground skirt was completed. This insulated ground skirt likely contributed to higher soil temperatures and lower soil moisture content inside of the greenhouse, which could have affected the results of this study.

Another limiting factor was the issues we ran into with the individual interventions. For example, the automated sidewall roll-up system stopped working for a short period of time unexpectedly. This required us to omit all of the data collected during the time period in which the system was not working from the study. Installing a real time data logger that could monitor the system remotely would have allowed us to know about and resolve this issue much sooner. Additionally, another issue encountered was that the sidewall roll-up system was not properly sealed at the bottom where it met the ground, allowing outside air to infiltrate the greenhouse even when it was in the rolled-down position, which could have potentially skewed the results. Sidewall roll-up systems are usually equipped with a one to two foot knee, or hip, wall topped with a channel that is installed into the ground underneath the sidewall. This allows the roll bar to descend into the channel and seal the greenhouse when the sidewall is in a rolled down position and decreases the draft on plants that are grown near or in the ground. However, this study could be used as a good reference point for future research on the effect of proper sealing for these systems. A grant is currently being written to apply for funding for materials to build a hip wall for this system at the Nexus greenhouse, with plans to install the system over the winter of 2023.

Another suggestion for further research would be to have a longer data collection period, or more specifically, at least a year long data collection period for each individual intervention. Due to the fact that the automated sidewall roll-up system was installed in May of 2022, and the data collection period for this study ended in October 2022, we were not able to analyze the effects of this system during the winter months. Especially because this study took place in an area with a moderately cold climate, it would have been extremely valuable to analyze the performance of this system during the winter months.

CONCLUSION

This study analyzed the effects of ventilation fans, double glazing, and an automated sidewall roll-up system on an unheated high tunnel greenhouse in the North Carolina High Country. The study also analyzed the effects of five systems, double glazing, ventilation fans, HAF fans, an insulated ground skirt, and an automated sidewall roll up, working in conjunction to identify their combined effect on greenhouse performance. There have been very few quantitative analyses performed to analyze the effects of these systems, and the study detailed in this paper hopes to fill in some of the gaps in the existing literature. The primary motivation for this study was to prove that an unheated high tunnel greenhouse in the North Carolina High Country is suitable for growing season extension, and to quantify the effects of the studied systems on a high tunnel greenhouse in this region to provide a resource for local farmers and agricultural producers. The study found that there was a 16.3% increase in the greenhouse's ability to maintain temperatures above 32°F, and a 20% increase in the greenhouse's ability to maintain temperatures under 90°F after the installation of all five systems analyzed in this study. Frequency of freezing and overheating events in the greenhouse were reduced significantly due to the effects of the five systems.

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Vita

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