Shallow Geothermal Earth-to-Air Heat Exchange: Cooling and Heating for Sustainable Season Extension

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Abstract

On-farm research collaborations between farmers and researchers can provide data-driven solutions that increase farm economic sustainability. Urban on-farm research is key in addressing production concerns that are specific to urban production, including heat island effects, intensive production pressure due to size constraints, and the need to develop high value specialty crops. Growing in protected environments like high tunnels, caterpillar tunnels, or hoop houses allow for season extension for urban food production which facilitates the production of crops that bring a higher price point. Non-electrified tunnels typically rely on passive ventilation and manual venting to manage internal conditions. To improve utility of high tunnels for season extension, additional capacity for ventilation and heating is needed, which can be a high cost to growers. Additionally, the most common options for high tunnel heating are propane-fueled heaters that have high operation costs and counteract sustainability efforts. One alternative that can provide both cooling capacity and heating at different parts of the year is a shallow geothermal earth-to-air heat exchanger (EAHX) that takes advantage of the soil's insulating properties at shallow depths of 1 to 2 meters. These systems temper ventilation air, bringing it closer to soil temperatures, and direct it into the growing environment. This paper describes efforts to evaluate the efficacy of this EAHX infrastructure for season extension in Ohio through local partnerships and on-farm research sites. Initial findings from a pilot system installation indicates that these EAHX systems can be installed on-farm for prices competitive with propane-powered heaters, retrofit to existing high tunnels and caterpillar tunnels, and provide impactful heating and cooling, with BTU equivalent gains of 4 gallons a week of propane for heating in fall and cooling equivalent to ¼ ton air conditioning unit. This paper details EAHX system installations at both a rural and urban farm, including the installation at Franklinton Farms, a multi-parcel urban farm that has been growing since 2007 in the economically disadvantaged, poorly canopied neighborhood of Franklinton, immediately adjacent to downtown Columbus, Ohio, the 14th most populous city in the US. We will address lessons learned from the installations, the potential benefits, and costs of EAHX for season extension and fostering fruitful on-farm research partnerships.

Keywords

high tunnel, ventilation, heating, environmental control, season extension

Disciplines

Agriculture

Comments

Detailed response to reviewer comments submitted as additional file

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INTRODUCTION

Season Extension using high tunnels is a formidable tool in the toolbox of a grower, allowing them to grow, harvest, and sell produce during an extended time period for a higher price point, which can provide for economic sustainability. Unfortunately, current production practices of temperature control for season extension are highly energy intensive, resulting in high environmental impacts and making up the second or third highest cost in greenhouse production (UW-Madison, 2015). These high energy costs may cause many farmers with existing high tunnels to cease growing through the winter, and this lack of year-round utility slows adoption of this infrastructure by new farmers. One SARE-supported on-farm study investigating costs and benefits of season extension in Ohio showed that heating to 1.7°C in a winter high tunnel increased yield of kale and spinach by 30 and 36% respectively compared to the unheated section (Hilfinger, 2023).

Providing lower-cost and environmentally friendly heating technologies for season extension could allow farmers to grow more produce year-round, strengthening local food systems. Additionally, increased year-round production could generate higher revenues and greater capacity to enter retail contracts, farmers markets, and community supported agriculture (CSA) programs. Investigating more environmentally friendly practices to improve season extension is necessary to pursue strong local food systems that will not further contribute to climate change impacts that will negatively impact producers.

One sustainable energy alternative for heating and cooling for season extension is the use of shallow geothermal resources. These heat exchange systems move air or fluid through underground tubes, sometimes called earth tubes, located 1-4 m underground and the tempered air is transmitted to the growing area. The insulating properties of soil and the constant heat generated by the earth's core create these 'shallow geothermal resources,' which lag behind seasonal weather changes and can provide relative cooling and heating at different parts of the year. (Figure 1). Figure 1 demonstrates how soil at greater depths has a more insulated temperature range and a longer lag compared to shallower soils and surface temperatures, which closely track air temperatures. Because the systems rely on soil's insulating capacity, they are not geographically constrained, in contrast to high-temperature geothermal resources found at great depths, primarily in the Western U.S. (US DOE, no date).

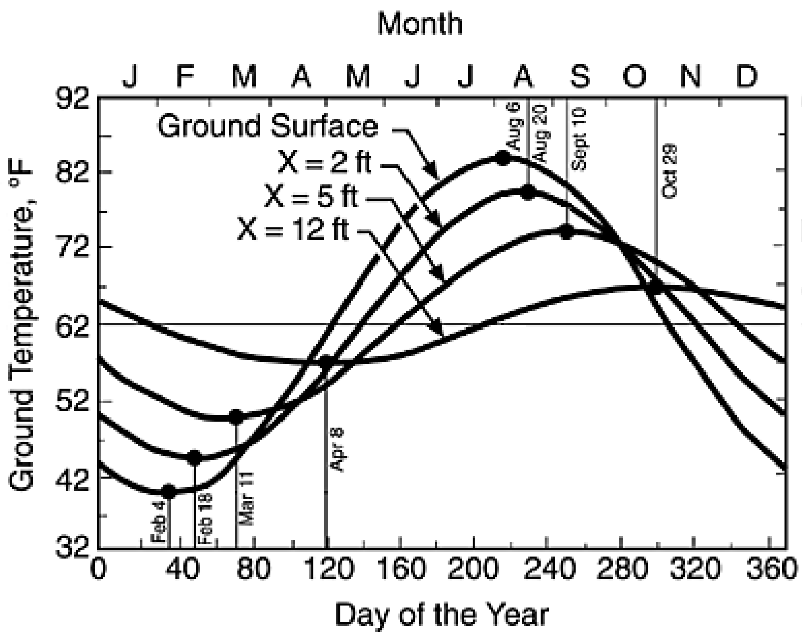

Figure 1 Soil temperature, time lag, and depth. Source: US DOE, n.d.

Geothermal heat pump systems have been in use since the 1940's in the United States for residential and commercial heating (US DOE, no date). The systems typically consist of a closed loop of antifreeze solution underground, with a heat exchanger used to transfer heat between the ground-source pump and the air circulated through the home (US DOE, no date). The use of these closed-loop systems for residential and commercial applications ensures indoor air quality. Direct air exchange, where outside air is pulled through underground tubes and circulated through the building, may carry a higher risk of microbial contamination as the air passes through potentially high-humidity, condensing conditions that occur in the underground tubes (Kang and Nagano, 2016). However, for protected environment agriculture applications, the use of direct air heat exchange may be acceptable when it would be used in conjunction with additional fresh air ventilation. More research is needed to evaluate air quality when using these systems.

Direct air circulation systems may be better candidates for on-farm installation because of the lower complexity compared to closed loop and heat pump systems. Additionally, the relatively shallow depth of earth pipes can be installed on-farm with non-specialized equipment (Sethi and Sharma, 2008). One design of direct air heat exchange systems that has garnered attention and interest is the Greenhouse in the Snow system, which was popularized in a video ‘Nebraska retiree uses earth’s heat to grow oranges in snow’, which has over 3 million YouTube views and offers greenhouse kits for sale (Dirksen, 2018). These proprietary systems utilize shallow geothermal heat with ‘air to air’ or ‘liquid to air’ systems and are often combined with sunken greenhouse designs for additional insulation capacity. Because of the need for extensive excavation for the sunken greenhouse and the series of underground pipes, this system would not be relevant to farmers with existing high tunnel infrastructure. To provide some of these same benefits to existing high tunnel growers, investigation into additional techniques was needed.

Because shallow geothermal earth-to-air heat exchangers (EAHX) offer many potential benefits for high tunnel growers, this project sought to investigate the costs and benefits of retrofitting EAHX systems to existing high tunnels. The specific objectives were to design and install an EAHX system retrofit to a production high tunnel, assess the EAHX system performance in providing heating and cooling to the growing environment, and to generate knowledge and insights for other farmers interested in providing additional heating and cooling for controlled environment agriculture using this sustainable alternative to fossil fuel-powered heating.

MATERIALS AND METHODS

Design and installation of EAHX pilot system at rural farm

1. Description of high tunnel.

The tunnel is a 9 x 29 m Gothic design, with double wall polyethylene covering, equipped with inflator fan, located at Oaks and Sprouts Limited in Urbana, Ohio. The tunnel had existing ventilation and heating infrastructure, along with four horizontal air flow circulation fans. The EAHX system outflow was directed towards air circulation fans to best distribute the tempered air to the growing area. (Figure 2)

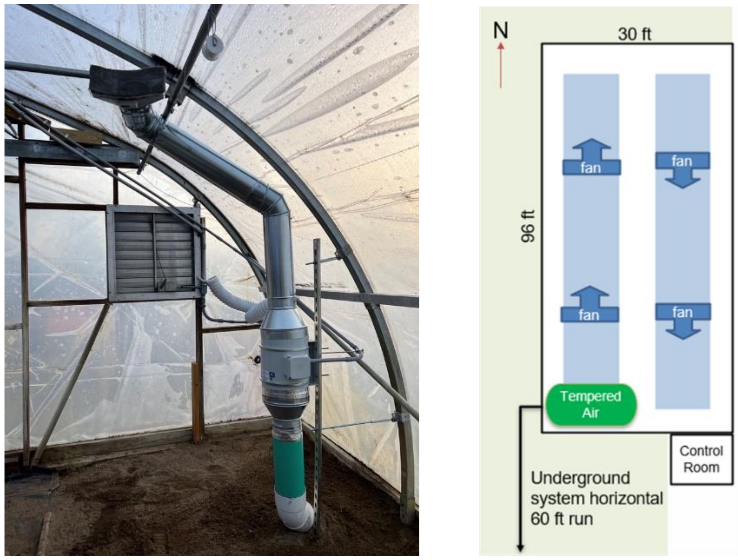

Figure 2 L: Fan and ductwork of EAHX System. R: Plan view of high tunnel and EAHX distribution point

2. EAHX system design.

Design of an EAHX system requires selection of system depth, pipe size, pipe length, and system fan. Because of the increasing insulation capacity at deeper soil depths, a target depth of 2 m was selected as being able to be accomplished without the need for specialized equipment. A pipe size of 15.2 cm (nominal 6”) was selected as it was readily available from local hardware stores and allowed more airflow capacity than 10 cm (nominal 4”) pipe. Corrugated pipe was selected as it provides greater surface area for effective heat transfer and has a low cost per length, though it requires a higher-powered fan compared to the same length of smooth pipe. Pipe length and fan selection are interrelated, as increasing system length is a primary factor in determining the pressure drop a fan must be able to overcome. The higher the airflow rate, the more capacity the system has to deliver tempered air, but at higher airflow rates, a larger fan (able to operate at higher pressures) is needed. Fan sizing, heat exchange performance equations, and corrugation friction factors were adapted from literature to achieve a target airflow rate of 0.5 air changes per hour in the tunnel, or around 215 cubic feet per minute (Spengler and Stombaugh, 1983; De Paepe and Janssens, 2003).

3. EAHX system installation and monitoring.

Before excavation, 811 was called to verify no buried utilities in the area. A backhoe with 18” bucket was used to create a trench with 20 m total length, an average depth of 2 m, and a slight grade towards one end to facilitate drainage to a pump point. Solid corrugated pipe and PVC pipe of 15.2 cm cross-section was joined with watertight connections. The system’s intake was a solid PVC pipe and was secured to exclude precipitation and pests. The system’s fan is a humid-environment rated in-line blower. The fan has run continuously since March 2023. Data logging sensors recording hourly temperature and relative humidity were placed at the intake and output of the EAHX system.

Design and installation of EAHX pilot system at urban farm

1. Description of caterpillar tunnel.

The caterpillar tunnel is a 4.6 x 12.2 m Gothic design, with a single layer of polyethylene covering, and equipped with roll-up sides and ends, and is located at Franklinton Farms in Columbus, Ohio. There was no existing heating or ventilation capacity in the tunnel. The EAHX distribution was located at the top center of the tunnel and directed towards each end of the tunnel with a wye fitting.

2. EAHX system design

The same design equations were used to create a system to deliver an airflow capacity of 0.5 air changes per hour. Because of the smaller volume of the tunnel and the lower airflow requirements, 10 cm (nominal 4”) piping was used throughout the system. Because of the lack of grid electric at the site, a solar PV array and batteries were erected at the site to power the fan of the EAHX (Figure 3)

Figure 3 L: EAHX air distribution in tunnel. R: solar panel at site

3. EAHX system installation and monitoring.

Prior to excavation, the 811 ‘Call Before You Dig’ service was contacted to verify the absence of buried utilities in the area. A walk-behind trencher with a 10 cm cutting width and rated digging depth of 1 m was used to dig the trench. However, the average depth achieved was 63 cm, and the trench sloped deeper for a pump access point and sloped up towards the entrance of the tunnel. The total run of the underground EAHX corrugated piping was 19.5 m. The system’s intake was a solid PVC pipe and was secured to exclude precipitation and pests, and watertight connections made between the solid and corrugated pipe. Data logging sensors recording hourly temperature and relative humidity were placed at the intake and output of the EAHX system.

Quantitative EAHX performance

The equivalent cooling and heating capacity were found by considering the British Thermal Unit (BTU) equivalent of the temperature change provided by the EAHX system (Equation 1), where ΔT= temperature difference, Q = volumetric airflow, Cp = specific heat, ρ = air density, and t = time.

Equation 1 : $BTU = \Delta T \times Q \times Cp \times \rho \times t$

It was taken that 12,000 BTU/h is equivalent to a ton of cooling capacity. The equivalent propane capacity was found considering that a gallon of propane contains approximately 91,450 BTU, and the efficiency of propane heaters was assumed to be 78% (Madison, 2015).

RESULTS AND DISCUSSION

Installation lessons learned

There were several lessons learned during the urban installation that should be used to inform future projects. It is not unusual for urban farms to be located on formerly developed parcels, including land available through local city and council land-banks. It is common for the history of the remediation and original structure to be unavailable through a record search. Potential problems include foundation remnants or rocky infill, making the excavation challenging. If the site is owned by a city or municipality, the urban farmer may have to get permission in writing prior to the installation or could have the installation permit declined to keep the property ready for potential development. It is also common for urban farms to lack electricity on-site necessitating either the installation of electric service or the use of solar with battery storage to run the system. Zoning may also challenge the installation if the high tunnel is already at the allowable developable property line.

Quantitative EAHX performance at rural farm

From one year of running the pilot EAHX system in the rural setting, the cooling capacity through was equivalent, at its maximum, to a ¼ ton air conditioning unit (Figure 4).

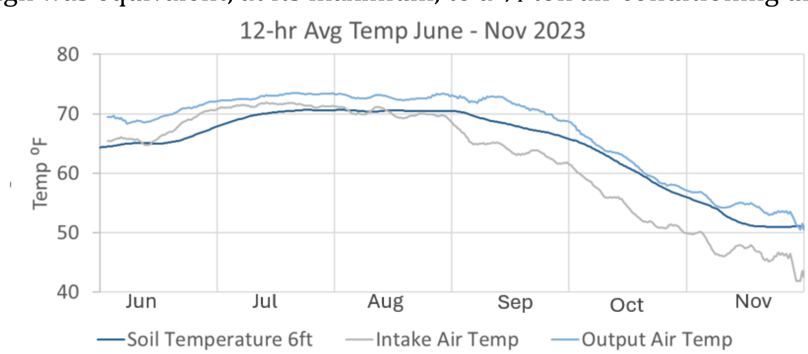

Figure 4: Average air and soil temperatures across six months in pilot EAHX system

Through Fall 2023, the average heat delivered was equivalent to 4.2 gallons of propane a week, approximately $10 of cost savings weekly. In addition, the continuous use of the EAHX system allowed for extended production of cherry tomatoes in the high tunnel through Thanksgiving 2023, when a local cold snap finished the season. In this period, the farmer was able to find additional avenues to market his fresh tomatoes. At the beginning of the 2024 growing season, the EAHX system provided necessary heating for the farmer to maintain conditions for seed starting, and the propane heating system was used for just one week to provide supplemental heat in a cold period. This performance in the first year of the system demonstrated the EAHX system may be a formidable tool to enhance the season extension and market production capacity of high tunnels in Ohio.

Monitoring is ongoing at the newer EAHX installation and neighboring control tunnel at the urban farm site.

CONCLUSION

Shallow geothermal earth to air heat exchangers show promise as a tool for the urban grower to improve season extended crop production. With global climate change impacting urban farms and disrupting production schedules, having the ability to adjust temperature in the high tunnel allows for longer growth cycles and season extended growth of high value specialty crops. This in turn can provide economic sustainability through improved cash flows. Shallow geothermal EAHX systems offer a unique solution for sustainable season extension, as they provide access to a renewable source of heating and cooling potential underneath the soil that can be accessed without specialized equipment. These systems use only electricity to power a fan, avoiding much of the carbon footprint and recurring cost of fossil fuel-derived heat sources. With installation costs in the $3,000 to $5,000 range, the cost of these systems could be covered with a one-time grant award or low-cost loan. The lack of permanent heating fixture means the system would be compatible with NRCS EQIP programs governing the use of high tunnels. Our preliminary studies have found that a system sized to provide 0.5 air changes per hour through an EAHX system provided meaningful cooling in the height of summer and warming throughout the fall, winter, and spring. Further studies are ongoing to quantify the heating and cooling provided by these systems compared to control unheated and passively ventilated high tunnel systems. Future work is needed to quantify impacts on plant production and utility in different scenarios, including system performance in different climates, soil types, and under different soil covers.

In summary, urban on-farm research collaborations between farmers and researchers can provide data-driven solutions that increase farm economic sustainability. This research is key in addressing production concerns that are specific to urban production, including heat island effects, land scarcity due to development, and the need to identify and produce high value specialty crops. Growing in protected environments like high tunnels, caterpillar tunnels, or hoop houses facilitates season extended urban food production, supporting the growing of crops that bring a higher price point. Adding EAHX systems to protected environments can provide a low-cost option for producers to maximize their season extended production.

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