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Quantifying How High Tunnels Create A Microclimate For Improved Crop Growth

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Abstract

Farmers in the Great Basin are investing in inexpensive low-tech greenhouses, known as high tunnels (HTs) or hoop houses. This study evaluated the microclimate inside HTs, how farmers were using HTs to grow crops and how the microclimate inside HTs led to improved crop growth. The HT microclimate varied by season, with more growing degree days inside the HT than outside in the spring, fall and winter. The way farmers managed HTs using manual ventilation, shade cloth and fans was the strongest determinant of how the climate inside the HT was different from outside. HTs increased vapor pressure, leading to potentially less need for irrigation water. By creating microclimates suitable to crop growth, farmers were able to extend the growing season, grow a wider variety of crops and improve yields. HTs improved the economic viability of farms for farmers who had been using them for several years. HTs in the high desert are only increasing in popularity and farmers are continuing to use and recommend them to other farmers.

Dedication

For the small farmers I was privileged to work with and small farmers around the world who face challenges, care for the land and run practical experiments everyday.

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Introduction

Globally, most farming still occurs at a small scale. Despite increasingly being displaced by larger operations, small farms grow a wide variety of nutrient-dense foods, often providing regional food security (Samberg *et al.*, 2016). Small farms produce on multiple scales, from a few hectares to hundreds of hectares. They tend to use a wide array of resources, land tenure systems and labor (Wolfenson, 2013). In the U.S., the United States Department of Agriculture (USDA) defines small farms as those with a gross annual income of $250,000 or less (*2007 Census of Agriculture: Small Farms,* 2007). Emerging technologies can allow local small farms to produce a wide variety of diverse and nutritious crops, strengthening the farms' economic viability (Waterer, 2003; Galinato and Miles, 2013; Hecher *et al.*, 2014). In regions such as the Great Basin, United States, where growing conditions are more difficult, high tunnels, also known as hoop houses, are one evolving technology increasingly being used by small farmers in cost effective ways to intensify production.

The term high tunnel (HT) refers to a single or multi-bay greenhouse-like structure covered in one or two layers of greenhouse plastic that manages heat manually through roll-up sides, vents or fans. The type of structure varies by location, based on the farmers' needs and local climate concerns such as wind, rain and snow load (Lamont *et al.*, 2002; Blomgren and Frisch, 2007). The use of HTs in agriculture has been increasing worldwide especially in Asia, Italy, Spain and the Middle East where HTs have been used for many decades (Lamont, 2009). More recently in the United States, HT adoption has increased as local food movements across the country have led to higher demand for fresh, local produce (Carey *et al.*, 2009). In general, HTs are used for growing high-value specialty crops, such as berries, tree fruit, cut flowers and a wide variety of vegetables (Lamont, 2009). As a result, most HT research has focused on crop growth and yield.

Study Objectives

Because the climate conditions in a HT are more controlled than growing in the field, but not as precisely as in greenhouses, they warrant their own research. The purpose of this study is to fill the gap that currently exists in HT research in the high desert. First, the study evaluated whether the HT climate was different from the climate outside and if the orientation, size and the way the HT was managed influenced the differences. Second, farmers were interviewed to understand how they were using HTs and how the HTs influenced their business. Third, leaf area index and yields were compared inside and outside to determine if the differences in climate also influenced the differences in yield. The objective of this research is twofold. The first to fill an important gap in the research by providing climate data on HTs in the high desert. The second to provide farmers who are using HTs with information on how the microclimate inside HTs is influenced by different management strategies.

Literature Review

High Tunnels in the High Desert

HT research is particularly lacking in the high desert environment where many small farmers are growing food to supply local urban areas (Gatzke, 2012a). In response to increased use of HTs in the Great Basin, University of Nevada, Cooperative Extension has begun conducting research on HTs. A study examining growing summer crops in HTs in the Great Basin found yields and quality of tomatoes, summer squash and some pepper varieties improved, although eggplant and melons grew better outside. Studies also found HTs provided some protection against pests, such as insects, insect vectored diseases and wild animals (Gatzke, 2012b; Davison and Lattin, 2015). By growing different high-value crop varieties and harvesting for a longer period of time, farmers can use HTs to produce a profitable crop (Bishop *et al.*, 2010).

Economics

Economic success with HTs is usually based on how well labor costs and crop rotations are managed, because HTs typically require more labor than field crops (Fitzgerald and Hutton, 2012). Crops grown in HTs are often managed similarly to field crops, using drip tape for irrigation, row covers for crop protection, and fertigation (Lamont, 2009). However, HTs often provided labor flexibility because farmers had more control over when to plant and could work in HTs even in bad weather. Labor in HTs could be balanced with field labor by focusing on HT work in the spring before field crops had been planted and working less in HTs during the summer (Conner *et al.*, 2010). When properly managed, HTs can increase farm profits. Because farmers reported harvesting produce from HTs one month earlier and later in the season, HTs extended the regular growing season by two months (Fitzgerald and Hutton, 2012).

Produce grown in HTs has the potential to fill niche markets available through the local food movement (Conner *et al.*, 2009). The season extension provided by HTs allowed farmers to sell a wider variety of produce for a premium price earlier in the season, while building and maintaining longer relationships with their customers, increasing their income for an extended period of time (Conner *et al.*, 2010; Maughan *et al.*, 2015). Customers also valued the increased availability of fresh produce, as well as developing relationships with farmers to gain information about how and where the crops were produced (Conner *et al.*, 2010).

The relatively low cost of this technology, from initial installation to continuing management, has made them a critical asset to farmers of all sizes. HTs had a relatively quick rate of return on investment, averaging four years to earn back the initial cost (Conner *et al.*, 2010). The increase in income and low cost of HTs led many farmers to feel that HTs were critical to the survival of their farm, and they would consider investing further in the technology (Fitzgerald and Hutton, 2012). Both local and regional economies also benefited from a longer growing season by allowing farmers to extend their market season in order to meet the local demand for fresh produce (Conner *et al.*, 2010).

Crop Growth

HTs are a flexible tool that farmers use to modify and improve field crop production. Many of the high-value crops that local markets demand grow well in HTs (Lamont, 2009). Thus, they are a useful tool for farmers who want to take advantage of the local food movement and maintain economic viability. Depending on management practices and crop choice, HTs can provide season extension, crop protection and production intensification (O'Connell *et al.*, 2012).

HTs often enhance crop development, which can lead to more produce earlier in the season (Waterer, 2003). From tomatoes to raspberries, produce was harvested earlier and more consistently from HTs than from outside, increasing profitability especially at the beginning and end of the season (Hanson *et al.*, 2011; O'Connell *et al.*, 2012; Sydorovych *et al.*, 2013). HTs also improved the yield of cut flowers while reducing the time to harvest and increasing the number of crop rotations (Wien, 2013; Owen *et al.*, 2016). Farmers reported that, in addition to higher yields, produce was of a higher quality inside HTs, reducing the time spent preparing the product before sale (Fitzgerald and Hutton, 2012). Because they were protected from wind, rain and cold damage, cherries, strawberries and cut flowers grown under HTs had higher marketable yields sometimes earlier in the season (Kadir *et al.*, 2006; Hanson *et al.*, 2011; Lang, 2014). HTs were even used to produce cool-season crops, such as lettuce, throughout the winter (Borrelli *et al.*, 2013). However, some crop varieties did not grow as well under the climate conditions inside HTs (Wallace *et al.*, 2012; Rudisill *et al.*, 2015). For example, some blackberry and melon varieties grew better outside (Hanson, 2012; Fernandez and Perkins-Veazie, 2013; Vescera and Brown, 2016).

Quantifying how crop growth changes over time inside and outside HTs may improve understanding of how HTs impact crop growth, particularly when that analysis is accompanied by climate monitoring. Leaf area index (LAI) is one metric used to assess changes in growth over time. LAI is a measure of the total leaf area per ground area (Larcher, 2003). While one study examined leaf area inside and outside the HTs and found it to be higher inside (Kadir *et al.*, 2006), no studies have examined the how growth rate over time differs inside and outside HTs. Taken over time, these measurements can indicate the rate of crop growth. By comparing LAI measurements inside and outside HTs, the rate of crop growth inside HTs can be better understood. HT design and management impact how much time crops spend in their optimal growing environment which in turn impacts the rate of crop growth. LAI provides a metric for assessing the speed and quality of crop growth over time by quantifying how quickly the crops grow and any damages the crops sustain.

Climate

One of the main proposed benefits of HTs is the ability to use them to create a microclimate to improve crop growth. The literature suggests that HTs modify the climate in two distinct ways. In tropical areas they provide protection from heavy rain, while in cold and temperate areas they moderate temperature. Both of these climate modifications act to extend the growing season and improve water efficiency which may increase produce quality, improve yields and reduce disease (Lamont, 2005, 2009). Because HTs utilize passive heating and cooling, they are highly influenced by the local climate conditions and management practices. Therefore, it is necessary to examine the microclimates of HTs in different locations. As a result of the popularity and economic success of HTs, universities and cooperative extensions have been researching and providing resources about HTs (Carey *et al.*, 2009). As use of HTs continues to grow, research and education will be necessary to address information gaps on labor management, soil and climate (Carey *et al.*, 2009; Montri and Biernbaum, 2009; Fitzgerald and Hutton, 2012).

Solar Radiation

The plastic covering on HTs reduces and diffuses incoming solar radiation (Blomgren and Frisch, 2007; Hemming *et al.*, 2008; Heuvelink and González-Real, 2008). Direct solar radiation creates an uneven distribution with more reaching the top of the plant than the bottom. However, diffuse solar radiation is more evenly distributed, decreasing the danger of the top of crops overheating and increasing the overall distribution of light to the entire plant (Hemming *et al.*, 2008). The diffuse solar radiation distribution can lead to increased photosynthesis, crop growth and fruit quality (Markvart *et al.*, 2010; Dueck *et al.*, 2012; Elingsa *et al.*, 2012).

Studies comparing solar radiation inside HTs to outside found that HTs consistently reduce the amount of incoming solar radiation by about 20 to 35%, with some HTs lowering it by as little as 15% (Table 1). The addition of shade cloth further decreases solar radiation by as much as 50% (Zhao and Carey, 2009). Comparison of existing studies suggests that the variability in how much solar radiation is reduced may be due to the site selection, orientation or covering of the HTs (Table 1).

Several factors influence the amount of incoming solar radiation inside HTs. In practice, a roof angle between 20° and 30° tends to transmit the most solar radiation (Giacomelli, 2009). As the angle of incoming solar radiation varies over the season, more solar radiation is transmitted when the angle of solar radiation becomes more perpendicular to the roof of the HT. East-west oriented HTs tend to transmit more incoming solar radiation than north-south oriented HTs, especially in the winter at high latitudes in the Northern Hemisphere (Blomgren and Frisch, 2007) and presumably in the Southern Hemisphere as well.

The thickness and film treatment of the plastic covering also affects the amount and quality of incoming solar radiation (Espí *et al.*, 2006). Coverings can be treated to absorb and reradiate infrared radiation, increasing the HTs' heat-retention capacity. However, if temperatures need to be reduced in HTs, a covering treatment or shade cloth can reflect solar radiation (Blomgren and Frisch, 2007). Finally as the cover ages, the amount of solar radiation transmitted by the cover can be reduced by as much as 7% after four years (Giacomelli, 2009).

Because most of the studies listed in Table 1 used standard 0.15 mm plastic, the additional variability not explained by shade cloth is likely due to the variability in siting and orientation of the HTs. Despite its important influence on the amount of incoming solar radiation, the orientation of the HT is not often reported (Table 1). As HT research continues, more consistent reporting of HT site, orientation and materials will improve understanding of how different HT management strategies influence incoming solar radiation. The types and treatments of plastic coverings are also rapidly evolving (Mormile *et al.*, 2017). As more varieties of plastic are adopted, further research will be necessary to understand how incoming solar radiation is reduced and the subsequent influence on crop growth.

Wind

Properly installed HT structures provide protection from excessive wind, while allowing farmers to control the growing conditions of crops by venting excess heat and moisture (Blomgren and Frisch, 2007; Lamont, 2009). Roll-up sides, end vents or fans give farmers flexibility to open or close HTs based on wind speed and direction while taking into account the progress of the crops' growth (Wells, 1996). The design of the HT also determines how and when farmers can vent without losing or damaging the plastic cover. Farmers often close their HTs during high wind events to keep the plastic and structure from sustaining wind damage (Blomgren and Frisch, 2007; Black *et al.*, 2011).

Across studies examining wind, HTs reduced wind speeds inside by 34 to 98% (Table 2). Wind reduction varies depending on how the HT is managed and the HT's location relative to prevailing winds. In Table 2, the largest wind reduction occurred when a woven fabric rather than greenhouse plastic covered the HTs. Positioning the HT so that the end is facing the prevailing wind direction lowers the wind exposure to the structure (Blomgren and Frisch, 2007). However, some HTs' roof shape and angle are designed to push air up over the structure when placed perpendicular to prevailing winds (Giacomelli, 2009). In practice, farmers consider the unique wind conditions of the location where the HT is being placed to determine the optimal type and orientation of the structure (Spaw and Williams, 2004; Blomgren and Frisch, 2007). While the covering and management of a HT does seem to influence the amount of wind reduction, each study varies in how much detail they provide on management and location of the HTs. Because of the sparse reporting of information in the literature, it is difficult to determine the relationship between management of HT ventilation and the amount of wind reduction.

Soil Temperature and Moisture

HTs' influence on soil temperature is highly variable (Table 3), depending on how the HT is managed. When HTs were closed, soil temperatures were higher inside than when HTs were vented (Rader and Karlsson, 2006). When a double air-inflated layer of plastic or infrared-blocking plastic was used, soil temperature increased further (Both *et al.*, 2007; O'Connell *et al.*, 2012). In addition to structural and management differences in the HTs, variations in the soil may also contribute, although it is difficult to draw conclusions from the information in Table 3, in part because soil type is not always reported.

Furthermore, the variability in soil temperature response may be related to differences in the management of soil inside and outside of HTs. Soil is often more intensively managed inside HTs to maintain higher production levels than outside (Montri and Biernbaum, 2009; Knewtson *et al.*, 2010). In addition, soil nutrient and salt levels can be different from outside (Knewtson et al. 2010), which in turn influences how crops are irrigated inside and outside. Different soil types and management practices may in part have led to the variable response from soil temperature across the studies (Table 3).

Soil temperature in HTs can vary over the season, but its response was inconsistent across studies. Several studies observed larger increases in HT soil temperature early in the spring, with less of an increase or even a slight decrease relative to outside in the summer (Lamont *et al.*, 2003; Reiss *et al.*, 2004; Zhao *et al.*, 2014). However, some studies found HT soil temperature increased more in the fall and winter than in the spring and summer when it was near or below outside soil temperatures (Rader and Karlsson, 2006; Ogden and Iersel, 2009). This research indicates that HTs influence on soil temperature is different depending on the time of year and management practices such as venting.

Little research has been done on soil moisture. HTs provide more control over when, where and how much water is applied to crops (Montri and Biernbaum, 2009). Further research will be necessary to understand how HTs impact the amount of moisture held in the soil, and in turn how that influences crop growth.

Air Temperature

While air temperature inside HTs varies depending on management practices, average air temperatures are generally higher inside HTs than outside (Table 4). However, HTs influence minimum and maximum air temperature differently. Across most HT designs and locations, maximum air temperature increases more than minimum air temperature.

Several factors influence the magnitude and direction of maximum air temperature differences between inside and outside HTs. Maximum air temperatures rise more inside HTs on sunny days than cloudy days (Ogden *et al.*, 2011; Powell *et al.*, 2014). Increases in air temperature inside HTs are reduced and often become negligible with more ventilation (Ogden and Iersel, 2009; Wien, 2009; Lang, 2014). In particular, when HTs have no sides or end walls air temperatures can be the same as or similar to outside (Thompson *et al.*, 2009; Powell *et al.*, 2014; Rogers *et al.*, 2016). Maximum air temperatures can be effectively lowered inside HTs, often below that of outside, using shade cloth (Rowley et al. 2011; Zhao and Carey 2009).

Minimum air temperatures inside HTs can slightly increase above (Ogden and Iersel, 2009; Rogers and Wszelaki, 2012), be the same as (Ogden and Iersel, 2009; Ogden *et al.*, 2011; Rogers and Wszelaki, 2012; Rogers *et al.*, 2016) or decrease below outside air temperatures (Ogden *et al.*, 2011; Wallace *et al.*, 2012). Nonetheless, HTs can provide protection from air temperatures below freezing (O'Connell *et al.*, 2012), such as in Florida where they buffered minimum air temperatures by several degrees (Santos and Salame-Donoso, 2012). In some cases, crops inside HTs benefit from an increase in both minimum air temperature and minimum soil temperature buffering extreme low temperatures (Zhao *et al.*, 2014).

Several processes inside HTs can lead to air temperatures lower than outside. Because of the lack of air movement inside HTs, especially when they are closed, warmer air from outside does not mix with the air inside, and less air movement leads to more stratification (Ogden *et al.*, 2011). This pattern is especially pronounced on clear nights. Additionally, some plastic coverings radiate more long wave radiation than the ground or crops, creating a thermal inversion effect (Montero *et al.*, 2005; Ogden *et al.*, 2011).

Two potential passive solutions to the lower minimum temperatures have been suggested in the literature. One is to cover HTs in an infrared-blocking greenhouse plastic. Summer nighttime air temperatures inside infrared-blocking HTs remained just above those outside (Both *et al.*, 2007; Wien, 2009), while winter nighttime air temperatures inside HTs dropped below outside air temperatures (Wien, 2009). Because of the variable results between seasons, the impact of different plastic coverings on minimum temperature warrants further research. Another solution is to use low tunnels or floating covers, a plastic or woven fabric that covers one row of crops either with small hoops or directly on the crop. HTs with low tunnels have been more effective increasing minimum air temperatures by several degrees (Martin and Sideman, 2012; Ward and Bomford, 2013; Santos *et al.*, 2014).

In many cases, HTs' effect on temperature varies depending on the season (Fig. 1, Table 4). HTs often increase temperature more during the winter, spring and fall, while during the summer, temperatures are closer to or lower than outside. This seasonal variation is likely a function of seasonal changes in management practices. HTs were often vented more in the summer in order to keep the HT from reaching extremely high temperatures (Reiss *et al.*, 2004; Kadir *et al*., 2006). Adding shade cloth in the summer months also lowered temperatures (Rowley *et al.*, 2011).

Not only do HTs change the seasonal variability of temperature, they also influence diurnal temperature range (DTR). Temperatures can increase and decrease faster inside HTs leading to higher DTR than outside (Wien, 2009; Ogden *et al.*, 2011; Bumgarner *et al.*, 2012). Across different climates, HTs increased the time crops spent in their optimal temperature growing ranges, but they also increased the number of temperature extremes crops experienced (Wien, 2009; Rowley *et al.*, 2011; Olberg and Lopez, 2016). Despite differences in HTs and crop varieties, crops generally benefit from increased time spent in optimal temperature ranges even if HTs also increase temperature extremes. While HTs provide a buffer to field climatic conditions, it is more difficult to manage HTs to maintain optimum temperatures for crops than traditional greenhouses (O'Connell *et al.*, 2012).

Growing Degree Days

Growing degree days (GDD) are a measure of heat accumulation over time used to determine plant growth rates. It is calculated by taking the average daily temperature and subtracting a base temperature at which plant growth is limited, often 10 °C

(McMaster and Wilhelm, 1997). It can be modified to include a particular crop's preferred temperature range by using peak and base temperatures, outside of which plant growth is considered to be limited and GDDs do not accumulate (Both *et al.*, 2007). The temperature range for a given crop is generally determined from existing research on the crop and the climate in which the crop is being grown. For example, one study calculated tomato GDDs using base and peak temperatures of 10 °C and 30 °C, respectively (Both *et al.*, 2007).

Growing degree days are in general higher inside HTs than outside (Table 5), and they often accumulate faster and earlier in the season inside HTs than outside (Borrelli *et al.*, 2013). The increase in GDD inside HTs can lead not only to earlier harvests, but also to improved crop growth, yield and quality (O'Connell *et al.*, 2012; Wallace *et al.*, 2012; Lang, 2014). When temperatures inside HTs are lower than outside, GDDs for heat tolerant crops, such as melons, are also lower inside HTs (Vescera and Brown, 2016). Based on the studies in Table 5, accumulation of GDDs inside HTs is generally increased for crops well suited to heat such as tomatoes. However, management practices still play a role. Managing HTs to lower temperature can lower the number of GDDs depending on the temperature range for the crop.

Humidity

Humidity is a critical but less commonly studied climate variable inside HTs. As illustrated by the studies in Table 6, relative humidity decreased if specific humidity remained the same as air temperatures increased inside HTs. At night, relative humidity rose as temperatures dropped. In one study, nighttime relative humidity increased as much as 12% (Both *et al.*, 2007). With only one study, it is difficult to determine if the large increase is typical or an anomaly. More research is needed to determine if this pattern occurs consistently across variable climates and management practices.

Methods

Data Collection

Weather Station Instrumentation

Research on HTs at University of Nevada, Reno, took place at Desert Farming Initiative (DFI, 39.5384°N, 119.8049°W), during the 2016-2017 growing season. DFI is a public-private partnership designed to be run similar to a commercial farm while providing research and resources for local farmers. The farm manager determined fertilizer plans, pest control and planting schedules. This study used existing FarmTek (Dyersville, IA, USA) HTs constructed from triple-galvanized structural steel tubing with a 0.254 mm woven fabric covering (85% light transmission) and roll up sides. Onset weather stations (U30-NRC, Bourne, Massachusetts, USA) were installed in two 24 ft. (7.3 m) by 124 ft. (37.8 m) HTs oriented east-west, two 24 ft. (7.3 m) by 96 ft. (29.3 m) HTs oriented north-south and in a nearby outside plot. Weather stations were placed in the center crop bed 12.5 m and 9.8 m from the HT entrance, respectively. Outside,one weather station was located in the center crop bed in the center of the plot. Each weather station had a temperature and relative humidity sensor covered in a solar radiation shield at 1 m and 16 cm above the soil surface (S-THB-M002, RS3, Bourne, Massachusetts, USA). The sensor recorded temperature with an accuracy of ± 0.21 °C and humidity with an accuracy of ± 2.5 %. Soil moisture sensors were located at 6 cm and 16 cm below the soil surface. They have an accuracy of ± 3.1 % (S-SMD-M005, Bourne, Massachusetts, USA; S-TMB-M003, Bourne, Massachusetts, USA). A soil temperature sensor with an accuracy of ± 0.2 °C was located 6 cm below the soil surface (S-TMB-M003, Bourne, Massachusetts, USA). A silicon pyranometer recorded incoming solar radiation with an accuracy of ± 10 W/m^2 (S-LIB-M003, M-LBB, M-LLA, Bourne, Massachusetts, USA), and an anemometer measured wind speed with an accuracy of ± 1.1 m/s (S-WSET-B, M-CAA, Bourne, Massachusetts, USA) at approximately 1.5 m. Weather stations recorded measurements every 15 minutes. Stealthcam cameras (G42NG, Bourne, Massachusetts, USA) were placed inside and outside the HTs recording photos every 15 minutes. Data were collected from March 2016 to April 2017. At the beginning of the experiment, soil samples from the HTs and outside plot were tested for texture using the sedimentation method (Taubner *et al.*, 2009).

Lettuce Leaf Area Index

At University of Nevada, Reno's Main Station Field Lab (39.5125°N, 119.7170°W), a 16 ft. (4.9 m) by 85 ft. (25.9 m) PVC HT was covered in 0.15 mm infrared-blocking plastic with 45% light transmission (Agriculture Solutions, Strong, Maine, USA). Green and Red Saladbowl lettuce (Johnny's Selected Seeds, Albion, Maine) was planted 50 seeds per foot in two beds, inside and outside on May 24, 2017. Inside the HT, tomatoes were planted for 6 m on either end of the tunnel to avoid edge effects. HTs were vented daily. An AccuPAR meter model PAR-80 (Decagon Devices, Pullman, Washington, USA) was used to measure Leaf Area Index (LAI) of the lettuce inside and outside the HTs. Based on methods determined by Tewolde *et al.* (2005), five randomly spaced readings were taken from each bed every nine days after planting between 11:30 am and 12:30 pm PDT. The meter recorded LAI on seven equally spaced segments of the sensor bar (Tewolde *et al.*, 2005). The instrument automatically calculated the zenith angle using the coordinates 39.51°N and 119.7°W. LAI was calculated using a chi of 1. The sensor was placed perpendicularly across a row the same length as the sensor bar. For the first two measurements after planting, LAI was difficult to measure because the leaves barely reached above the sensor. Due to some stormy weather, the cover blew off the HT for about one week during the second week of the experiment. Lettuce was harvested inside July 3, 2017 and outside July 4, 2017.

Farms and School Gardens Instrumentation

The Cooperative Extension and DFI identified farms and schools across northern Nevada with operating HTs for potential instrumentation. Ten farms and schools were asked to participate, and eight accepted. Farms ranged in size from less than an acre to over 2000 acres. School gardens were using HTs to educate children about healthy food and provide fresh produce to the local communities. Each farmer and extension agent managed their HTs according to the needs of the farm or school. High-value crops were grown using both conventional and organic methods. Due to the operational nature of the farms, there are some data gaps when equipment was used in the HTs (See Appendix Table 1). For descriptions of each HT and further information on farming practices see Table 7.

A total of 25 HTs and 13 outdoor plots were instrumented with temperature and humidity sensors (Logtags HAXO8, Auckland, Auckland, New Zealand). The sensors had an accuracy of less than ± 0.5 °C temperature and ± 3% relative humidity. Each Logtag sensor was shielded with two white plastic funnels (3816, 3832WN-2, Canaan, Connecticut, USA) separated by a 1 ½" schedule 80 PVC pipe spacer 4 cm long. Equally spaced holes were drilled into the funnels and the PVC pipe to provide ventilation.

While the temperature shields protected the sensors from direct solar radiation, they did not protect from indirect solar radiation. Therefore, these temperatures cannot be directly compared to air temperature. Temperatures from these sensors will be referred to as indirect solar air temperature (ISAT).

At the farms, sensors attached to a post at 1 m and 16 cm were placed in the center crop bed inside and outside the HTs. Each set of sensors was located at one-third and two-thirds of the total length of the HT, similar to the placement of weather stations at DFI. At the school gardens, one sensor was placed at 1 m only. Each sensor was located in the center of a crop bed at one-half the length of the HT. All sensors recorded every 15 minutes. Data were downloaded once per month weather permitting. Cooperative extension staff were tasked with downloading the data from the sensors at the school HTs. Data was collected from April 2016 to April 2017.

Farms and School Gardens Interviews

Small farmers and extension staff in northern Nevada currently using HTs in their farms and school gardens were interviewed on their HT practices. Observations of HT management practices were made each time data was collected from sensors. A total of five farmers and two extension staff were interviewed. Semi-structured interview questions were developed to address how farmers use HTs and what economic benefits the HTs provide (Table 8). Follow-up prompts to answers were given where appropriate (Hay, 2005).

Data Analysis

Quantitative

Analysis was completed using the R programming language (R Core Team, 2017). All data was quality assured and controlled. Occasionally, 15-min measurements were missing either when sensors were downloaded or the sensor temporarily malfunctioned. For data from all sensors, 15-minute measurements were averaged to hourly including hours where 15-minute measurements were missing. All measurements were in Pacific Daylight Time (PDT). At each of the farms where two sensors were in each HT, the duplicates were averaged together. All further analysis was conducted on the averaged data.

Data collected from HTs where the cover ripped off for the majority of the study were removed from analysis. Several HTs were not in continuous operation for the entire year. Only data during HT operation was used. Two additional HTs were removed from the statistical analysis: one HT not planted or ventilated during the experiment was removed from analysis because it was not representative of a functioning HT and as such had anonymously high temperature readings; one HT was regularly moved by the farmer at unknown dates making the data difficult to compare to other HTs.

Daily maxima and minima were isolated from each complete 24-hour period for all climate variables except solar radiation and wind where only maxima were isolated. For temperature, vapor pressure and vapor pressure deficit (VPD), the diurnal range was calculated using the daily maxima and minima. In addition, to understand HT's influence on air stratification, daily maxima and minima at 16 cm were subtracted from daily maxima and minima at 1 m.

Leaf Area Index

The average and standard deviation were calculated for each nine-day LAI measurement. Yields were summarized as kg/m^2. Statistical comparisons were not calculated because of the small sample size.

Solar Radiation, Wind and Soil Temperature

Average, minimum and maximum percent reductions of solar radiation and wind inside HTs were calculated for the entire period of data collection. Average, minimum and maximum differences in soil temperature between inside and outside HTs were calculated for each season. Spring was April, May and June. Summer was July, August and September. Fall was October, November and December. Winter was January, February and March. Due to the small sample size, statistical tests were not conducted to determine if inside was statistically different from outside.

Growing Degree Days

Modified growing degree days (GDD) were calculated for lettuce and tomatoes. The following equation was used:

$$GDD = \left(\frac{Maximum\ Temperature + Minimum\ Temperature}{2}\right) - \ base\ temperature$$

When temperatures were higher and lower than the plants optimal growing range, the observed maximum and minimum temperature was replaced with a peak and/or base temperature (Nielsen, 2001). For lettuce, GDD was calculated with temperatures measured at 16 cm using a base of 4 °C (Fraisse *et al.*, 2011) and a peak of 27 °C (Wildung and Johnson, 2012). For tomatoes, GDD was calculated with temperatures measured at 1 m using a base temperature of 10 °C (Fraisse *et al*, 2011) and a peak of 27 °C (Wildung and Johnson, 2012).

Vapor Pressure and Vapor Pressure Deficit (VPD)

Relative humidity was converted to vapor pressure. Saturation vapor pressure and vapor pressure were calculated using the Clausius-Clapeyron equation in the humidity package (Cai, 2016). Vapor pressure was subtracted from saturation vapor pressure to calculate the VPD (Abtew and Melesse, 2013).

Statistical tests

For statistical analysis, daily maxima and minima were averaged monthly. GDD were summed by month. Statistical comparisons were calculated for temperature, vapor pressure and VPD. Months with less than 90% complete data were not used in the statistical analysis. The statistical significance of the difference between maxima, minima and diurnal range inside and outside HTs was tested on data from sensors at 16 cm and 1

m. In addition, differences between maxima and minima at 1 m and 16 cm were also tested. Because the sample size was small, it was difficult to verify normality. A two-sided Student t-test and a two-sample Wilcoxon test, also known as Mann-Whitney test (Bauer, 1972; Holander and Wolfe, 1973), were used to test statistical significance (Appendix Table 2-4).

Linear regression

Linear regression (Wilkinson and Rogers, 1973; Chambers, 1992) was used to compare monthly mean temperature and vapor pressure across HT type, area, height and material. Mean temperature and vapor pressure were treated as a continuous response variable. HT type, area, height and material were treated as categorical predictor variables. HT type compared quonset and gothic. Three different plastic covering thicknesses were used: 0.15, 0.28 and 0.30 mm. HT areas were 15 values between 19.5 and 267.8 m^2, while HT heights were 10 values between 1.5 and 4.3 m^2. Area and height were treated as categorical because HTs are purchased from a standard set of sizes and heights.

Contrasts for each categorical variable were set using treatment with gothic compared to quonset and the smallest area, height and material thickness compared to the larger ones. Models with coefficients of determination of 0.80 or higher were evaluated. All model residuals and Q-Q plots were examined for normality. For all statistical tests, p-values of 0.05 and 0.10 were used to determine where differences were statistically significant and at what level.

Qualitative

Interview responses were coded thematically. Responses to each question were quantified by how many farmers mentioned each response. For the purpose of this research, couples running a farm were considered as one respondent. Seven respondents were interviewed. Information mentioned outside of direct question responses was summarized (Hay, 2005).

Results and Discussion

High Tunnel Management: Farmer Interviews

In response to interview questions, farmers and extension staff indicated a wide variety of applications for and benefits to using HTs in Nevada. HTs have been used in Nevada since the late 1990s with a recent increase in popularity in response to the growing local food movement. Farmers and extension staff in Nevada used Utah State University's HT program (*Production Horticulture: High Tunnels*, no date) as an early example of how to implement HTs in a farm or school garden environment in a similar climate. Farmers placed HTs on their farms to take advantage of already existing infrastructure. HTs were often oriented the same direction as existing crop rows, typically east-west. Each farmer then customized the HT with manual sides, fans and/or shade cloth depending on the time of year and what crops they grew. The most common covering for the houses was 0.15 mm plastic. Farmers worked with each other and shared knowledge as they implemented this new technology on their farms. During the course of this project, three of the farmers purchased new HTs, and the school garden program expanded to two additional schools. The university farm also invested in seven more HTs and increased their outreach to support farmers installing HTs. Clearly the use of HTs is increasing across northern Nevada.

There were several reasons farmers and extension staff made the initial investment in HTs. The majority of the farmers (four of seven farmers interviewed) were looking to extend the high desert's short growing season. Farmers felt that HTs would be an important tool to mitigate the harsh climate through reducing wind and moderating extreme temperatures. Farmers also invested in HTs to improve crop production by increasing the number and consistency of crops throughout the season while reducing pests. Economics was mentioned as a factor when deciding whether to purchase HTs. Farmers indicated that it made economic sense for their business and gave them the potential to access new customers by growing crops they would not otherwise be able to grow. All paid for some or part of their HTs out of pocket, while four used the Natural Resources Conservation Services' (NRCS's) High Tunnel System Initiative or other grants to pay for part of their HTs.

Once farmers invested in HTs, they used the same farming practices inside the HTs as they had outside. Farmers and extension staff vented their HTs according to the climate of their specific location. If it became windy, closing HTs was important for reducing damage to both crops and the structure. One farm opened and closed sides on a daily basis, while one opened the sides after the last frost and before the first frost. Where HTs had fans, one farmer used the fans consistently in the summertime and according to weather conditions the rest of the year. Another farmer used a HT with no manual ventilation; that HT was cooled with automatic fans that turned on when the temperature exceeded 29.4 °C. The school gardens left the doors open in the summer.

Management practices changed throughout the seasons. Two farms and all the school gardens planted cover crops inside in the winter. One farmer mentioned the need to remove snow on the HT cover in the winter. Early in the spring or in the winter, low tunnels (three of seven farmers interviewed) and mid-tunnels (one of seven farmers interviewed) were added to provide extra crop protection. Two farmers added shade cloth to their HTs in the spring and summer. One farmer moved the HTs over different crops at different times of the year in an effort to produce more crops from one HT. Farmers took advantage of the flexibility of HTs, often using them only when they needed them for season extension by taking them down or leaving them fallow for the summer. For example, some farmers used shaded HTs in the summer to cool crops or operated HTs at the end or beginning of summer to extend the season.

The most important reported advantages HTs provided are: wind protection (five of seven farmers interviewed), season extension (four of seven farmers interviewed), pest protection (three of seven farmers interviewed), improved climate for the crops through modification of temperature and/or humidity (three of seven farmers interviewed), and the ability to grow year around (two of seven farmers interviewed). When discussing climate modification, farmers mentioned that HTs reduce solar radiation and increase humidity. Farmers were able to modify the climate all year by cooling crops in the summer and keeping snow off of them in the winter. HTs also provided important advantages by increasing the types, yield and quality of the crops grown.

In addition to providing clear benefits, HTs also had several disadvantages including: initial cost (three of seven farmers interviewed), wind damage to the structure and cover (three of seven farmers interviewed) and increased labor (two of seven farmers interviewed). Upkeep and maintenance of the HT structure and cropping system were higher than outside. In addition, more management decisions needed to be made about when to open and close HTs or remove the plastic. The limited space made cropping decisions more critical, as farmers wanted to manage the area for the highest yield. One farmer noted that the larger the farm the more difficult it was to manage labor inside small scale HTs to take advantage of the potential for increased yield. While HTs keep out many pests, if a pest got inside the infestation was often worse and harder to get rid of than outside.

HTs need to produce higher yields and better quality product in order to justify their upfront cost. Farmers were generally positive about the impacts of HTs on their business. They were able to grow and sell crops in the winter (three of seven farmers interviewed) and produce high-value crops they were unable to grow previously, such as tomatoes and turmeric (two of seven farmers interviewed). HTs increased yield and quality for a longer period of time, allowing farmers to increase their income over a longer season. As long as the structure was secured, most farmers indicated that maintenance costs were low (four of seven interviewed). However in one case, labor to plant in the HTs was high, and the farmer was still trying to find the best crops to produce in HTs to make the investment profitable. When asked whether HTs directly increased the farms profitability, three said yes while two said no.

HTs enabled farmers to enter niche markets by growing high-value specialty crops such as vegetables, melons, fruit, nuts, berries and greenhouse/nursery plants. Commodity crops including corn, soybeans, wheat and other grains (MacDonald *et al.*, 2013) were not grown in HTs. The crops farmers grew in HTs included: radishes, turnips, beets, various leafy greens, bok choy, arugula, cucumbers, peppers, eggplant, tomatoes, spinach, chard, asparagus, beans, broccoli, cabbage, carrots, garlic, herbs, onion, peas, potatoes, sweet potatoes, Hawaiian ginger, turmeric, raspberries and blackberries. HTs provided critical protection from pests for many of these crops. For example, HTs protected tomatoes from the beet curly top virus (Davison and Lattin, 2015). The ability to have increased control over the crops' growing conditions, through the HT modifying temperature, humidity, wind and solar radiation, allowed farmers to grow a wider variety of crops. However, sprawling crops such as squash and cantaloupe did not grow well in HTs because they took up too much space to be economically viable.

All interviewed farmers felt that HTs were a worthwhile investment and would recommend them to other farmers (seven of seven farmers interviewed). Experienced farmers with knowledge about what crops to grow and what markets to sell to would be best prepared to take advantage of HTs. In practice, farmers of all experience levels and backgrounds are investing in HTs. With the increased ability to control the environment in which the crops are growing, farmers are able to mitigate many of the climate and pest stresses common in the high desert. As one farmer noted, crops experience "far less tragedies" inside HTs. Because farmers in the Great Basin are using HTs to protect their crops from the variable and sometimes harsh climate conditions, it is important to examine the environment inside HTs to help farmers manage their tunnels better for improved crop growth. The environment inside the HT may vary depending on location and management practices.

Lettuce Leaf Area Index

Several previous studies have found HTs to be effective at improving the quality and sometimes the yield of lettuce by enhancing the crop's growing environment. (Rader and Karlsson, 2006; Wallace *et al.*, 2012; Galinato and Miles, 2013). In order to quantify crop growth rates inside and outside HTs, LAI was measured for lettuce inside and outside HTs at Main Station. Lettuce inside the HT grew quickly (Fig. 2) and was harvested a week earlier than planned, yielding 1.55 kg/m^2. Lettuce outside grew intermittently and yielded only 0.04 kg/m^2. The farmer felt that the main factor in the lettuce not growing outside was most likely high air temperatures. Lettuce inside HTs spent less time exposed to hot temperatures outside their optimal growing range.

Climate

Solar Radiation

Maximum Solar Radiation

Maximum solar radiation at DFI was reduced by 45 to 52% on average, with daily reductions of as little as 16% (Fig. 3). This reduction is greater than the current 15 to 36% reported in the research (Table 1), in part because the HTs used in this study were covered by a thicker woven fabric than coverings used in previous studies. Maximum solar radiation was reduced by 95% to 96% when the HTs were covered with snow after winter storms.

Solar radiation was reduced relative to outside in all HTs in all seasons. However, the amount of reduction varied depending on the orientation of the HT and the time of year. The north-south HTs experienced greater reductions in solar radiation than the east-west HTs (Fig. 3). Although this study's results mirror what is reflected in the literature (Blomgren and Frisch, 2007), the small number of HTs did not allow for statistical evaluation of the effect of orientation. Early in the season, maximum solar radiation rises quickly inside the HTs, similar to trends outside the HT. Solar radiation in HTs levels off from May to July, irrespective of HT orientation, before decreasing in August (Fig. 3). The summertime plateau in radiation is unexpected because the HT covers allow 85% light transmission. However, the amount of incoming solar radiation that the HT cover transmits varies with the angle of the sun relative to the angle of the HT roof. While quonset HTs generally transmit the most solar radiation in the summer when the sun is highest in the sky, gothic HTs, such as those at DFI, receive the most solar radiation in the spring and fall when the angle of the incoming solar radiation is more perpendicular to the angle of the HT roof. This effect is increased in east-west oriented gothic HTs (Blomgren and Frisch, 2007).

Studies examining solar radiation inside HTs have not examined variability in solar radiation over a season or from year to year. Further research will be necessary to confirm the patterns seen in this study and fully determine what is causing them. Sensors could be placed in different locations vertically and horizontally in HTs to determine if different locations in the HTs receive different amounts of solar radiation. In order to further explain the seasonal and daily variation, HTs in different regions of the U.S. could be compared to determine if the patterns seen in this research occur across a wider variety of structures and locations. Finally, variations in solar radiation with respect to HT orientation, roof angle and cover type could be tested to further characterize the relationship between the angle of the sun and the amount of light reduction and diffusion. Such evaluation would allow farmers to make improved choices about the structure types, coverings and orientations that best meet their needs.

Diurnal Solar Radiation Variability

HTs influenced the daily distribution of solar radiation. Maximum solar radiation peaked inside 1 to 2 hours earlier inside than outside (Appendix Fig. 1). This diurnal pattern was also found with other variables in the HT, such as soil and air temperature.

Wind

Wind speed at DFI was reduced 87% to 93% on average, with daily decreases as low as 35%. The average reductions in wind speed seen in this study are similar to the reduction seen in other studies where woven fabric was used (Table 2). Inside the HTs, wind was reduced by 95% or greater 40% of the time. While the anemometers used in this experiment are inaccurate at low wind speeds ('Wind Speed Smart Sensor (S-WSB-M003) Manual', no date), differences in wind speeds were substantial enough that the differences seen here are unlikely to result from lack of instrumental precision.

HTs reduced the speed and variability of wind, particularly from November through February when the HTs were closed most or all of the time (Fig. 4). The HTs used at DFI are designed to be placed perpendicular to the prevailing wind to allow air to flow over them reducing wind inside (FarmTek, *personal communication*). Wind speed was slightly lower in the north-south HTs because they were perpendicular to the prevailing west to east wind direction. Because of the lower wind speeds, HTs likely slow the movement of air within the HT as well as reducing the exchange of air between inside and outside. Further research investigating air flow inside HTs as well as flow in and out of the HTs will be necessary to determine how air moves within the HT and how much air exchange there is with outside.

Soil Temperature and Soil Moisture

Maximum and Minimum Soil Temperature

Seasonally, HTs reduced the range of soil temperatures crops experienced by lowering variability between the winter and summer (Fig. 5). Both maximum and minimum soil temperatures were lower inside the HTs in the spring and summer. On average during these seasons, maximum soil temperatures were 1.7 to 4.8 °C lower inside the HT, while minimum soil temperatures were the same as outside or lower by 1.0 °C, with decreases of as much as 6.0 °C in minimum temperature and 14.3 °C in maximum temperature. However, late into the fall and winter, HTs were particularly effective at keeping soil temperatures higher than outside. Maximum and minimum soil temperatures were higher by an average of 1.9 to 4.4 °C and 2.1 to 3.7 °C inside the HT with increases of as much as 9.6 °C and 7.1 °C, respectively. Higher soil temperatures inside HTs often created an environment that allowed crops to grow through the winter (Knewtson *et al.*, 2010; Zhao *et al.*, 2014).

Previous studies found similar patterns of seasonal variability, wherein HTs lowered temperatures in the spring and summer (Rader and Karlsson, 2006; Ogden and Iersel, 2009). In this study, management practices may have played a role, because the

HTs were vented early in the spring through the summer and then closed in the fall and winter. Although this study's results are similar to some of the results found in the literature, the small number of HTs at DFI did not allow for statistical evaluation of the differences between inside and outside. Further research investigating HTs influence on soil temperature under different soil types, irrigation methods and soil management strategies will be necessary to fully understand HTs relationship to soil temperature.

Diurnal Soil Temperature Variability

At DFI, soil DTR was also often lower inside HTs. These results were corroborated by another study where soil DTR was always lower inside (Chenhui Li *et al.*, 2014). In winter, HTs often increased maximum soil temperature more than minimum soil temperature leading to increased diurnal variability inside. The daily maximum soil temperatures occurred slightly earlier in the day inside HTs following the pattern of solar radiation and air temperature (Appendix Fig. 2).

Soil Moisture

Due to the observational nature of the study, with farmers at DFI watering according to their planting needs, clear differences in soil moisture inside and outside HTs could not be determined from the data (See Appendix, Fig. 3). However, farmers commented that they needed to apply less irrigation water inside than outside. Not only does the HT plastic covering seem to reduce water loss through evaporation, HTs can also facilitate the use of more water-efficient irrigation strategies, such as drip tape, overhead sprinklers or subirrigation. It has been suggested that increased control over soil moisture inside HTs could reduce stress crops experience from high and low temperature extremes (Montri and Biernbaum, 2009). Further research using a controlled setting would be necessary to determine the HT's influence on soil moisture, irrigation water use and the resulting effect on crops.

Air/Indirect solar air temperature

Maximum temperature

HTs' influence on maximum temperatures varied in response to different management strategies (Fig. 6, Appendix Fig. 4). As observed in other studies (Ogden and Iersel, 2009; Wien, 2009; Lang, 2014), increased HT ventilation in the summer months lowered maximum temperatures close to those outside. Since this practice was more common during the summer than at any other time of the year, management practices reduced seasonal variability in maximum temperature inside HTs relative to ambient conditions. In contrast, the HT at School 2 remained completely closed, with no crops grown, and temperature continued to rise throughout the summer (data not shown). At Farm 3 and DFI, maximum temperatures noticeably increased in October when the HTs were completely closed.

Shade cloth often reduced maximum temperatures below those outside in the summer, consistent with other studies using shade cloth (Rowley et al. 2011; Zhao and Carey 2009). In the case of Farm 2, despite the use of shade cloth, the farmer managed to keep HT temperatures high through minimal venting. Farm 3's caterpillar HTs experienced temperatures slightly lower than those outside in the summer despite not being covered in shade cloth. When the farmer at Farm 4 replaced the plastic and decreased venting of the unshaded HTs, maximum temperature markedly increased from November to April.

Minimum Temperature

Minimum temperatures were less influenced by management practices than maximum temperatures. Similar to some of the current findings on minimum temperature in HTs (Ogden and Iersel, 2009; Ogden *et al.*, 2011; Rogers and Wszelaki, 2012; Wallace *et al.*, 2012), minimum temperatures were similar inside and outside at all of the sites in this study. At 1 m, minimum temperatures in the HT were the same, slightly lower or slightly higher than outside (Appendix Fig. 5). At 16 cm, minimum temperatures were almost always higher inside the HT than outside, irrespective of covering type (Fig. 7). Depending on how the HT was managed, the increased temperature was more pronounced from late summer through early winter, possibly due to the fact that soil temperatures inside the HT were increased during the same part of the year (Fig. 5).

Diurnal Temperature Variability

As discussed above, HTs do little to increase minimum temperatures while increasing maximum temperatures, especially in the fall and spring. Thus, the DTR was generally increased inside at both 1 m and 16 cm (Appendix Figs. 6-7). However, in the spring and summer, the DTR was sometimes lower inside than outside. This pattern occurred when maximum temperature in the HT was lower than outdoors due to the use of shade cloth or in the case of the caterpillar HT. Rather than moderating DTR and decreasing large temperature swings, most HTs increased them. Another study found similar results; HTs most often increased DTR while sometimes having little effect, possibly when HTs were vented more (Chenhui Li *et al.*, 2014). This result may seem counter-intuitive to improved crop growth. However, low minimum temperatures at night limit the resources plants expend on respiration (Nelson, 2003). Meanwhile, higher temperatures during the day, especially in the spring and fall, can increase crop growth by allowing crops more time in their optimal temperature ranges. Nevertheless, plants inside HTs are still subject to temperature extremes that could negatively impact crop growth (Wien, 2009; Rowley *et al.*, 2011; Olberg and Lopez, 2016). Crops could be buffered from temperature extremes due to increased soil moisture inside HTs (Montri and Biernbaum, 2009).

As noted in previous studies (Wien, 2009; Ogden *et al.*, 2011; Bumgarner *et al.*, 2012), daily temperature patterns were also influenced by HTs. Temperatures at 1 m tended to increase and decrease faster, often peaking earlier inside HTs, especially in the fall and winter (Appendix Fig. 8). Temperatures at 16 cm followed a similar pattern, but with peak temperatures occurring closer to the peak outside during the spring and summer (Appendix Fig. 9). This pattern is consistent with solar radiation and soil temperature also peaking earlier in the day within HTs. Nonetheless, management of the HTs plays a role in the daily pattern. For example, shade cloth would reduce temperature increases and potentially adjust when temperatures peak.

Temperature Variability with Height

Temperature differences between sensors at 1 m and 16 cm above the soil surface exhibited contrasting patterns inside and outside HTs. In HTs, maximum temperatures were higher at 1 m than 16 cm inside (Fig. 8). Minimum temperature exhibited the opposite pattern with temperatures higher at 16 cm than 1 m (Fig. 9). Outside the pattern was reversed. Because there is less air exchanging with outside, air stratification may occur inside HTs, especially at night as air temperature drops (Ogden *et al.*, 2011). During the day, as air temperature increases and air begins to rise, HTs seem to increase temperatures more with height. Crops closer to the ground experience less temperature variability with slightly higher temperatures at night and slightly cooler temperatures during the day. Taller crops have to contend with the temperature differences in height as they grow; however they may still benefit from moderated temperature regimes near their roots.

Temperature Variability Across HT Structures

Because HTs vary in size, configuration and material, HTs may differ in how they alter temperature relative to the HTs' characteristics. This study found no clear pattern between temperature and the characteristics of the HTs. While it may be the case that HT size and other factors change the microclimate created by the HT, in this study management practices were the clearest driver of the microclimates created by the HTs. Neither the type of HT nor the thickness of the covering displayed a strong relationship with temperature (Fig. 10-13). Area and height may have more of an influence on temperature, however the relationship varies between months and may have been influenced by management practices.

However, because each farmer is managing the HTs for the conditions the crop requires, it is difficult to determine whether size and height or high tunnel management are driving temperature changes. For example, many farmers felt that their larger HTs increased temperature more than their smaller tunnels. As a result, they managed their larger tunnels to reduce heat build-up. On the other hand, farmers growing crops that needed high temperatures managed their tunnels to increase temperatures no matter the size. The sample sizes used were also relatively small, increasing the influence of management practices at individual farms on the results. A controlled experiment or larger sample size would be necessary to determine if height and area influence temperature.

Growing Degree Days

Consistent with the studies listed in Table 5, HTs increased lettuce GDDs, shown in Figure 14, and tomato GDDs (Appendix Fig. 10). Similar to maximum temperature (Appendix Fig. 4, Fig. 6), GDDs increased more in the spring, winter and fall than in the summer. GDDs, particularly for tomatoes, were sometimes slightly lower during the summer inside HTs, in part because HTs increased maximum temperatures beyond the plants' optimal growing range. Despite the fact that HTs do not increase minimum temperature as much as maximum temperature, crops still experienced an increase in GDDs inside. The increased GDDs allow for lettuce production most or all of the year, an advantage which three of the farmers and the University farm regularly took advantage of. While not directly part of the GDD calculation, crops also spend more time in their optimum temperature range inside because HTs increase temperature faster at the beginning of the day (O'Connell *et al.*, 2012).

Vapor Pressure

While relative humidity is the most common water vapor metric used in HT research (Table 6), vapor pressure is generally used in the greenhouse literature. Partial and saturated vapor pressure are then often used to calculate vapor pressure deficit (VPD) (Nelson, 2003). Management strategies and VPD thresholds for improving plant growth have been established for many crops (Gates *et al.*, 1998; Leonardi *et al.*, 2000; Gazquez *et al.*, 2008; Lu *et al.*, 2015). Using vapor pressure and VPD as metrics for water vapor instead of relative humidity would allow HT research to take advantage of the greenhouse VPD research already established in the literature. In addition, using vapor pressure as apposed to relative humidity is often recommended to farmers because it can be interpreted without knowing the temperature (Wollaeger and Runkle, 2015).

Maximum and Minimum Vapor Pressure

Vapor pressure was highly variable both inside and outside the HT. Overall, minimum and maximum vapor pressure were higher inside the HT than outside by statistically significant amounts (Fig. 15-16, Appendix Fig. 11-12). Management practices clearly influenced maximum vapor pressure, notably at Farm 3 where maximum vapor pressure increased when HTs were closed in October (Fig. 15). By reducing air exchange with outside, HTs increase vapor pressure inside, potentially lowering irrigation water use, which is particularly important in high deserts such as the Great Basin. However, vapor pressure within the HT occasionally dipped below that of outside, and maximum vapor pressure was consistently lower inside than outside at 1 m inside Main Station HTs (Fig. 15). These results indicate that irrigation, crop type, HT management and outside climate conditions play a role in determining vapor pressure inside HTs. Further research will be necessary to understand HTs impact on vapor pressure and what conditions can lead to a drier environment inside HTs.

Diurnal Vapor Pressure Variability

While relative humidity was often more consistent on a daily basis inside HTs than outside, vapor pressure provided a clearer picture of how HTs impact humidity. The diurnal range of vapor pressure was generally higher inside HTs than out following a similar pattern to that of air temperature (Appendix Fig. 13-14). Vapor pressure tended to follow the pattern of solar radiation, air and soil temperature often rapidly rising and peaking higher, sometimes earlier in the day inside HTs (Appendix Fig. 15-16), suggesting enhanced evapotranspiration due to increasing temperatures. Daily variations in vapor pressure may be influenced by the farmers' irrigation schedule. Unlike air temperature, there were no clear patterns in differences between sensor heights (data not shown).

Vapor Pressure Variability Across HT Structures

Similar to temperature, vapor pressure may vary inside HTs depending on size, configuration and material. However, the results of this study found no clear pattern between vapor pressure and the characteristics of the HTs. As with temperature, management practices were the clearest indicator of the microclimates created by the HTs. The type of HT and material thickness did not have a strong relationship with vapor pressure. Area and height do seem to influence vapor pressure, although temperature was influenced more (Fig. 17-20). As with temperature, it is difficult to disentangle the effects of HT size from management practices, since farmers tended to manage different HTs differently according to their assessments of crop requirements. Thus, a controlled experiment or larger sample size would be necessary to determine if height and area consistently influence vapor pressure.

Vapor Pressure Deficit

Maximum and Minimum Vapor Pressure Deficit

Maximum VPD closely tracked maximum temperature (Fig. 21, Appendix Fig. 17). Similar to the pattern of relative humidity seen in Table 6, when temperature rose VPD also rose. By adjusting the ventilation and covering of the HT, farmers not only modify temperature but also VPD. Minimum VPD was strongly variable across the season, increasing from May through September (Fig. 22, Appendix Fig. 18). During those months, minimum VPD at 1 m was consistently lower inside HTs than outside, especially when the tunnel was covered in shade cloth. The rest of the year it was close to that of outside. At 16 cm, minimum VPD was more variable sometimes lower or higher than outside. VPD varies with temperature as well as timing and amount of irrigation water. Presumably as irrigation water increases, VPD would decrease, but this would depend on how temperature varied as well. Because of the uncontrolled nature of this study, it is difficult to determine what combination of factors led to the variability seen in the data.

Diurnal Vapor Pressure Deficit Variability

The diurnal range of VPD followed a similar pattern to that of maximum VPD and air temperature (Appendix Fig. 19-20). As expected, daily VPD followed the pattern of solar radiation, temperature and vapor pressure, rising faster earlier in the day and sometimes peaking before outside. The difference was more pronounced in the fall and winter (Appendix Fig. 21-22). Relative to outside, the increased control provided by HTs warrants further research on VPD. While VPD has traditionally been studied in greenhouse settings, future research could investigate crops in HTs to determine whether they spend more time in their optimal VPD range.

Conclusions

HTs provide a flexible, yet relatively simple technology for small farmers to improve crop growth and economic viability. Although there were similarities in microclimate patterns inside HTs across a wide variety of farm management practices, microclimates inside HTs varied over the course of the season and could be strongly influenced by management practices. Solar radiation and wind were consistently reduced, a climate modification that is particularly useful in a high desert climate with a large number of sunny, windy days.

Maximum temperatures were generally higher in HTs than outside during the fall, winter, and spring, but moderated during the summer when HTs were often ventilated more and/or covered in shade cloth. Meanwhile minimum temperatures were more similar to outside all year around. New plastic coverings with IR-blocking properties have the potential to increase minimum temperature inside HTs. Seasonal variability in temperatures was moderated inside; however, crops inside HTs could still experience extreme low and high temperatures on a daily basis. These climate conditions led to an increase in GDDs, particularly in the spring, fall and winter.

Vapor pressure increased inside across HT configurations. Increased vapor pressure can reduce evaporative demand, potentially reducing the amount of irrigation water needed inside. Maximum VPD, similar to maximum temperature, was highly influenced by management practices while minimum VPD was not. HTs influence on both maximum temperature and VPD can be managed by farmers.

Given the observed seasonal variability in the effect of HTs, it seems likely that most HT designs and management strategies would also exhibit a seasonal influence. The response of microclimates inside to ventilation and shade cloth was similar across a variety of conditions. Farmer's working in a wide variety of climates could expect similar results. Nonetheless, further research will be necessary to confirm if these seasonal patterns exist over a wider variety of HTs in different climates.

With a variety of ventilation strategies and covering types, HTs provide farmers the conditions to grow a wider variety of crops while increasing yield and quality of the produce. Through the use of temperature-controlled fans and multiple layers of plastic, HTs provide the farmer with the unique ability to be high tech or low tech. As farmers continue to experiment with technologies to improve yields and increase income, HTs will play a significant role in their continued economic viability as a business.

On-Farm Climate Monitoring

With a wide variety of sensors available, farmers have an opportunity to monitor the climate of their HTs to better manage their crops. By investing in a turn-key weather station for their HT, farmers could monitor air temperature, relative humidity, soil temperature and soil moisture. Some sensors will even calculate vapor pressure and VPD.

With the information provided by air temperature, farmers can in real-time determine when to vent their HTs to lower the temperature and humidity. If their sensors calculate vapor pressure deficit, then farmers will have further information they can use to maintain vapor pressure deficit within the optimal range of the crop. Venting can be customized to increase the time crops spend in their optimal temperature and VPD growing ranges. By monitoring soil moisture, irrigation water can be used more efficiently. Soil temperature could provide important information about the root environment, particularly for winter crops close to the ground such as leafy greens and root vegetables. While not necessary, outside sensors provide information about crops outside the HTs. Farmers could compare conditions inside HTs with outside. For example, it may be more difficult to cool the HT when temperatures outside are higher. If farmers do not want to invest in the expense of outside sensors, they could compare their measurements to that of a near by weather station, although it would not be as precise. A study testing different sensor configurations would help farmers choose a sensor set that fits their budget, provides reliable data and is simple to use. Additional monitoring through turn-key sensor configurations would allow them to save water and maximize yields, further improving the farms economic viability.

Future Research Directions

HTs provide improved control over crop growth and yield in a wide variety of climates. Future research should focus on several questions not yet addressed here or in the literature. First, determining how the roof angle and orientation influence incoming solar radiation. Because HTs are passive, there may be a design and orientation that best maximizes incoming solar radiation. In addition, how do the properties of the plastic covering influence temperature inside HTs, particularly minimum temperature.

Initial results show that HTs impact the amount of irrigation water needed and the amount of evaporation. Controlled studies would be needed to quantify how much HTs reduce irrigation water use. In addition, experiments could be run to see if HTs can be managed to allow crops to spend more time in their optimal VPD ranges, much the way this study looked at GDDs. Understanding how the roof angle, HT orientation and covering type effect climate variables can help farmers manage irrigation water and maximize crop growth inside HTs.

Tables and Figures

Table 1. Summary of statistics from studies of average solar radiation in HTs in the U.S. Covering refers to the thickness, number of layers and type of covering. Orientation refers to whether or not the HTs end walls faced North-South or East-West.

Location	Covering	Orientation	Solar Radiation Change	Reference
Washington State	Single layer 0.15 mm	N/A	- 27 to - 36%^{y}	(Borrelli *et al.*, 2013)
Washington State	Single layer 0.15 mm	N/A	- 23%^{y}	(Cowan *et al.*, 2014)
Oregon	Single layer 0.15 mm	N/A	- 31%^{y}	(Thompson *et al.*, 2009)
Michigan	Three-season single layer 0.15 mm	N/A	- 15 to - 26%^{z}	(Lang, 2009, 2014)
Indiana	Single layer 0.15 mm	N/A	- 33%^{z}	(Owen *et al.*, 2016)
Indiana	Single layer 0.15 mm	N/A	- 27%^{z}	(Olberg and Lopez, 2016)
Ohio	Single layer 0.15 mm	N/A	- 23%^{y}	(Bumgarner *et al.*, 2012)
Pennsylvania	Polyethylene plastic	N/A	- 25%^{y}	(Lang *et al.*, 2011)
New Jersey	Single layer 0.15 mm infrared-blocking plastic	North-South	- 24%^{z}	(Both *et al.*, 2007)
New Jersey	Single layer 0.15 mm	North-South	- 26%^{y}	(Reiss *et al.*, 2004)
Arkansas	Single layer 0.15 mm	N/A	- 17 to - 20%^{y}	(Rom *et al.*, 2010)
Kansas	Single layer 0.15 mm	East-West	- 16 to - 36%^{y}	(Zhao and Carey, 2009)
Kansas	Single layer 0.15 mm with 39% white shade cloth	East-West	- $\geq$ 50%^{y}	(Zhao and Carey, 2009)

^{y}Photosynthetically Active Radiation; ^{z}Daily light integral: Total PAR/m^2/day

Table 2. Summary of statistics from studies of average wind in HTs in the U.S. Covering refers to the thickness, number of layers and type of covering. Ventilation refers to the ventilation mechanisms each HT had.

Location	Covering	Ventilation	Wind Change	Reference
Washington State	Single layer 0.15 mm	Open end doors and manual sides	- 61%	(Cowan *et al.*, 2014)
Washington State	Single layer 0.15 mm	Manual end doors and sides	- 61%	(Wallace *et al.*, 2012)
Michigan	Three-season single layer 0.15 mm	Open end doors and sides	- 50%	(Lang, 2009)
Texas	Woven greenhouse fabric	Manual end doors and sides	- 98%	(Wallace *et al.*, 2012)
Kansas	Single layer 0.15 mm	Manual end doors and sides	- 34 to - 41%	(Zhao and Carey, 2009)
Tennessee	Single layer 0.15 mm	Manual end doors and sides	- 57%	(Wallace *et al.*, 2012)

Table 3. Summary of statistics from studies of average soil temperature in HTs in the U.S. Covering refers to the thickness, number of layers and type of covering. Ventilation refers to the ventilation mechanisms each HT had. Soil type refers to the texture of the soil. Growing season refers to the length of the study.

Location	Covering	Ventilation	Soil Type	Growing Season	Soil Temperature Change	Reference
Alaska	Single layer 0.15 mm	Manual end doors and sides	Loam	May to September	- 0.7 to + 2.6 °C[tu] - 0.9 to + 2.6 °C[ux] - 0.5 to + 2.5 °C[uv]	(Rader and Karlsson, 2006)
Washington State	Single layer 0.15 mm	Manual end doors	Fine-Silt	November to March	+ 1.4 °C[xw] + 3.1 °C[xw]	(Borrelli *et al.*, 2013)
Washington State	Three-season woven greenhouse fabric	Manual end doors and sides	Fine-Silt	April to September	+ 1.1 °C[x]	(C Li *et al.*, 2014; Chenhui Li *et al.*, 2014)
Oregon	Single layer 0.15 mm	Open end doors and sides	Fine-Silt	September to November	Same[x]	(Thompson *et al.*, 2009)
New Jersey	Single layer 0.15 mm infrared-blocking plastic	Manual end doors and sides	N/A	March to May	+ 6.7 °C[y]	(Both *et al.*, 2007)
New Jersey	Single layer 0.15 mm	Manual end doors and sides	N/A	May to August	+ to slightly -[uz]	(Reiss *et al.*, 2004)
Rhode Island	Single layer 0.153 mm	Manual sides and automatic roof vents	Silt-Loam	May to August	+ 0.2 °C[x]	(Vescera and Brown, 2016)
New York	Single layer 0.15 mm infrared-blocking	Manual end vents and sides	N/A	January	+ 2 °C[x]	(Wien, 2009)

	plastic					
Texas	Woven greenhouse fabric	Manual end doors and sides	Fine-Loam	April to September	+ 2.6 °C[x]	(C Li *et al.*, 2014; Chenhui Li *et al.*, 2014)
Kansas	Single layer 0.15 mm plastic with 39% white shade cloth	Manual end doors and sides	N/A	July to August	- 3.4 °C[t] - 0.2 °C[v]	(Zhao and Carey, 2009)
Mississippi	Single layer 0.15 mm	Manual end doors and sides	Fine sandy loam	April to July	+ 6.3 to + 1.9 °C[tu] + 5.6 to + 1.1 °C[ux] + 4.9 to + 0.7 °C[uv]	(Zhao *et al.*, 2014)
Georgia	Single layer 0.15 mm	Manual sides	N/A	December to July	+ to - [tuz] + to slightly + [uvz]	(Ogden and Iersel, 2009)
Tennessee	Woven greenhouse fabric	Manual end doors and sides	Silt-Loam	April to September	+ 0.45 °C[x]	(C Li *et al.*, 2014; Chenhui Li *et al.*, 2014)
North Carolina	Double layer, inflated 0.152 mm	Manual end doors and automated sides	Sandy-Loam	March to August	+ 5 to + 7 °C[x]	(O'Connell *et al.*, 2012)

[t] Maximum; [u] Seasonal temperature difference at the beginning and end of the season. See text for details.; [v] Minimum; [w] Study conducted in multiple locations; [x] Average; [y] Average nighttime temperature; [z] Study only indicated direction of change

Table 4. Summary of statistics from studies of air temperature in HTs in the U.S. Maximum, minimum and average temperatures indicated by footnotes. Covering refers to the thickness, number of layers and type of covering. Ventilation refers to the ventilation mechanisms each HT had.

Location	Covering	Ventilation	Growing Season	Air Temperature Change	Reference
Alaska	Single layer 0.15 mm	Manual end doors and sides	May to September	- 1.3 to + 1.5 °C[qr] + 0.5 to + 2.5 °C[tr] + 2.3 to + 5.1 °C[sr]	(Rader and Karlsson, 2006)
Washington State	Single layer 0.15 mm	Open end doors and manual sides	May to October	+ 2.7 °C[q] + 0.8 °C[s]	(Cowan *et al.*, 2014)
Washington State	Single layer 0.15 mm	Manual end doors and sides	April to October	+ 3.3 °C[q] + 0.5 °C[s]	(Wallace *et al.*, 2012)
Washington State	Three-season polyethylene plastic	Open end doors and sides	May to October	+ 1 to 2 °C[t]	(Powell *et al.*, 2014)
Washington State	Single layer 0.15 mm	Manual end doors	December to April	+ 1.9 °C[t]	(Borrelli *et al.*, 2013)
Washington State	Three-season woven greenhouse fabric	Manual end doors and sides	May to October	+ 0.9 °C[t]	(Chenhui Li *et al.*, 2014)
Oregon	Single layer 0.15 mm	Open end doors and sides	May to October	Same[t]	(Thompson *et al.*, 2009)
Wyoming	Single layer 0.15 mm	Manual sides	September to November	+ [uq] + [us]	(Shiwakoti *et al.*, 2016)
Minnesota	Single layer 0.15 mm	Open end doors until ends were covered in mesh	March to August	+ [uq] Same[s]	(Rogers *et al.*, 2016)
Michigan	Three-season single layer 0.15 mm	Manual end doors and sides	April to June	+ 10 to + 30 °C[vw] + 1 °C[x]	(Lang, 2014)
Utah	Single layer	Manual end	August to July of	+ ≤ 4.2 °C[s]	(Rowley *et al.*, 2011)

	0.15 mm	doors	the following year		
Utah	40% shade cloth	Manual end doors	August to July of the following year	- 4 °C[q]	(Rowley *et al.*, 2011)
New York	Single layer 0.15 mm infrared-blocking plastic	Manual end vents and sides	Summer: June Winter: January	+ summer[ruw] Slight + summer[rux] + winter[ruw] Slightly – winter[rux]	(Wien, 2009)
New Hampshire	Single layer 0.15 mm infrared-blocking plastic	Manual and sides automatic fans	September to April of the following year	+ ≤ 16.9 °C[s]	(Martin and Sideman, 2012)
New Jersey	Single layer 0.15 mm infrared-blocking plastic	Manual end doors and sides	May to August	+ 0.9 °C[sx]	(Both *et al.*, 2007)
New Jersey	Single layer 0.15 mm	Manual end doors and sides	May to August	+ to same[rt]	(Reiss *et al.*, 2004)
Rhode Island	Single layer 0.153 mm	Manual sides and automatic roof vents	May to July	+ 4.5 to - 2.3 °C[qr] + 2.7 to - 0.7 °C[rs]	(Vescera and Brown, 2016)
Connecticut	Single layer 0.1 mm	Automatic end doors	September to June of the following year	+ 10 °C[q] + 1 to 2 °C[s]	(Gent, 2002)
Texas	Woven greenhouse fabric	Manual end doors and sides	March to June	+ 5.2 °C[q] - 4.5 °C[s]	(Wallace *et al.*, 2012)
Texas	Woven greenhouse fabric	Manual end doors and sides	April to November	+ 3.2 °C[t]	(Chenhui Li *et al.*, 2014)

Arkansas	Single layer 0.15 mm	Manual sides	April to November	+ ≤ 5 °C[x]	(Rom *et al.*, 2010)
Kansas	Single layer 0.15 mm	Manual end doors and sides	July to August	+ 0.3 °C[q] + 0.2 °C[s]	(Zhao and Carey, 2009)
Kansas	Single layer 0.15 mm plastic with 39% white shade cloth	Manual end doors and sides	July to August	- 0.4 °C[q] + 0.5 °C[s]	(Zhao and Carey, 2009)
Kansas	Single layer 0.15 mm	Manual sides	December to March	+ 14 to + 3 °C[qr] + ≤ 17 °C[y] + 1 to + 2 °C[rs] + ≤ 7 °C[z]	(Kadir *et al.*, 2006)
Mississippi	Single layer 0.15 mm	Manual end doors and sides	April to June	+ 4.3 to + 1.8 °C[qr] + 1.3 to + 0.5 °C[rs]	(Zhao *et al.*, 2014)
Indiana	Single layer 0.15 mm	Manual end-wall peak vents and sides	July to October	+ 0.5 °C [t]	(Owen *et al.*, 2016)
Indiana	Single layer 0.15 mm	Automated sides	April to June	+ 2.7 to + 1.8 °C[rt]	(Olberg and Lopez, 2016)
Ohio	Three-season single layer 0.15 mm	Open ends	March to April October to November	+ [tu]	(Bumgarner *et al.*, 2012)
Kentucky	Double layer 0.15 mm infrared-blocking plastic	Manual end doors and sides	February to June of the following year	+ 4.9 °C[s]	(Ward and Bomford, 2013)
Tennessee	Double layer, non-inflated 0.15 mm plastic	Manual end doors and sides	March to August	+ [qu] Same[s]	(Rogers and Wszelaki, 2012)

Tennessee	Woven greenhouse fabric	Manual end doors and sides	February to June	- 1.8 °C[q] - 3.4 °C[s]	(Wallace *et al.*, 2012)
Tennessee	Woven greenhouse fabric	Manual end doors and sides	March to October	+ 0.65 °C[t]	(Chenhui Li *et al.*, 2014)
Georgia	Single layer 0.15 mm	Manual sides	December to July	+ ≤ 15 to same °C[qr] Same or slightly - [rs]	(Ogden and Iersel, 2009; Ogden *et al.*, 2011)
North Carolina	Single layer 0.15 mm	Manual end doors and sides	November to May of the following year	+ [qu] + [su]	(Gu *et al.*, 2017)
North Carolina	Double layer, inflated 0.152 mm plastic	Manual end doors and automated sides	March to August	+ 1.77 to + 0.07 °C[qr] + 2.98 to + 0.60 °C [rs]	(O'Connell *et al.*, 2012)
Florida	Three-season single layer 0.15 mm	Manual end doors and sides	September to April of the following year	Same[q] + 6 to + 7 °C[s]	(Santos and Salame-Donoso, 2012)
Florida	Polyethylene plastic	Manual end doors and sides	October to February	+ 7 °C[s]	(Santos *et al.*, 2014)

[q]Maximum; [r]Seasonal temperature difference at the beginning and end of the season. See text for details.; [s]Minimum; [t]Average; [u]Study only indicated direction of change; [v]Confirmed accuracy with author; [w]Average daytime air temperature; [x]Average nighttime air temperature; [y]Maximum crown (temperature of the crop canopy); [z]Minimum crown (temperature of the crop canopy)

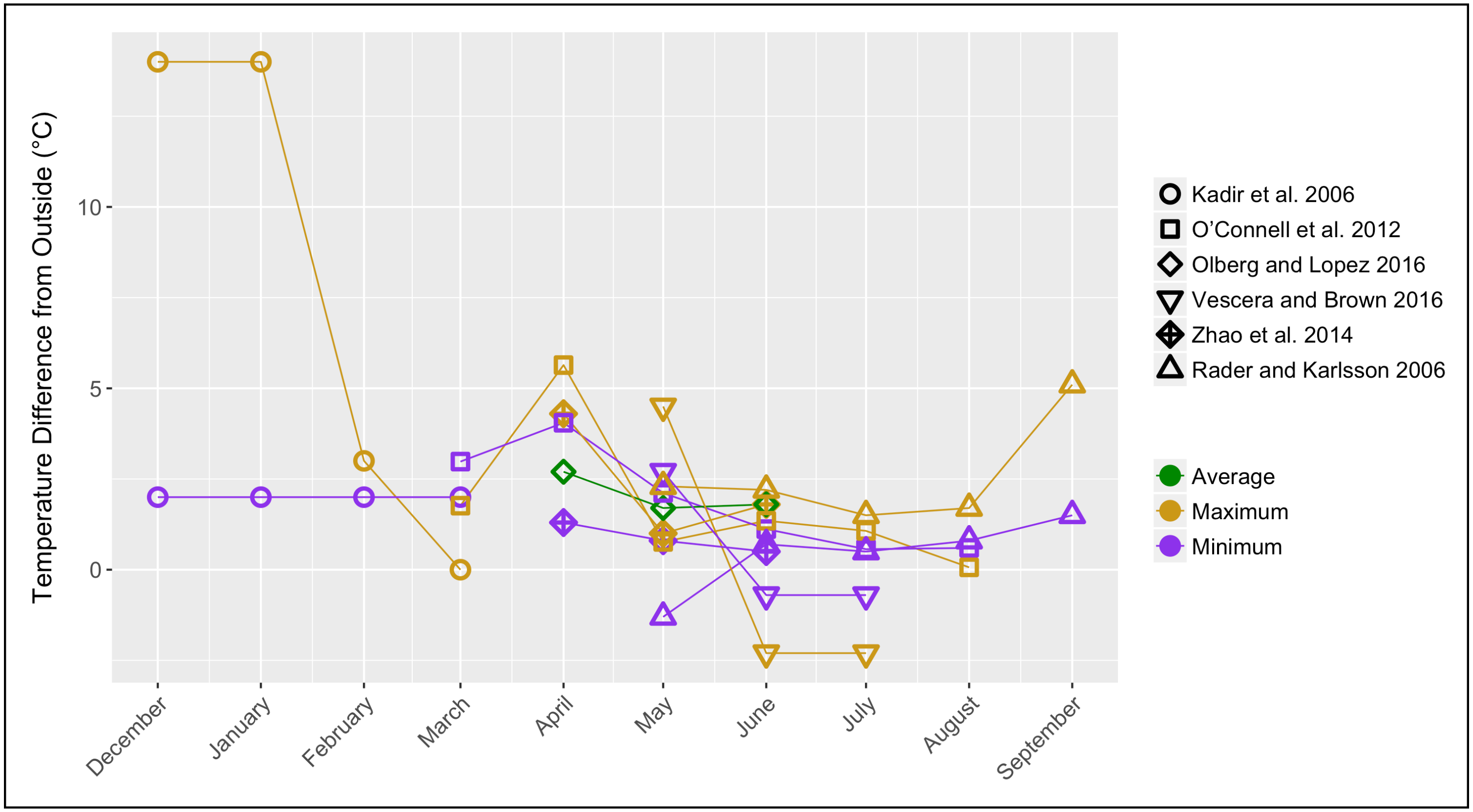

Fig. 1. Summary of statistics from studies of seasonal temperature variability in HTs in the US. See Table 4 for more details.

Table 5. Summary of statistics from studies of growing degree days (GDD) within HTs in the U.S. Covering refers to the thickness, number of layers and type of covering. Ventilation refers to the ventilation mechanisms each HT had. Temperature limits refers to the temperatures used to calculate GDD. Average seasonal GDD values are the average total number of GDD unless otherwise noted.

Location	Covering	Ventilation	Temperature Limits	Average Seasonal GDD Change	Reference
Washington State	Single layer 0.15 mm	Open end doors and manual sides	Base temperature of 10 °C	+ 291	(Cowan *et al.*, 2014)
Washington State	Single layer 0.15 mm	Manual end doors and sides	Base temperature of 5.5 °C	+ 52.5	(Wallace *et al.*, 2012)
Michigan	Three-season single layer 0.15 mm	Open end doors and sides	Base temperature of 10 °C	+ ~10%	(Lang, 2009, 2014)
Pennsylvania	Polyethylene plastic	Open end doors and sides	Base temperature of 10 °C	+ ~10%	(Lang *et al.*, 2011)
New Jersey	Single layer 0.15 mm infrared-blocking plastic	Manual end doors and sides	Tomato: Base temperature of 10 °C and maximum temperature of 30 °C	+ 239	(Both *et al.*, 2007)
Rhode Island	Single layer 0.153 mm	Manual sides and automatic roof vents	Melon: Base temperature of 14 °C and maximum temperature of 40 °C	- [z]	(Vescera and Brown, 2016)
North Carolina	Double layer, inflated 0.152 mm plastic	Manual end doors and automated sides	Base temperature of 10 °C	+ 300	(O'Connell *et al.*, 2012)

[z] Study only indicated direction of change.

Table 6. Summary of statistics from studies of humidity in HTs in the U.S. Structure refers to whether the HTs are stand alone structures or part of a multi-bay structure. Covering refers to the thickness, number of layers and type of covering. Ventilation refers to the ventilation mechanisms each HT had.

Location by State	Covering	Ventilation	Average Humidity Change	Temperature Change	Reference
Washington State	Three-season polyethylene plastic	Open end doors and sides	- 1% to - 5%	+ 1 to + 2 °C	(Powell *et al.*, 2014)
Washington State	Single layer 0.15 mm	Open end doors and manual sides	- 2.9%	+ 0.8 to + 2.7 °C	(Cowan *et al.*, 2014)
Oregon	Single layer 0.15 mm	Open end doors and sides	Same	Same	(Thompson *et al.*, 2009)
Minnesota	Single layer 0.15 mm	Open end doors until ends were covered in mesh	Same[wx] - [yw]	+ [wx] Same[yw]	(Rogers *et al.*, 2016)
New Jersey	Single layer 0.15 mm infrared-blocking plastic	Manual end doors and sides	+ 12%[z]	+ 0.9 °C[z]	(Both *et al.*, 2007)
Kansas	Single layer 0.15 mm	Manual end doors and sides	Same	+ 0.2 to + 0.3 °C	(Zhao and Carey, 2009)

[w]Study only indicated direction of change; [x]Maximum; [y]Minimum; [z]Nighttime

Table 7. Summary of farm and school HTs. Type refers to the structure of the tunnel. Caterpillar are long-skinny PVC-pipe HTs ranging from 108.1 to 181 m^2. Quonset refers to tall metal-hoop HTs. Large range from 87.4 to 174.1 m^2, and small range from 23.5 to 41.9 m^2. Gothic refers to tall pointed-roof with straight sides HTs. Large range from 89.3 to 267.8 m^2, and small range from 28.3 to 37.9 m^2. Mid-T refer to short tunnels covering at least two rows of crops ranging from 19.5 to 20.2 m^2. Covering refers to the thickness of the plastic covering. Orientation refers to the direction HTs end walls face: North-South, East-West or Northeast-Southwest. Ventilation refers to the different HT ventilation mechanisms each HT had. Shade cloth refers to the percent solar radiation reduction according to the manufacturer. The season and location of shade cloth was included if applicable.

Location and Number of HTs		Type						Plastic Covering (mm)	Orientation			Ventilation	Shade cloth
		Caterpillar	Quonset		Gothic		Mid-T		N-S	E-W	NE-SW		
			Large	Small	Large	Small							
Desert Farming Initiative (DFI)	4	0	0	0	4	0	0		2	2	0	Manual sides	None
Farm 1 (F1)	5	0	0	0	0	3	2	0.15	1	0	4	Manual end doors	None
Farm 2 (F2)	2	0	1	0	1	0	0	0.28	0	2	0	3-5 automatic fans and 4 vents	40% in summer
Farm 3 (F3)	7	2	3	0	2	0	0	0.15	1	6	0	Manual sides	40% on 2 Large Quonset
Farm 4 (F4)	3	0	0	0	3	0	0	0.15	0	3	0	Manual sides and 2 fans	50% only on 1 HT spring and summer

University Main Station (MS)	2	2	0	0	0	0	0	None	0	2	0	Manual sides and open ends	30% only
School 1 (S1)	2	1	0	1	0	0	0	0.28	2	0	0	End doors	50%
School 2 (S2)	1	0	0	1	0	0	0	0.30	1	0	0	End doors	None
School 3 (S3)	1	0	0	1	0	0	0	0.30	0	1	0	End doors	None
School 4 (S4)	1	0	0	1	0	0	0	0.30	0	1	0	End doors	None

Table 8. Semi-structured interview questions.

Semi-Structured Interview questions:
1. Would you be interested in answering some questions about your experience growing in HT?
2. When did you first purchase your HT? Did you continue to purchase HT over time? If so, what was you time frame?
3. Why did you initially decide to invest in HT?
4. How has investing in HT affected your profitability?
5. Did you use NRCS's hoop house program to help pay for the HT?
6. Have HT paid off as an investment?
7. How important are maintenance costs in maintaining the economic viability of HT?
8. What crops have you grown in HT? Which crops have been successful? Which haven't?
9. What management practices have you used in your hoop house? What has been successful? What hasn't?
10. Do HT play an important role in your ability to survive as a business?
11. Would you recommend HT to other farmers?
12. Why do you think HT help you extend the season and grow a wider variety of crops?
13. Are there any downsides to growing in HT?
14. What are your future plans for your HT?
15. Will you invest more in the technology either through purchasing more HT or improving your current HT?
16. What do you consider to be the most important advantage HT provide? Season extension? Ability to grow different crops? Other?
17. Is there any other information you would like to share?
18. Are there any questions that I missed that you feel are important to answer?

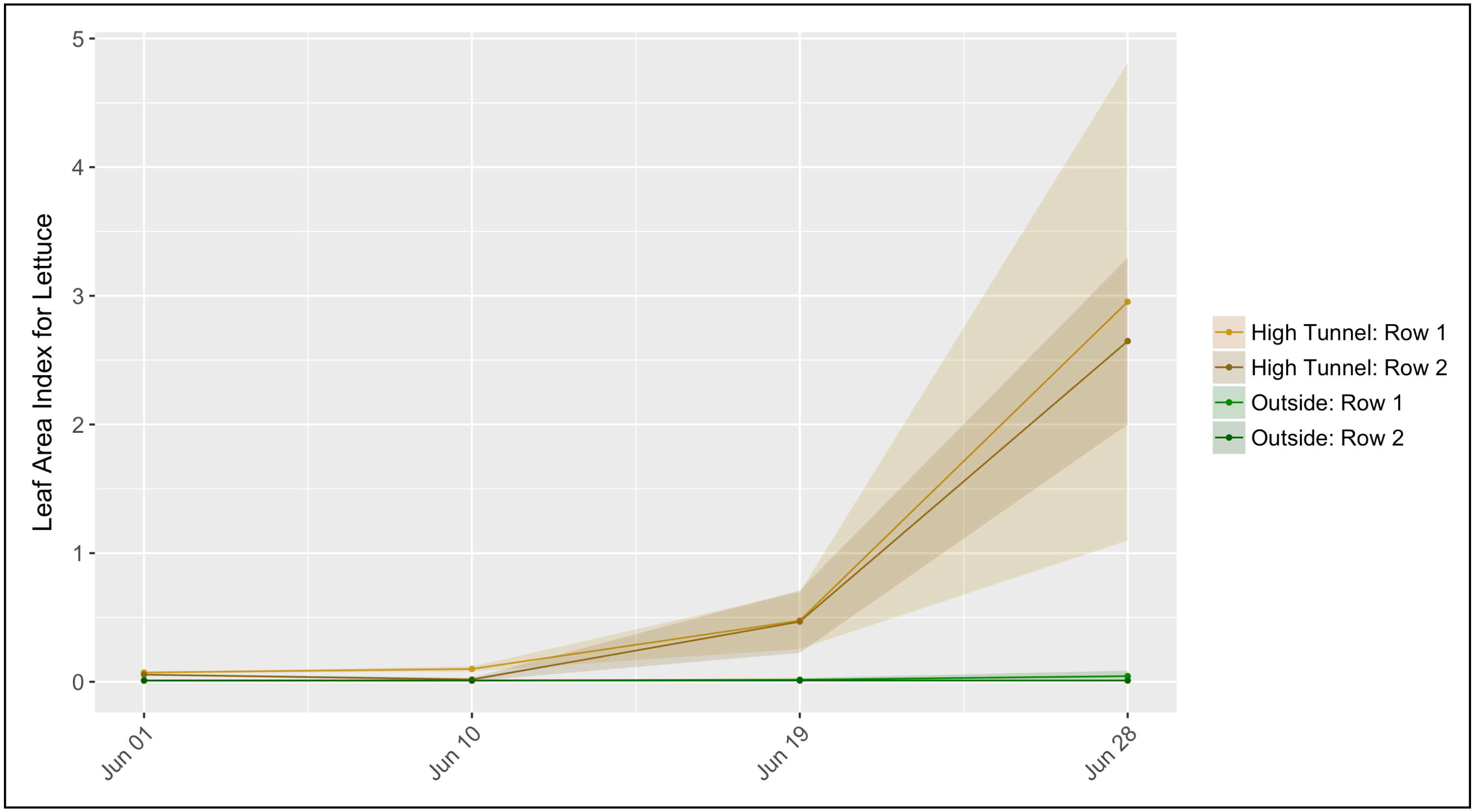

Fig. 2. Leaf area index of lettuce grown in June 2017. Shading shows the standard deviation across measurements.

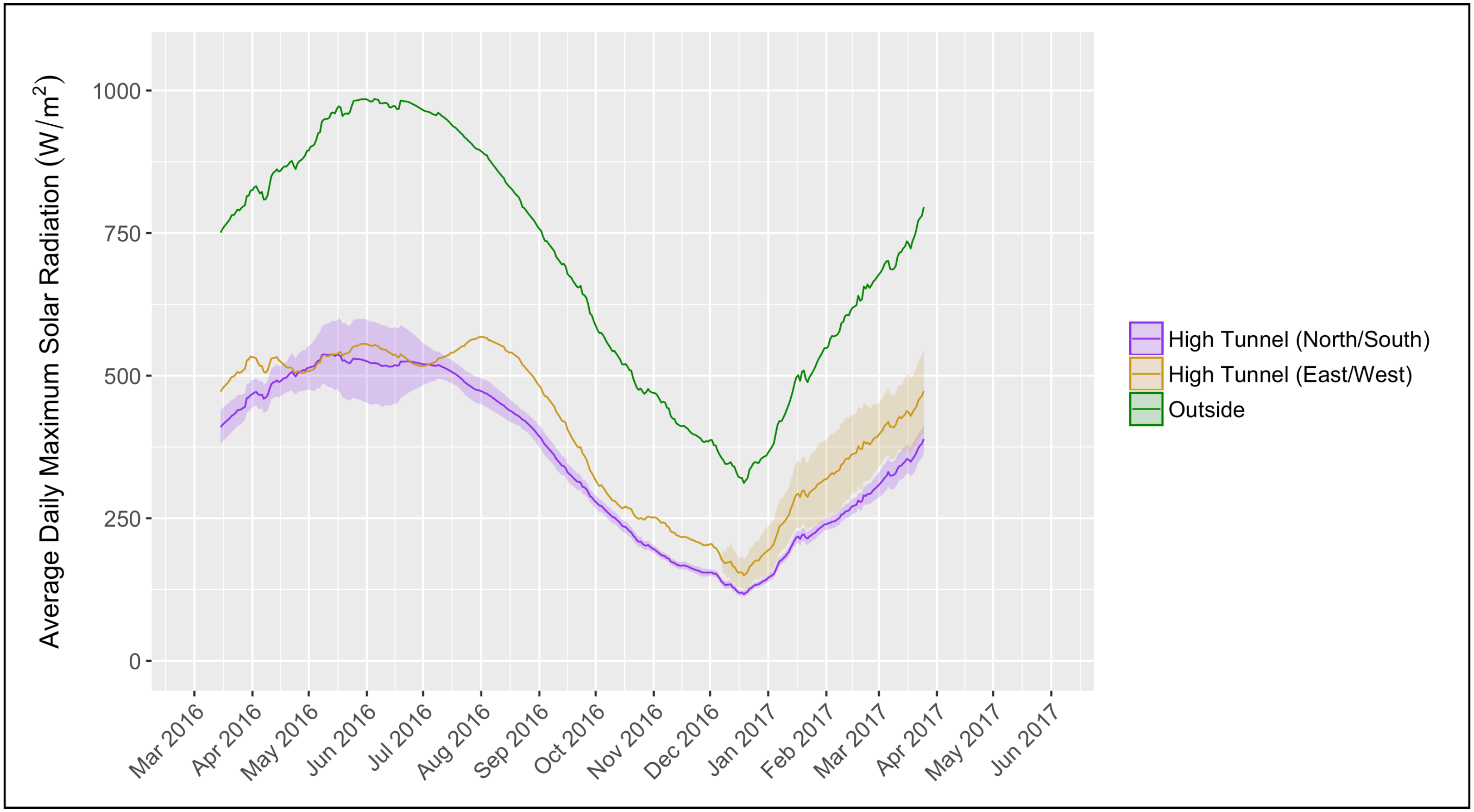

Fig. 3. The 31-day moving average of maximum solar radiation at DFI. HTs were closed from November to February. Values are plotted against the center date. Shading shows the standard deviation across sensor. The outside plot had no replicate. The East/West high tunnel had replicates only for January through April due to sensor and high tunnel failures.

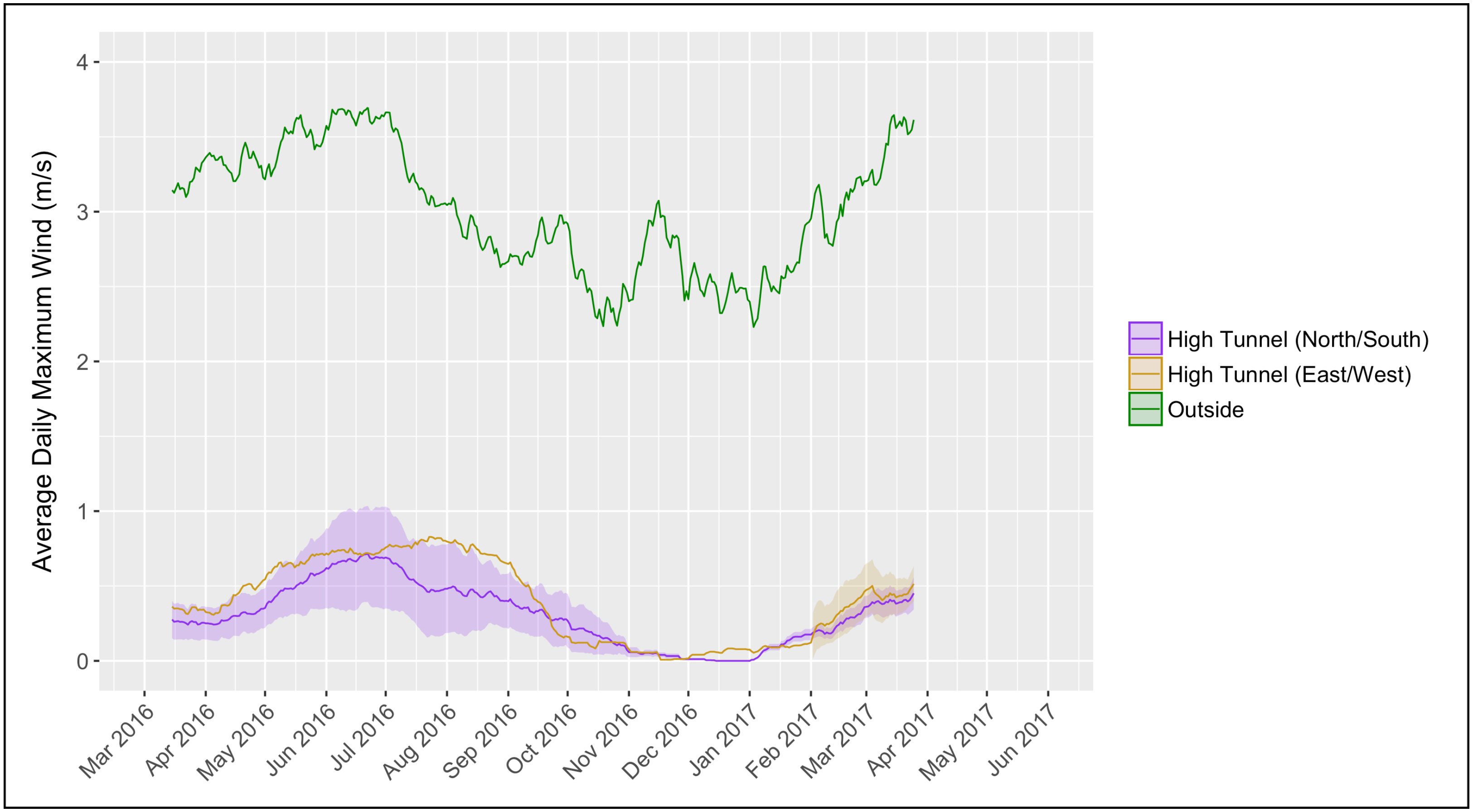

Fig. 4. The 31-day moving average of maximum wind at DFI. HTs were closed from November to February. Values are plotted against the center date. Shading shows the standard deviation across sensor. The outside plot had no replicate. The East/West high tunnel had replicates only for January through April due to sensor and high tunnel failures.

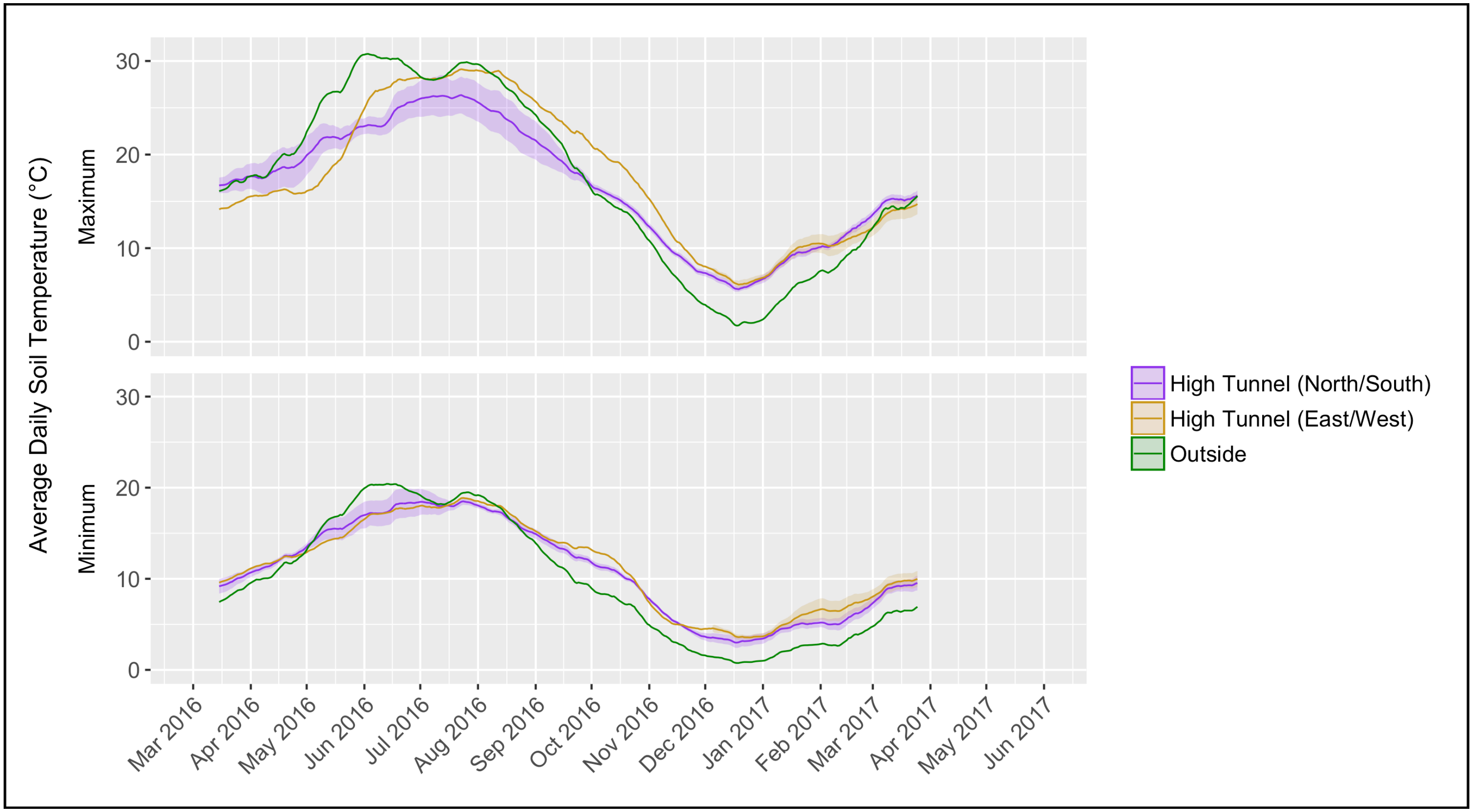

Fig. 5. The 31-day moving average of soil temperature at DFI. HTs were closed from November to February. Values are plotted against the center date. Shading shows the standard deviation across sensor. The outside plot had no replicate. The East/West high tunnel had replicates only for January through April due to sensor and high tunnel failures.

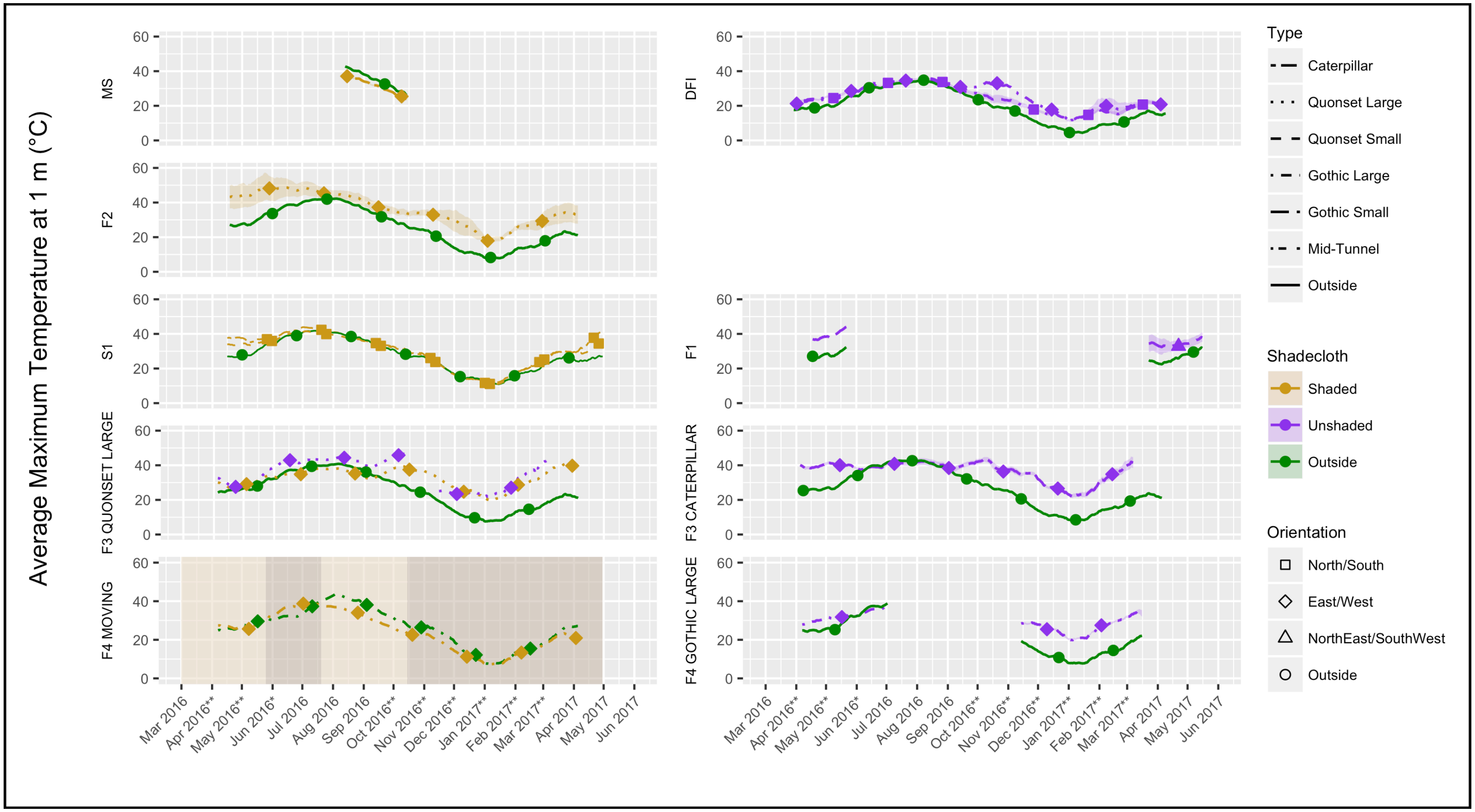

Fig. 6. The 31-day moving average of maximum air temperature at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

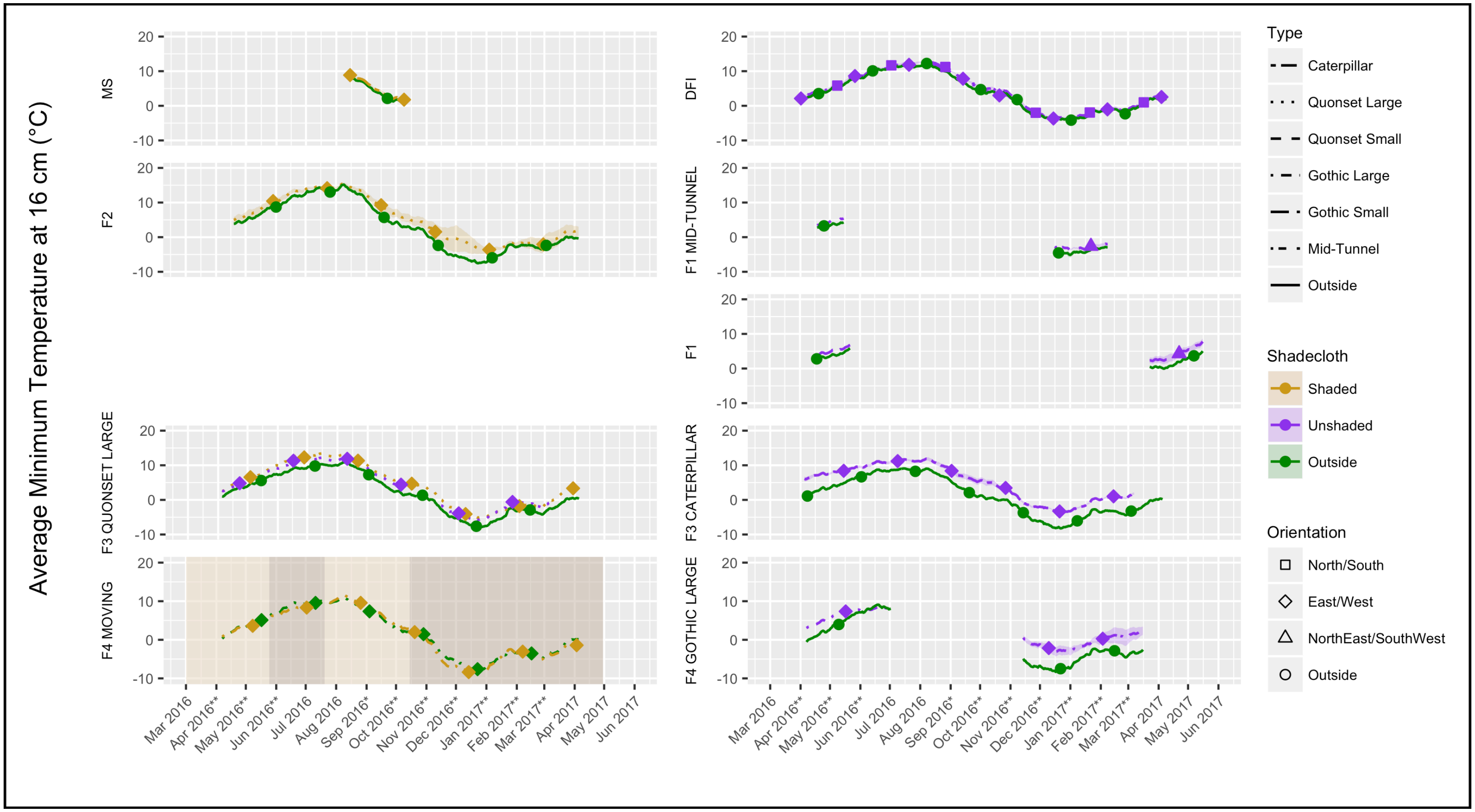

Fig. 7. The 31-day moving average of minimum air temperature at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

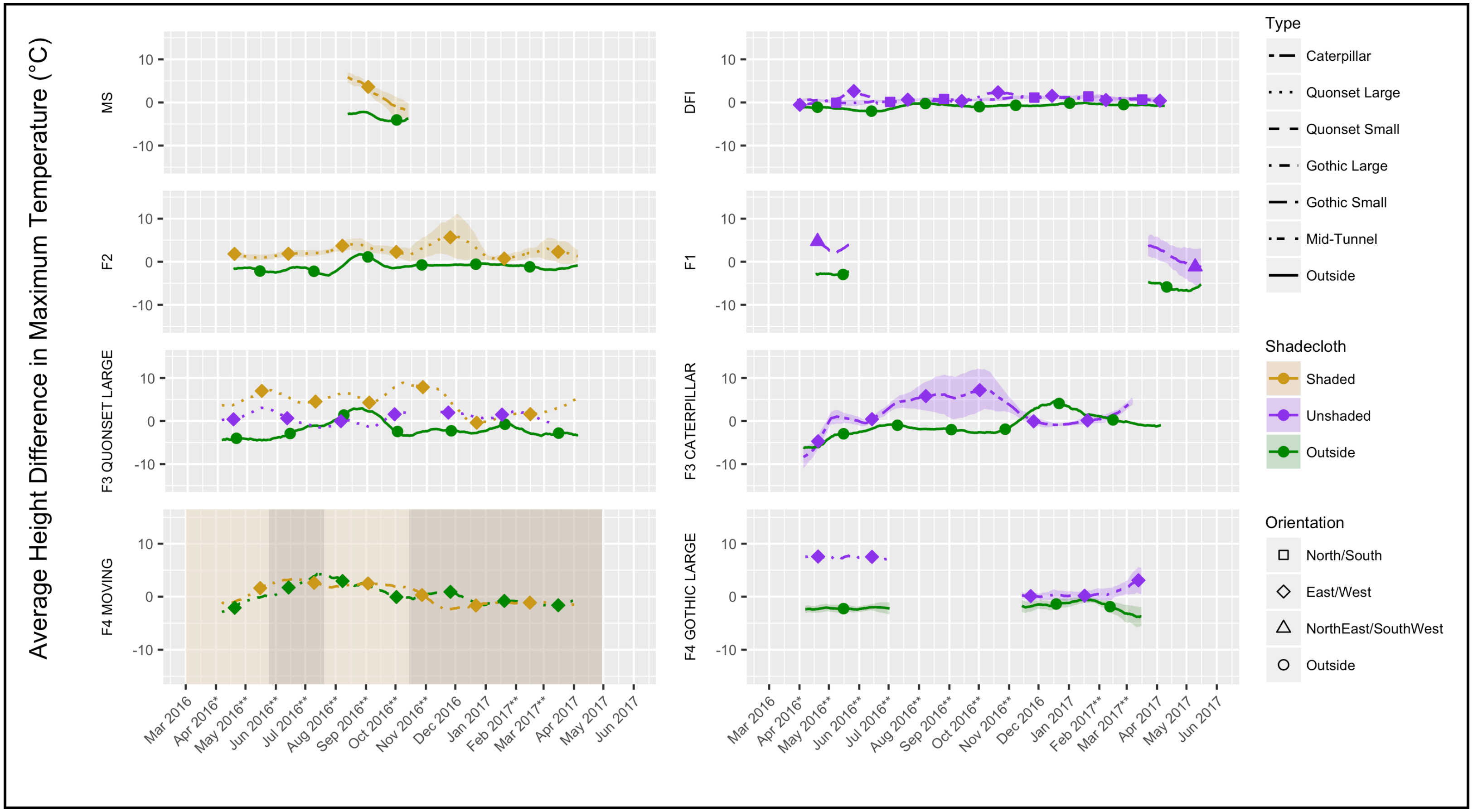

Fig. 8. The 31-day moving average of differences between 1 m and 16 cm of maximum air temperature. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

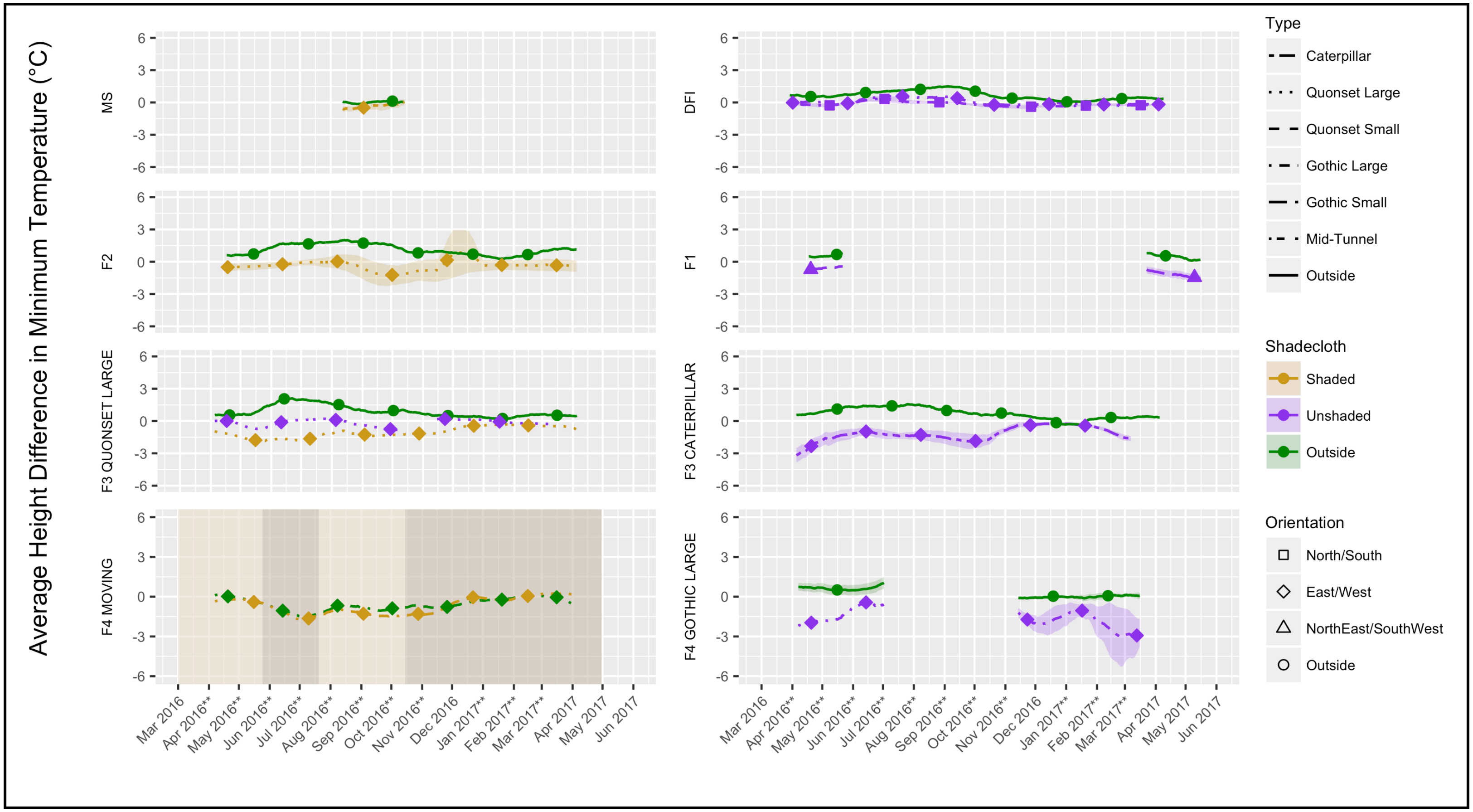

Fig. 9. The 31-day moving average of differences between 1 m and 16 cm of minimum air temperature. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

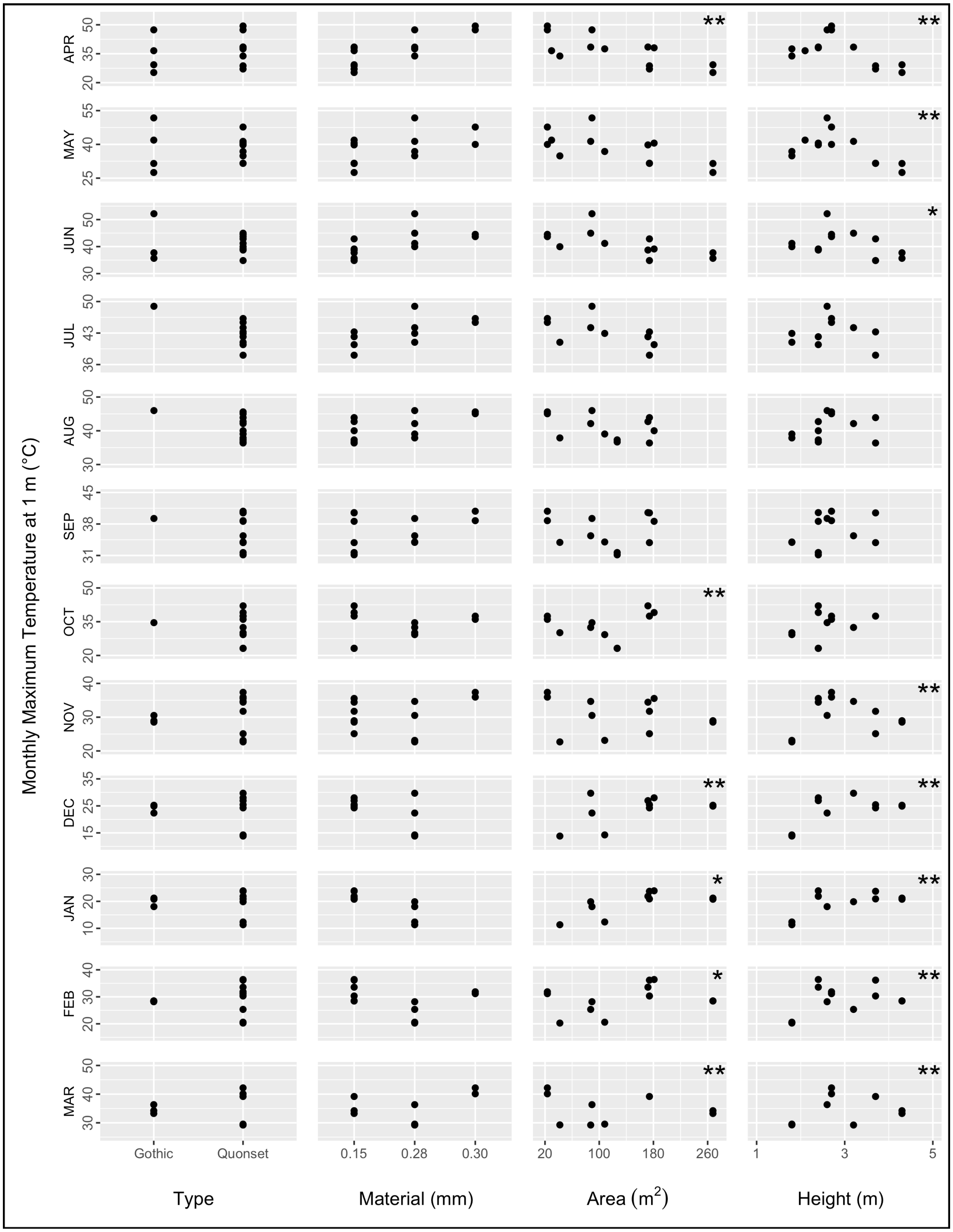

Fig. 10. Linear regression comparing observed monthly maximum temperature at 1 m to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

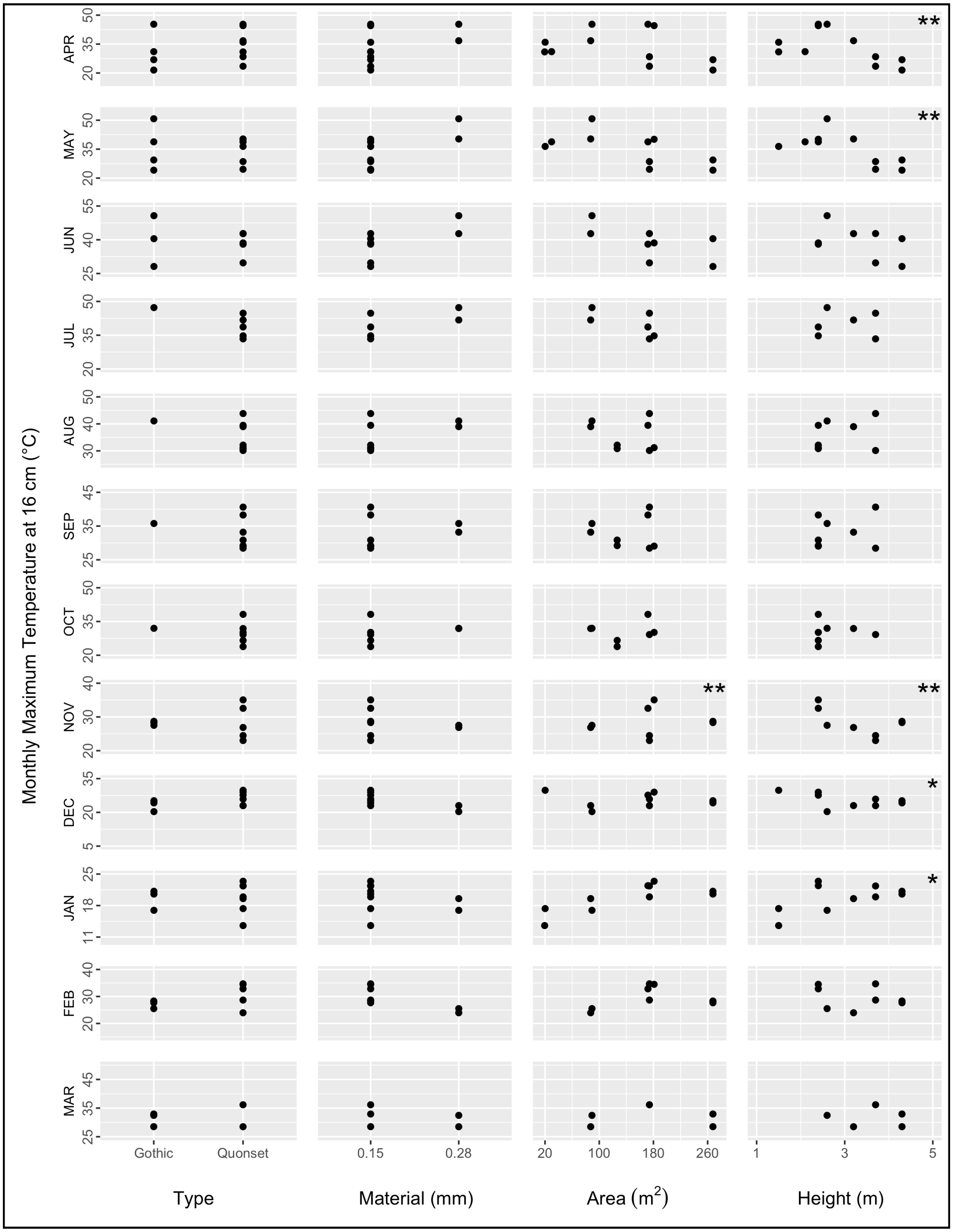

Fig. 11. Linear regression comparing monthly maximum temperature at 16 cm to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

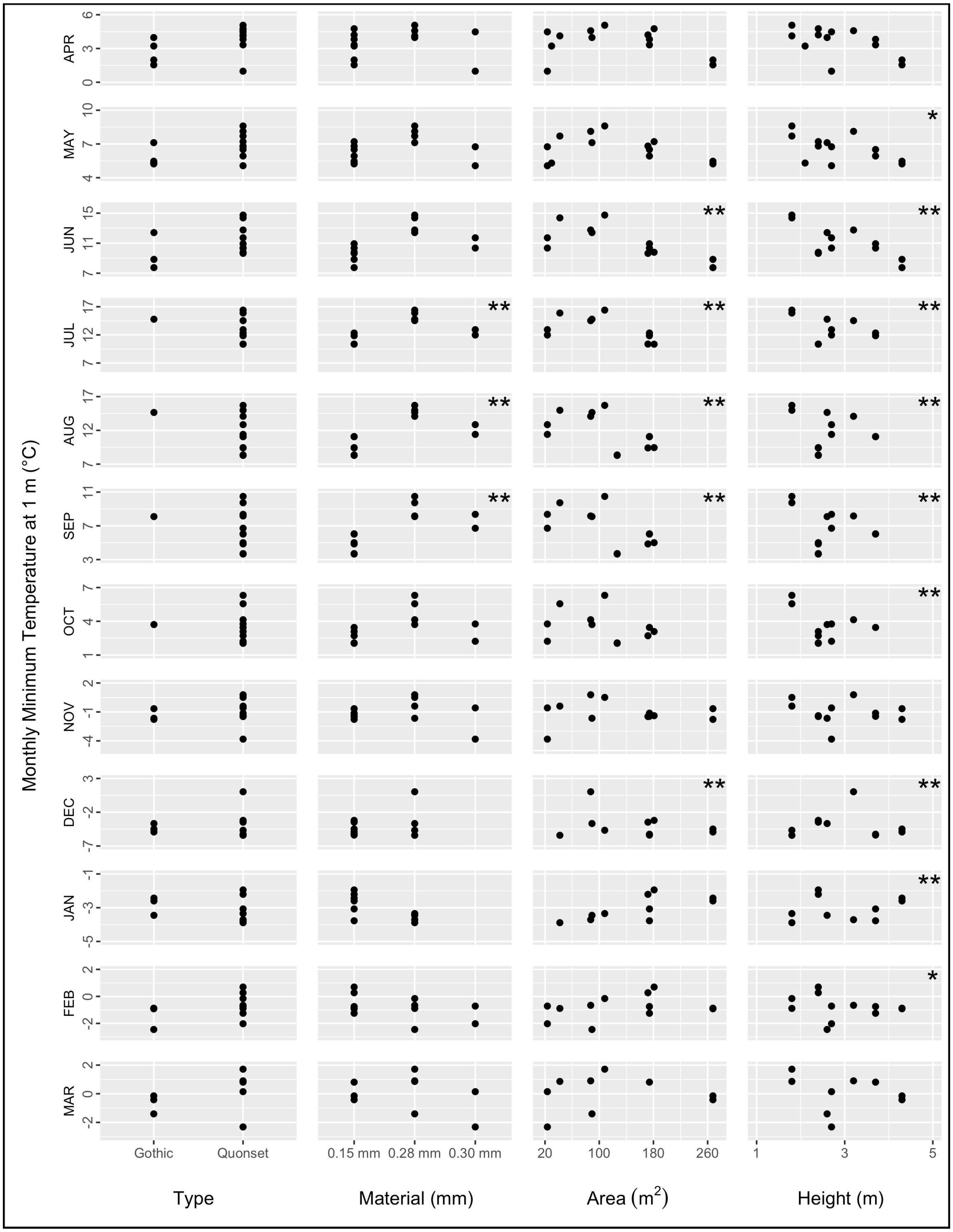

Fig. 12. Linear regression comparing monthly minimum temperature at 1 m to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

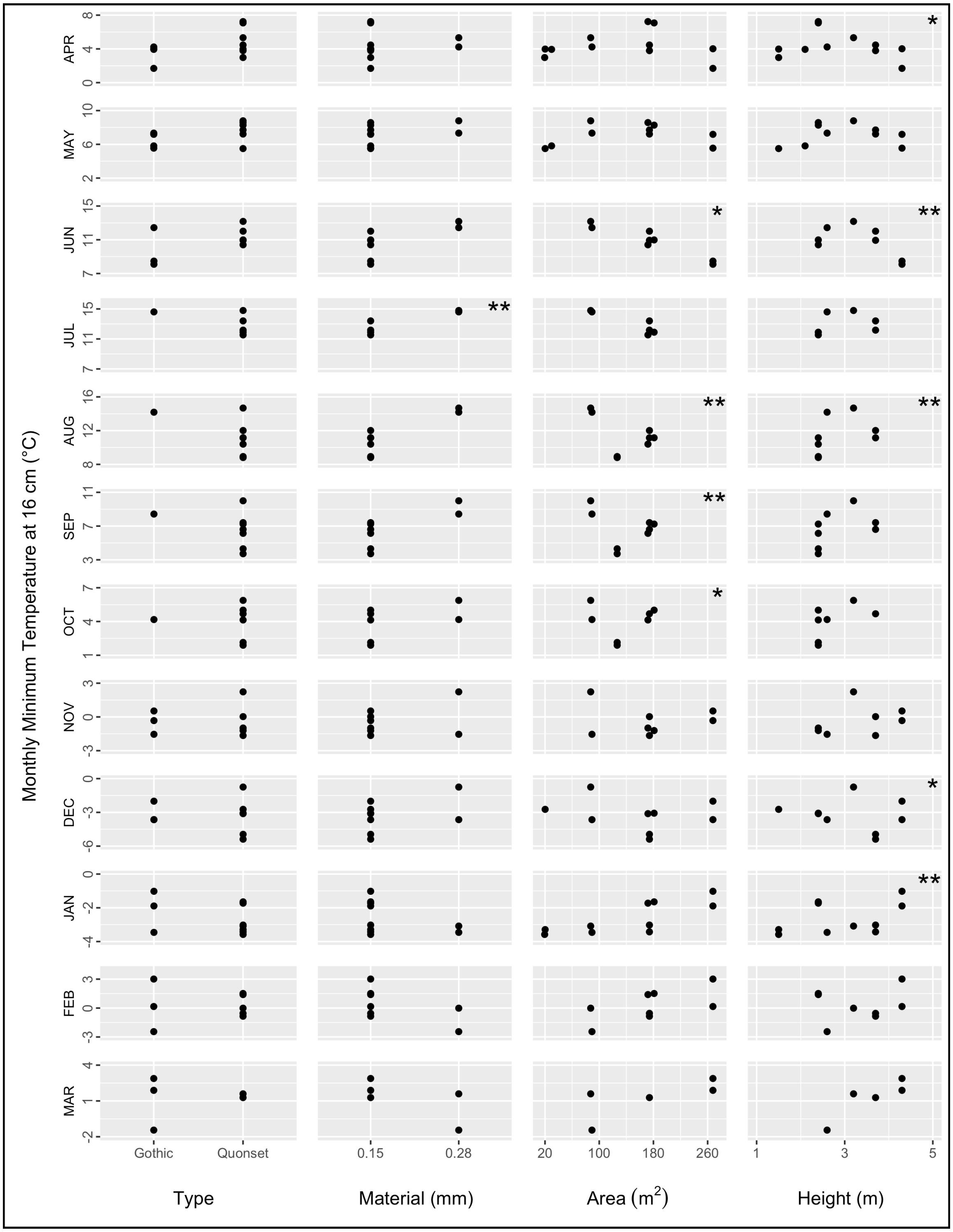

Fig. 13. Linear regression comparing monthly minimum temperature at 16 cm to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

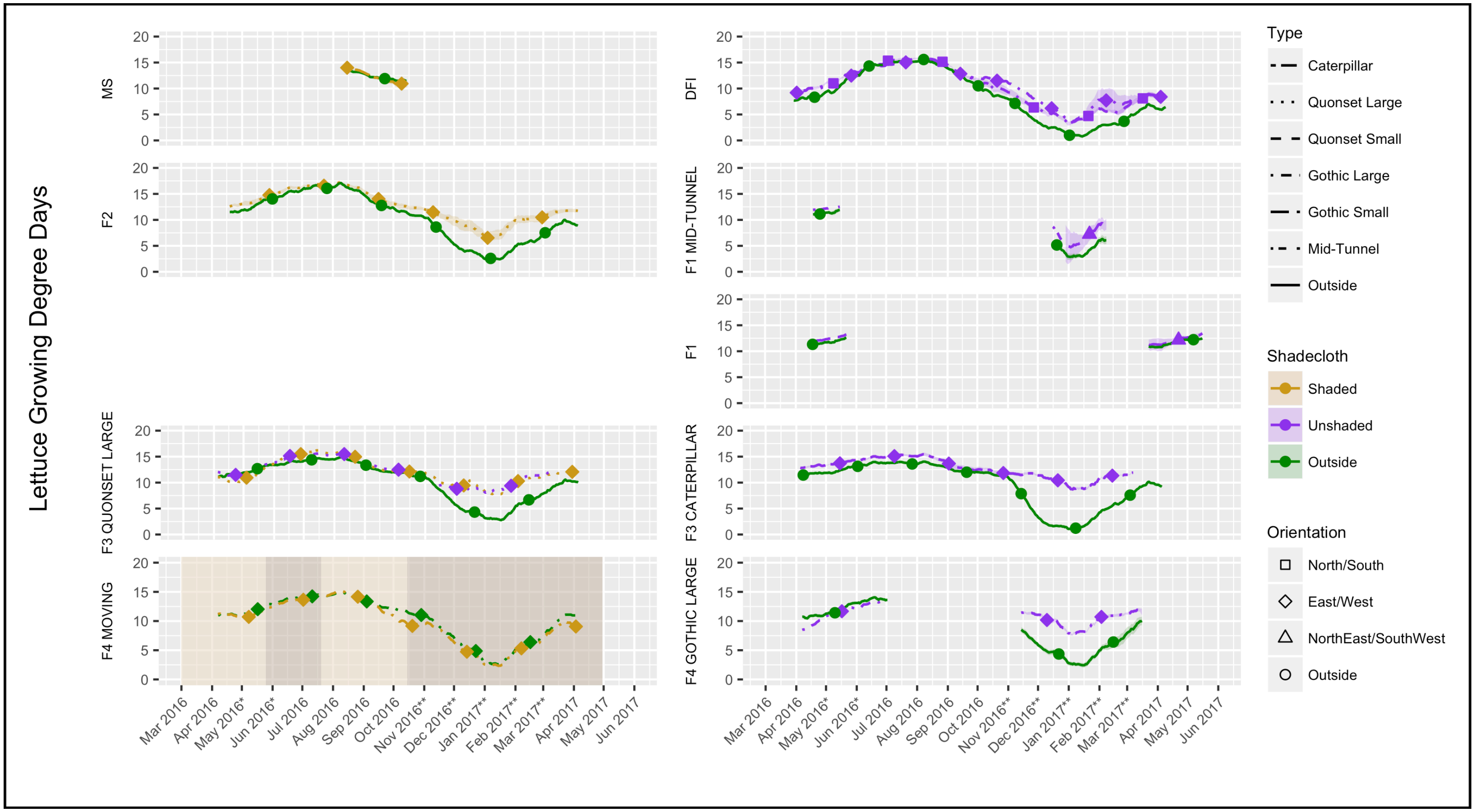

Fig. 14. The 31-day moving average of lettuce growing degree days. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

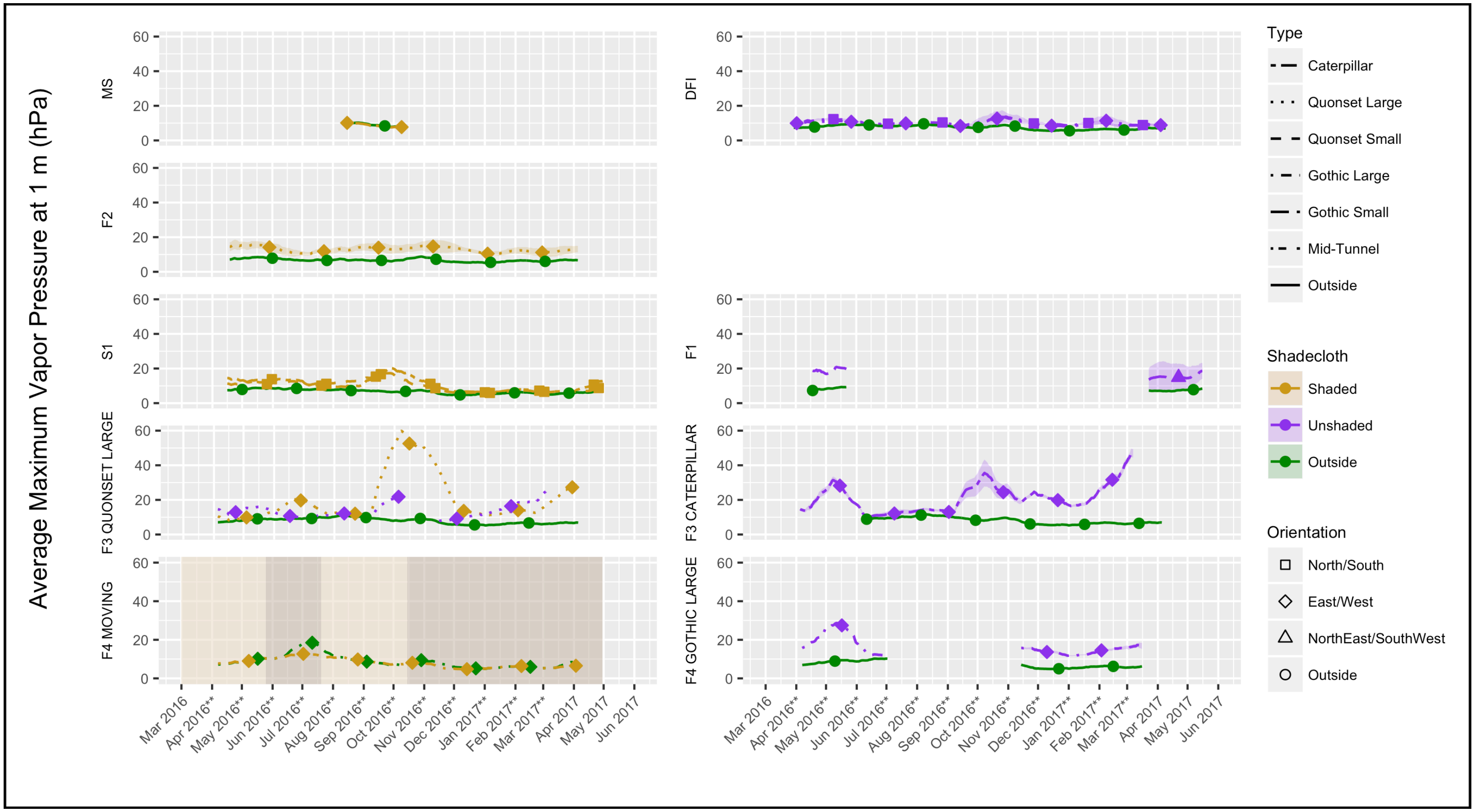

Fig. 15. The 31-day moving average of maximum vapor pressure at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

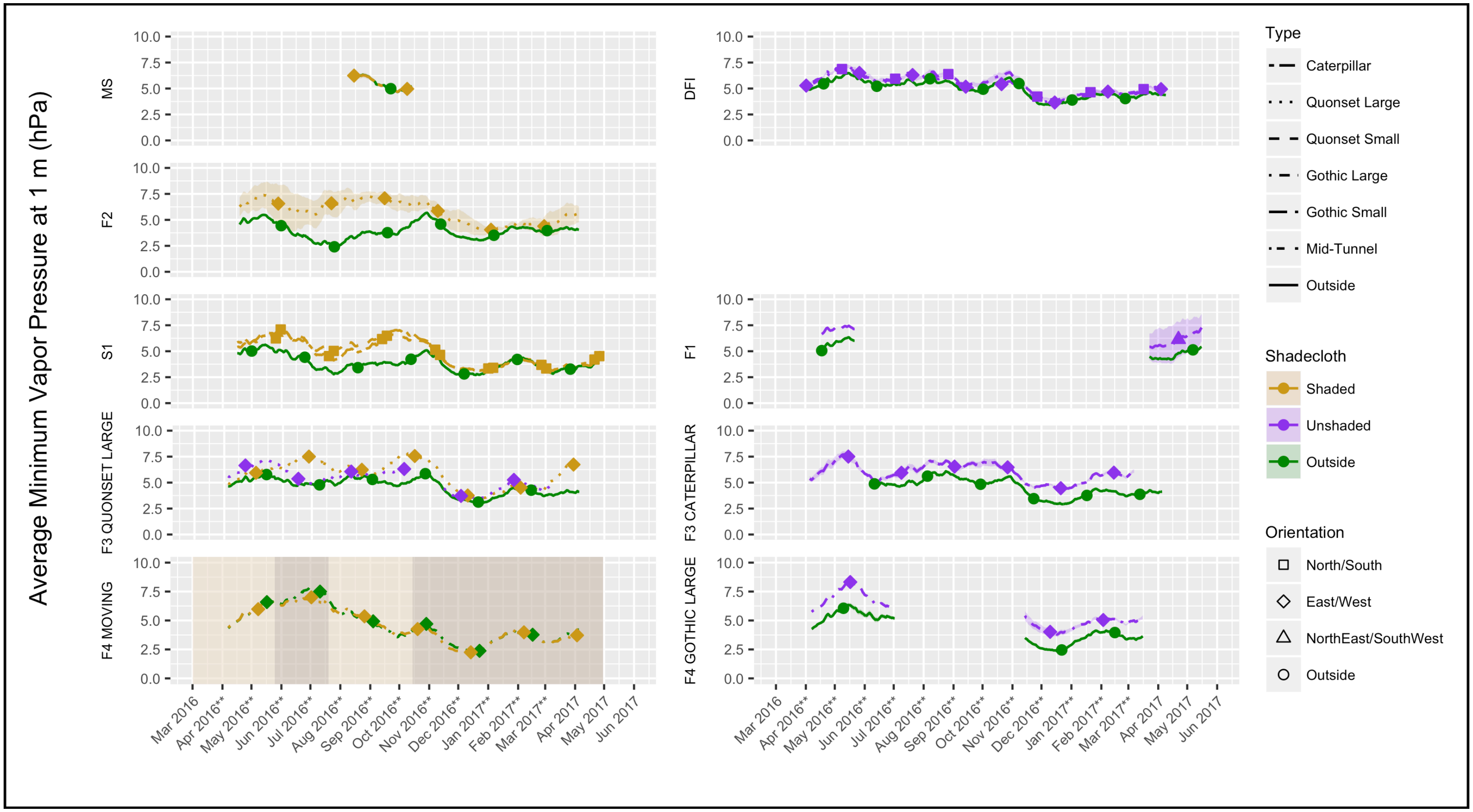

Fig. 16. The 31-day moving average of minimum vapor pressure at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

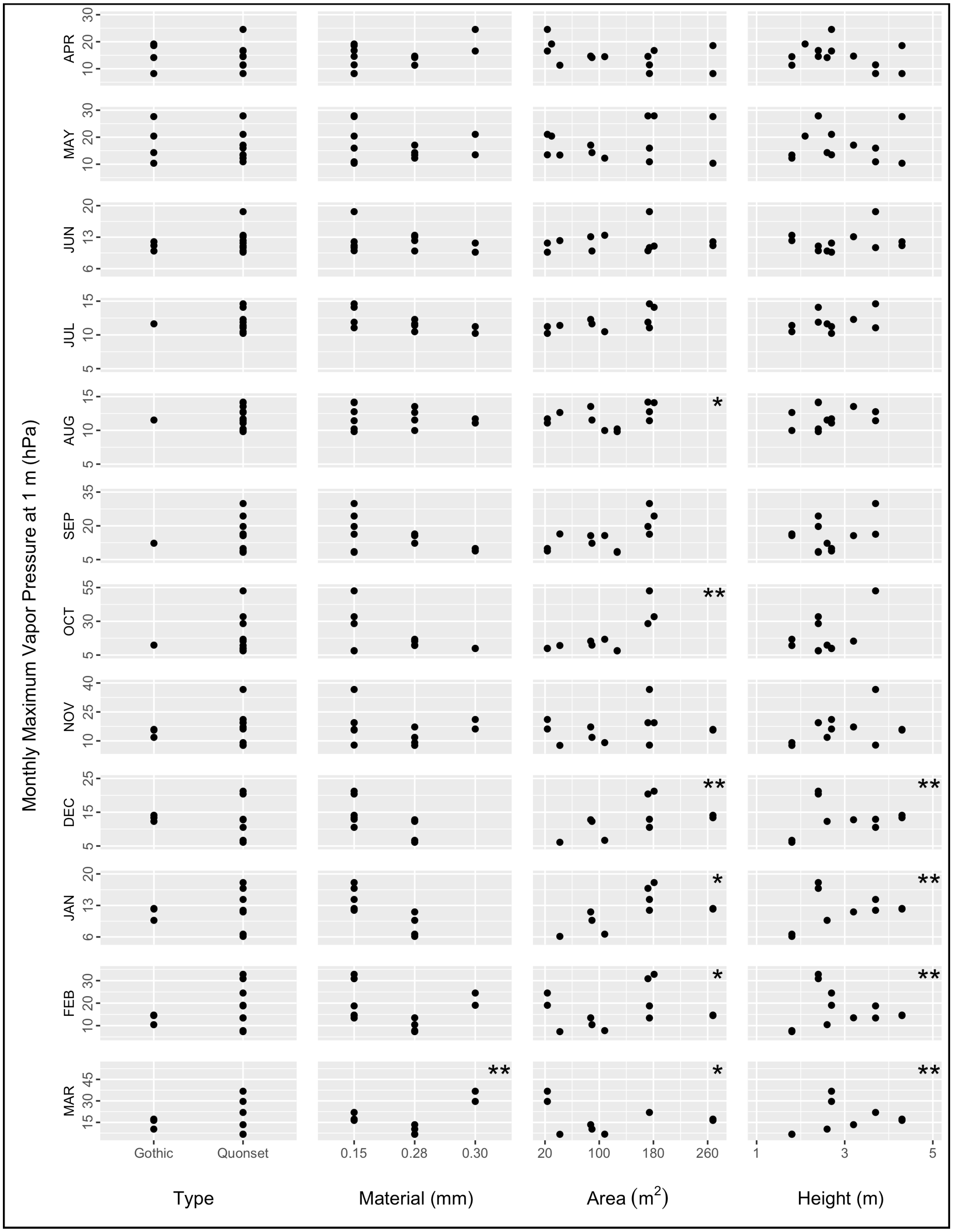

Fig. 17. Linear regression comparing monthly maximum vapor pressure at 1 m to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

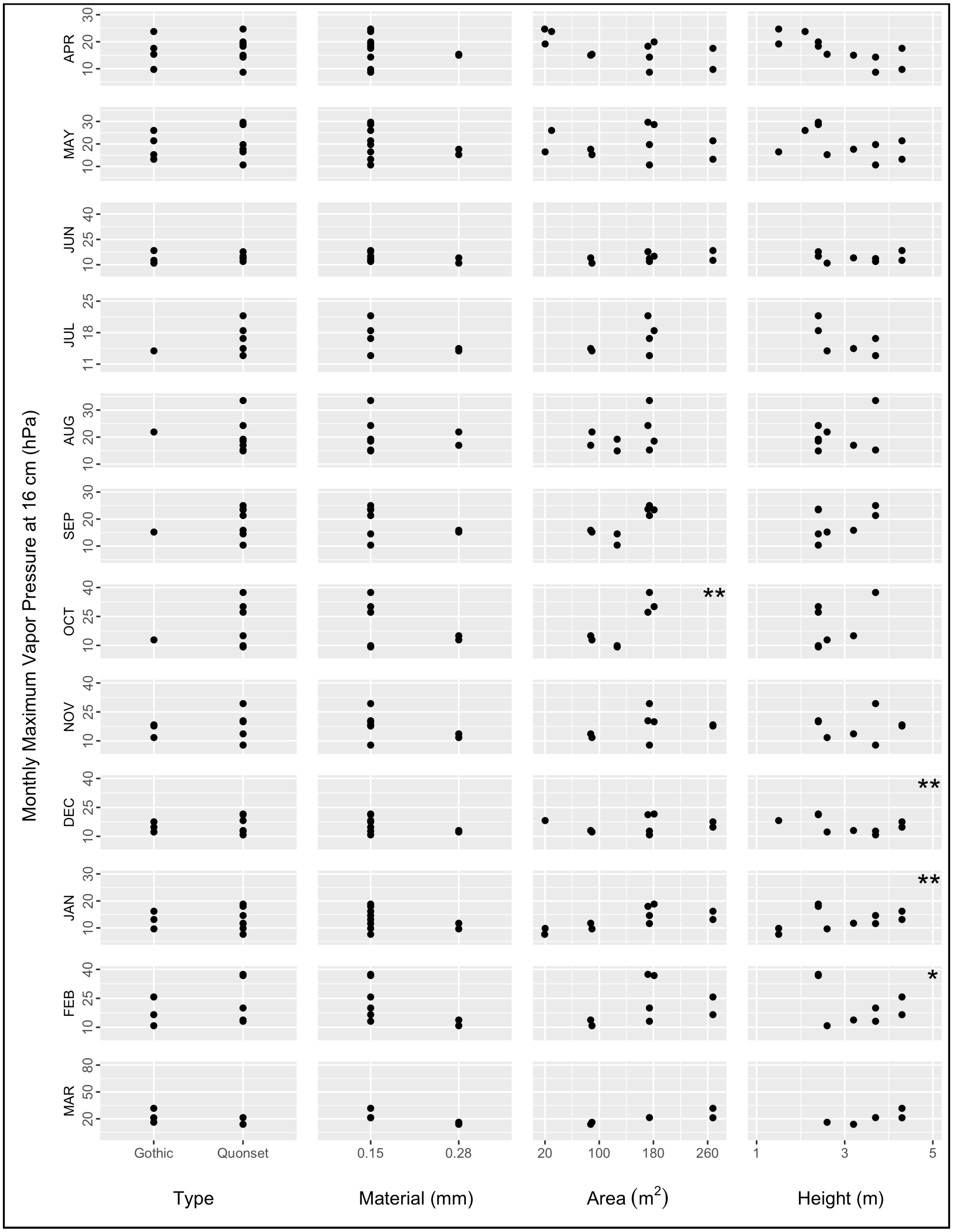

Fig. 18. Linear regression comparing monthly maximum vapor pressure at 16 cm to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

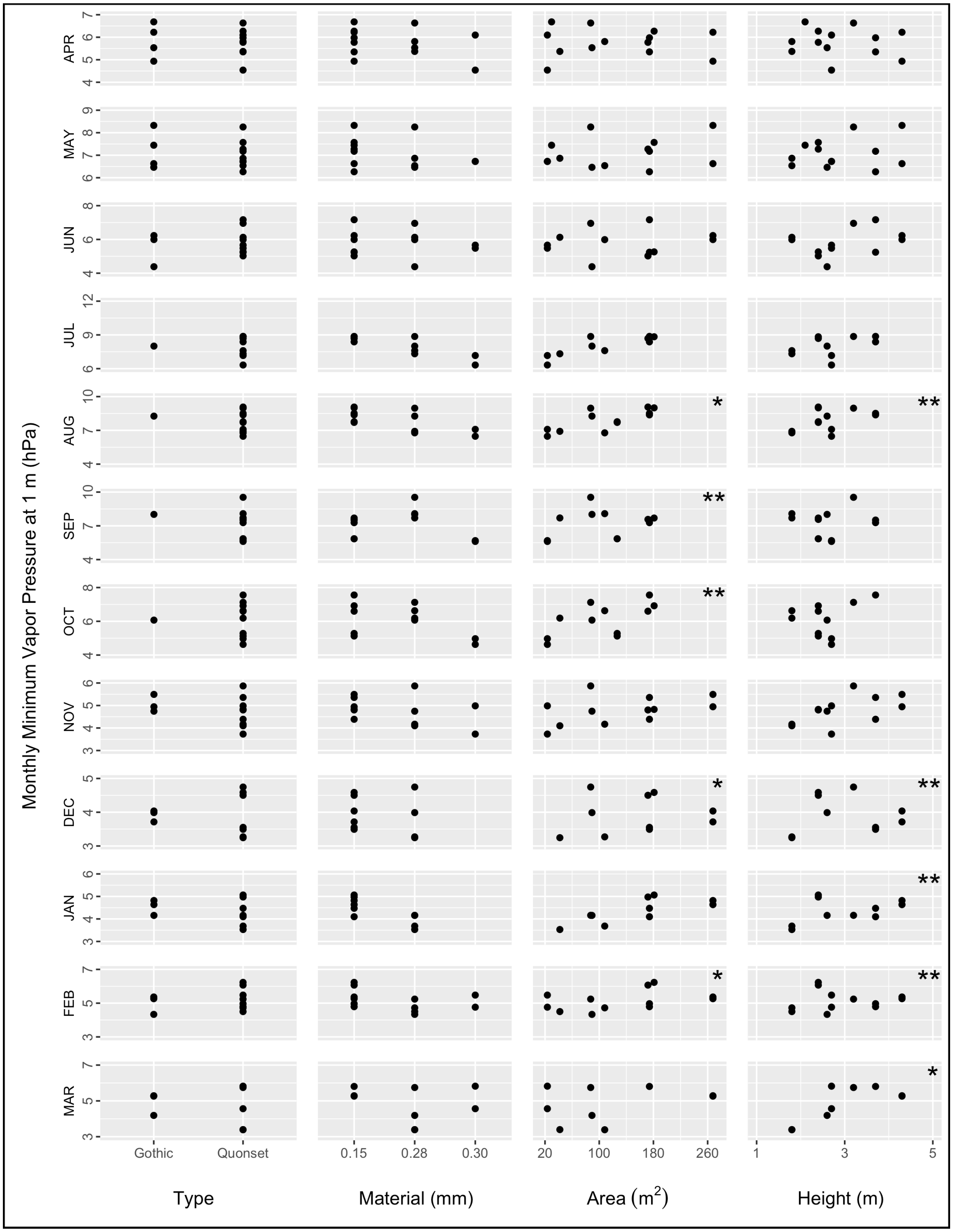

Fig. 19. Linear regression comparing monthly minimum vapor pressure at 1 m to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

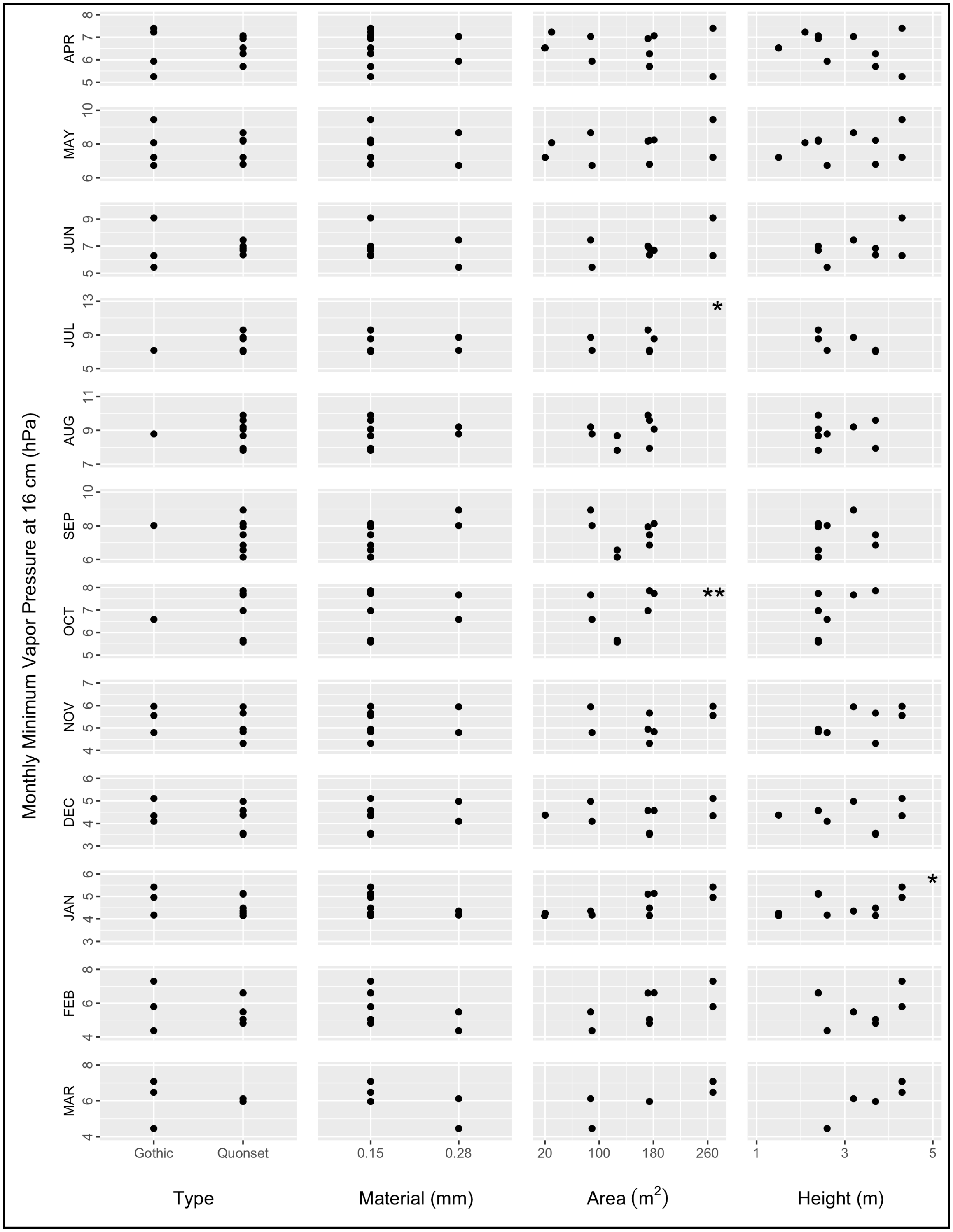

Fig. 20. Linear regression comparing monthly minimum vapor pressure at 16 cm to type, area, height and material. One asterisk indicates a statistical significance of 0.10, and two indicate a statistical significance of 0.05.

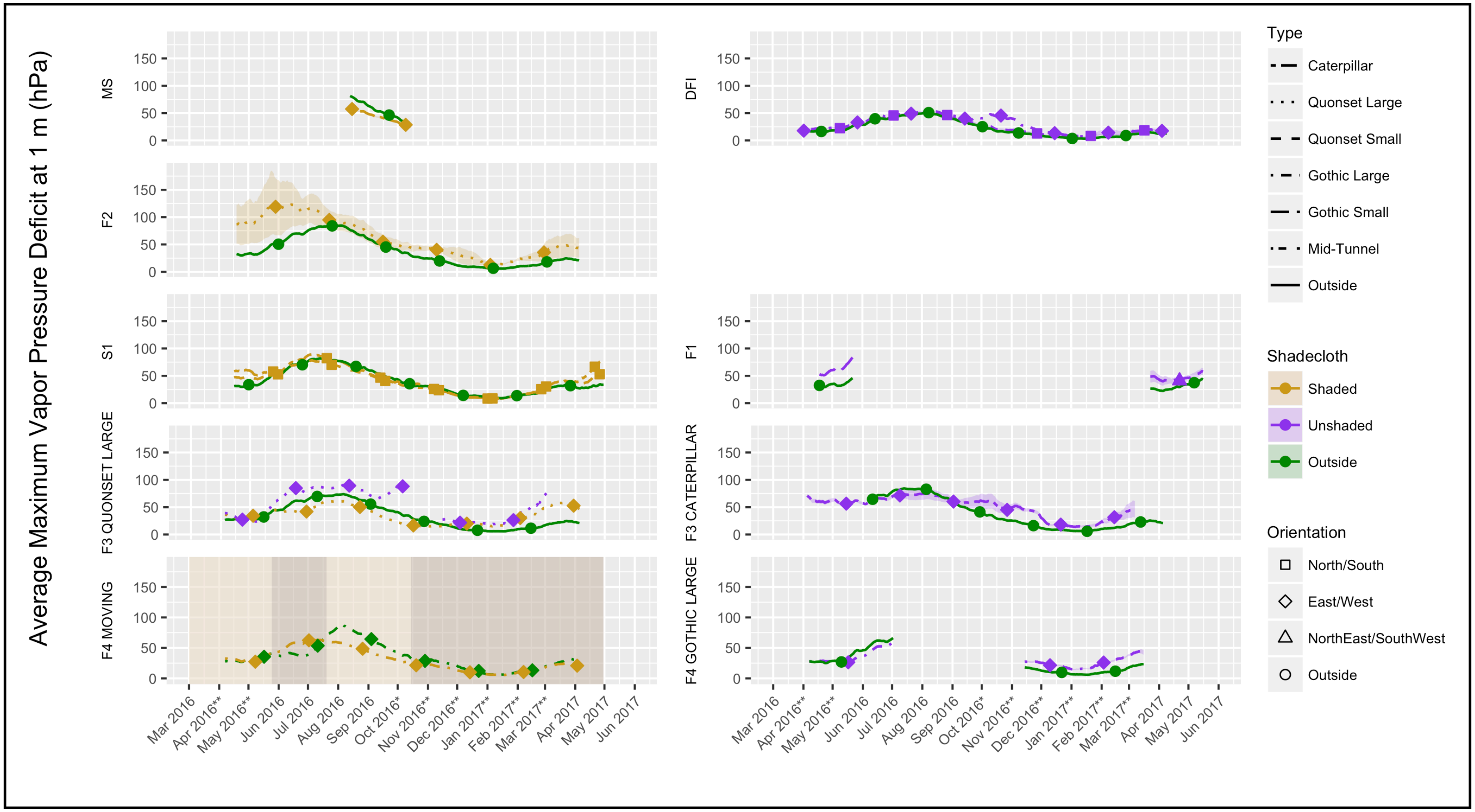

Fig. 21. The 31-day moving average of maximum vapor pressure deficit at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

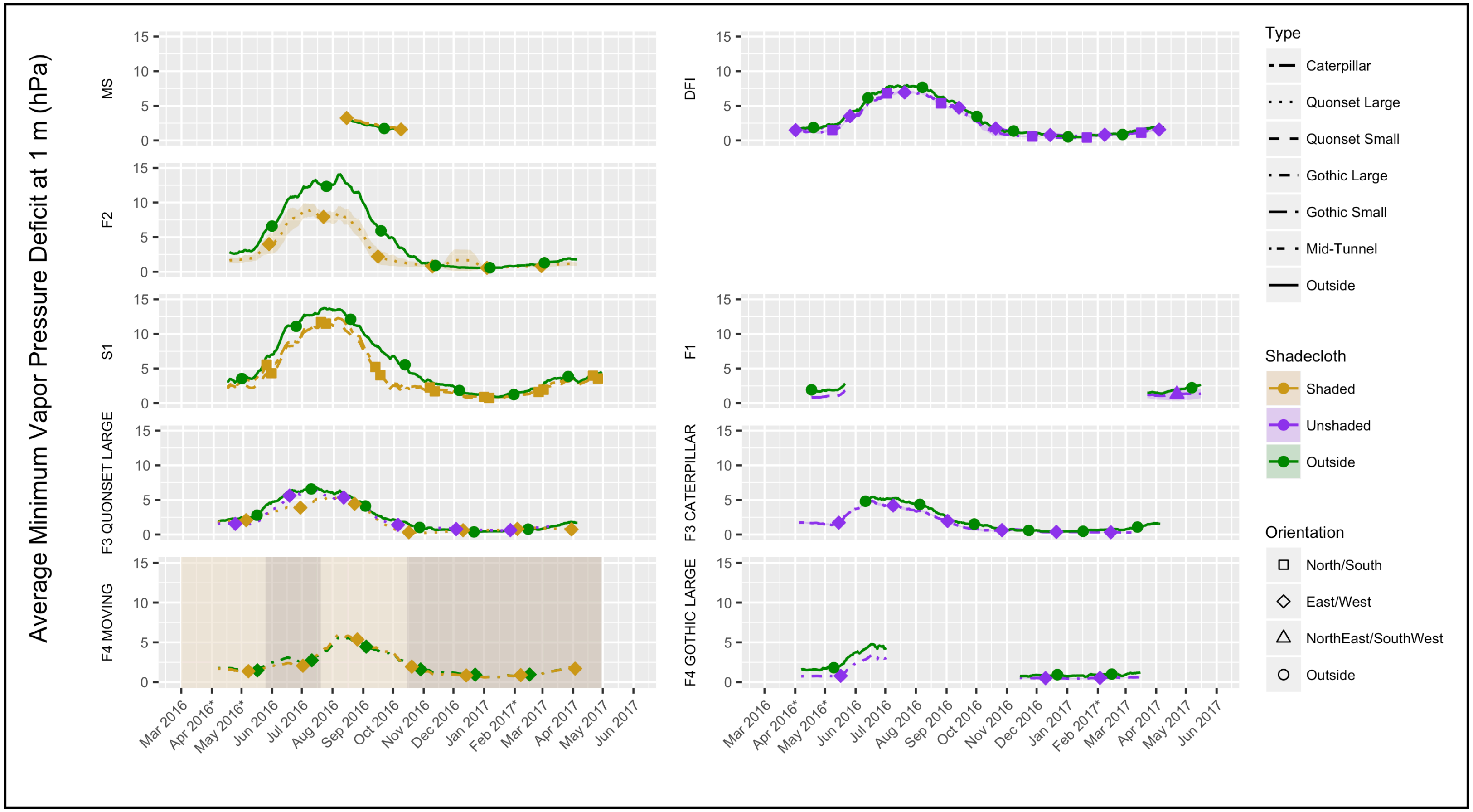

Fig. 22. The 31-day moving average of minimum vapor pressure deficit at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

Appendix

Table 1. Summary of data completeness for each HT.

Location	HT	Type	Start Date	Data Gaps	End Date	Notes
DFI	1	Large Gothic: East-West	2016/03/15	2016/10/15: Artificial heating brought in for farm to table dinner	2017/04/24	
DFI	2	Large Gothic: East-West	2017/01/04	None	2017/04/24	Short record due to cover ripping off and weather station battery failed
DFI	3	Large Gothic: North-South	2016/03/15	None	2017/04/24	
DFI	4	Large Gothic: North-South	2016/03/15	None	2017/04/24	
DFI	Outside		2016/03/15	None	2017/04/24	
Farm 1	1	Small Gothic	2016/04/03	None	2016/06/06	
Farm 1	2	Mid-T	2016/04/03	None	2016/06/21	Removed because cover removed shortly after sensors were installed
Farm 1	3	Mid-T	2016/04/03	None	2016/06/21	Removed because cover removed shortly after sensors were installed
Farm 1	Outside 1		2016/04/03	None	2016/06/06	
Farm 1	4	Small Gothic	2017/03/08	None	2017/05/31	
Farm 1	5	Small Gothic	2017/03/08	None	2017/05/31	

Farm 1	Outside 2		2017/03/08	None	2017/05/31	
Farm 1	6	Mid-T	2016/04/03	2016/05/30 - 2016/12/01: Mid-Ts taken down and put back up	2017/02/23	
Farm 1	Outside 3		2016/04/03	2016/05/30 - 2016/12/01	2017/02/23	
Farm 1	7	Mid-T	2016/04/03	2016/05/03 - 2016/12/14: Mid-Ts taken down and put back up	2017/02/23	
Farm 1	Outside 4		2016/04/03	2016/05/30 - 2016/12/14	2017/02/23	
Farm 2	2	Large Gothic	2016/04/04	None	2017/04/20	
Farm 2	2	Large Quonset	2016/04/04	None	2017/04/20	
Farm 2	Outside		2016/04/04	None	2017/04/20	
Farm 3	1	Large Quonset	2016/03/21	None	2017/04/20	
Farm 3	2	Large Quonset	2016/03/21	2016/10/26 - 2016/10/31: Sensors temporarily removed for equipment	2017/03/22	
Farm 3	3	Large Gothic	2016/03/21	None	2017/04/20	Removed because cover ripped off for most of the record
Farm 3	4	Large Gothic	2016/03/21	None	2017/04/20	Removed because cover ripped off for most of the record
Farm 3	Outside 1		2016/03/21	None	2017/04/20	
Farm 3	5	Caterpillar	2016/03/21	One sensor at 1 m between 2016/06/10 - 2016/06/27	2017/03/22	Sensors were sometimes temporarily moved inside to allow for equipment
Farm 3	6	Caterpillar	2016/03/21	None	2017/03/22	Sensors were sometimes temporarily moved inside to allow for equipment

Farm 3	7	Large Quonset	2016/03/21	None	2017/04/20	Removed because cover ripped off for most of the record
Farm 3	Outside 2		2016/03/21	Sensor malfunction: humidity data starts 2016/05/24	2017/04/20	
Farm 4	1	Large Gothic	2016/03/23	2016/07/17 - 2017/10/30: HTs taken down and put back up	2017/03/31	
Farm 4	Outside 1		2016/03/23	2016/07/17 - 2017/10/30	2017/04/01	
Farm 4	2	Large Gothic	2016/03/23	2016/07/17 - 2017/10/30: HTs taken down and put back up	2017/04/02	
Farm 4	Outside 2		2016/03/23	2016/07/17 - 2017/10/30	2017/04/03	
Farm 4	3	Large Gothic	2016/03/23	None	2017/04/20	Tunnel moved
University Main Station	1	Caterpillar	2016/07/29	None	2016/10/29	
University Main Station	2	Caterpillar	2016/07/29	None	2016/10/29	
University Main Station	Outside		2016/07/29	None	2016/10/29	
School 1	1	Caterpillar	2016/04/01	None	2017/05/15	
School 1	2	Small Gothic	2016/04/01	None	2017/05/15	
School 1	Outside		2016/04/01	None	2017/05/15	
School 2	1	Small Gothic	2016/04/01	2017/01/31 - 2017/03/07:	2017/05/27	Extension agents downloaded data
School 2	Outside		2016/04/01	2016/11/09 - 2016/11/17, 2017/02/06 - 2017/03/11	2017/05/31	Extension agents downloaded data

School 3	1	Small Gothic	2016/04/01	2016/12/26 - 2017/01/05	2017/04/20	Extension agents downloaded data
School 3	Outside		2016/04/01	2016/12/26 - 2017/01/05	2017/04/20	Extension agents downloaded data
School 4	1	Small Gothic	2016/04/01	2016/12/26 - 2017/01/05	2017/04/20	Extension agents downloaded data
School 4	Outside		2016/04/01	2016/10/04 - 2016/10/14	2017/04/20	Extension agents downloaded data

Table 2. Results comparing the Student t-test and the Wilcoxon test for temperature and GDDs because normality could not be confirmed due to small samples. Light grey indicates statistical significance of 0.10 and white indicates statistical significance of 0.05.

		Temperature								GDD	
Date	**Test**	**Min 1 m**	**Min 16 cm**	**Max 1 m**	**Max 16 cm**	**Diurnal 1 m**	**Diurnal 16 cm**	**Min 1 m - 16 cm**	**Max 1 m - 16 cm**	**Tomato 1 m**	**Lettuce 16 cm**
Apr 16	**wilcox**	0.2773	0.0001	< 0.0001	0.1011	0.0001	0.1457	0.0007	0.1419	0.0011	0.4871
	t-test	0.3744	0.0013	0.0003	0.0710	0.0004	0.2053	0.0014	0.0633	0.0002	0.4307
May 16	**wilcox**	0.5079	0.0006	< 0.0001	0.2766	< 0.0001	0.2766	0.0007	0.0007	0.0104	0.1672
	t-test	0.4565	0.0002	0.0003	0.1912	0.0004	0.5470	< 0.0001	0.0004	0.0154	0.0888
Jun 16	**wilcox**	0.8404	0.1490	0.1288	0.7551	0.0060	0.2677	0.0007	0.0007	0.9340	0.1667
	t-test	0.9691	0.0348	0.0909	0.6870	0.0889	0.2689	0.0002	0.0019	0.9977	0.0754
Jul 16	**wilcox**	0.6354	0.2619	0.4923	0.7143	0.4278	0.2619	0.0238	0.0952	0.5496	0.2619
	t-test	0.7042	0.3580	0.4815	0.2764	0.4432	0.0973	0.0005	0.0073	0.6504	0.3489
Aug 16	**wilcox**	0.7732	0.2141	0.9018	0.1535	1.0000	0.0727	0.0081	0.0162	0.7031	0.2019
	t-test	0.7442	0.3527	0.9079	0.0784	0.8779	0.0847	0.0122	0.0148	0.6947	0.3216
Sep 16	**wilcox**	0.9671	0.0727	0.1956	0.4606	0.2268	0.1535	0.0040	0.0162	0.7667	0.5697
	t-test	0.9552	0.0675	0.1079	0.3842	0.2329	0.1446	0.0036	0.0129	0.6412	0.1888
Oct 16	**wilcox**	0.5249	0.0242	0.0365	0.6485	0.0782	0.4121	0.0121	0.0424	0.0436	0.3152
	t-test	0.6971	0.0078	0.0047	0.4356	0.0096	0.6012	0.0024	0.0173	0.2297	0.5458
Nov 16	**wilcox**	0.0124	0.0016	< 0.0001	0.0016	0.0030	0.0451	0.0109	0.0109	0.0002	0.0016
	t-test	0.0434	0.0005	< 0.0001	0.0007	0.0004	0.0474	0.0049	0.0080	< 0.0001	< 0.0001
Dec 16	**wilcox**	0.0031	0.0008	0.0007	0.0004	0.0031	0.0004	0.1274	0.0932	0.0012	0.0004
	t-test	0.0042	< 0.0001	< 0.0001	< 0.0001	0.0002	< 0.0001	0.2216	0.3509	< 0.0001	< 0.0001
Jan 17	**wilcox**	0.0031	0.0001	0.0001	0.0001	0.0001	0.0001	0.0451	0.1274	0.0008	0.0007
	t-test	0.0036	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0307	0.2206	< 0.0001	< 0.0001
Feb 17	**wilcox**	0.0825	0.0187	< 0.0001	0.0016	< 0.0001	0.0016	0.0016	0.0031	0.0002	0.0043
	t-test	0.2178	0.0031	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0164	0.0043	< 0.0001	< 0.0001
Mar 17	**wilcox**	0.1388	0.0318	0.0001	0.0079	0.0001	0.0556	0.0079	0.0079	0.0006	0.0079
	t-test	0.2366	0.0088	< 0.0001	0.0040	0.0003	0.0923	0.0430	0.0009	< 0.0001	0.0004

Table 3. Results comparing the Student t-test and the Wilcoxon test for vapor pressure because normality could not be confirmed due to small samples. Light grey indicates statistical significance of 0.10 and white indicates statistical significance of 0.05.

		Vapor Pressure							
Date	**Test**	**Min 1 m**	**Min 16 cm**	**Max 1 m**	**Max 16 cm**	**Diurnal 1 m**	**Diurnal 16 cm**	**Min 1 m - 16 cm**	**Max 1 m - 16 cm**
Apr 16	**wilcox**	0.0007	0.0001	< 0.0001	0.0003	< 0.0001	0.0009	0.0187	0.5237
	t-test	< 0.0001	< 0.0001	< 0.0001	0.0001	0.0001	0.0004	0.0157	0.1765
May 16	**wilcox**	0.0001	0.0025	< 0.0001	0.0016	< 0.0001	0.0016	0.1709	0.5237
	t-test	0.0001	0.0014	0.0003	0.0023	0.0005	0.0041	0.1011	0.6013
Jun 16	**wilcox**	0.0012	0.0177	0.0002	0.0480	0.0003	0.1061	0.5303	0.8763
	t-test	0.0012	0.0120	0.0014	0.1192	0.0041	0.3318	0.4134	0.8927
Jul 16	**wilcox**	0.0017	0.0476	0.0005	0.1667	0.0160	0.2619	0.7143	0.7143
	t-test	0.0035	0.0893	0.0006	0.1593	0.0125	0.2634	0.9821	0.7801
Aug 16	**wilcox**	0.0098	0.0162	0.0037	0.2141	0.0358	0.4606	0.3677	0.8081
	t-test	0.0182	0.0740	0.0034	0.0868	0.0223	0.1503	0.2196	0.2865
Sep 16	**wilcox**	0.0026	0.0081	0.0026	0.0283	0.0098	0.1535	0.4606	0.4606
	t-test	0.0004	0.0033	0.0025	0.0145	0.0070	0.0419	0.5463	0.3129
Oct 16	**wilcox**	0.0273	0.0242	0.0048	0.2303	0.0103	0.3152	0.0727	0.0424
	t-test	0.0027	0.0072	0.0275	0.0656	0.0361	0.0870	0.0514	0.0872
Nov 16	**wilcox**	0.0007	0.0016	< 0.0001	0.0016	0.0001	0.0062	0.1274	0.7242
	t-test	0.0003	0.0004	0.0010	0.0032	0.0016	0.0056	0.0961	0.4049
Dec 16	**wilcox**	0.0001	0.0004	0.0001	0.0040	0.0001	0.0004	0.1709	0.6216
	t-test	0.0001	< 0.0001	0.0006	0.0001	0.0010	0.0001	0.1337	0.3903
Jan 17	**wilcox**	0.0068	0.0001	0.0001	0.0001	0.0001	0.0001	0.7242	1.0000
	t-test	0.0013	0.0005	0.0006	0.0002	0.0006	0.0003	0.7233	0.4742
Feb 17	**wilcox**	0.0022	0.0109	< 0.0001	0.0016	< 0.0001	0.0016	0.1274	0.6216
	t-test	0.0010	0.0061	0.0009	0.0062	0.0009	0.0070	0.1470	0.1433
Mar 17	**wilcox**	0.0274	0.0079	0.0002	0.0079	0.0001	0.0079	0.0952	0.5476
	t-test	0.0087	0.0096	0.0098	0.0119	0.0122	0.0151	0.1557	0.2741

Table 4. Results comparing the Student t-test and the Wilcoxon test for VPD because normality could not be confirmed due to small samples.. Light grey indicates statistical significance of 0.10 and white indicates statistical significance of 0.05.

		Vapor Pressure Deficit							
Date	**Test**	**Min 1 m**	**Min 16 cm**	**Max 1 m**	**Max 16 cm**	**Diurnal 1 m**	**Diurnal 16 cm**	**Min 1 m - 16 cm**	**Max 1 m - 16 cm**
Apr 16	**wilcox**	0.1569	0.6965	0.0073	0.9654	0.0030	0.9654	0.1709	0.1709
	t-test	0.0578	0.9549	0.0042	0.2074	0.0037	0.2011	0.2792	0.3589
May 16	**wilcox**	0.0574	0.6058	0.0124	0.2766	0.0073	0.2766	0.1709	0.0016
	t-test	0.0795	0.4680	0.0107	0.3627	0.0090	0.3675	0.4646	0.0002
Jun 16	**wilcox**	0.5448	0.4318	0.3511	0.7551	0.1774	0.7551	0.2677	0.0025
	t-test	0.3008	0.8224	0.2132	0.8593	0.1607	0.8391	0.6179	0.0001
Jul 16	**wilcox**	0.2635	0.5476	0.8749	0.3810	0.8749	0.2619	0.0238	0.0476
	t-test	0.2811	0.9176	0.8630	0.2364	0.6599	0.1865	0.0224	0.0096
Aug 16	**wilcox**	0.3845	0.6828	0.4320	0.0485	0.5358	0.0485	0.0727	0.0081
	t-test	0.3765	0.9977	0.5781	0.0454	0.7692	0.0503	0.1046	0.0275
Sep 16	**wilcox**	0.1673	0.5697	0.7732	0.1535	0.9671	0.1535	0.0283	0.0040
	t-test	0.1484	0.9611	0.9141	0.0922	0.6449	0.0981	0.0745	0.0146
Oct 16	**wilcox**	0.3011	0.9273	0.4043	0.7879	0.3502	0.7879	0.0242	0.0424
	t-test	0.2007	0.8326	0.0707	0.4291	0.0500	0.4302	0.0119	0.0283
Nov 16	**wilcox**	0.4727	0.5237	0.0041	0.0295	0.0041	0.0295	0.3543	0.0031
	t-test	0.4753	0.3412	0.0028	0.1455	0.0025	0.1476	0.3131	0.0042
Dec 16	**wilcox**	0.6009	0.9546	0.0012	0.0004	0.0020	0.0004	0.1709	0.6216
	t-test	0.8622	0.7870	0.0018	0.0001	0.0012	0.0001	0.4895	0.2141
Jan 17	**wilcox**	0.3148	0.8125	0.0004	0.0001	0.0004	0.0001	0.0451	0.0109
	t-test	0.2454	0.8606	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0463	0.0183
Feb 17	**wilcox**	0.0473	0.5237	< 0.0001	0.0016	< 0.0001	0.0016	0.0295	0.0016
	t-test	0.0568	0.2593	< 0.0001	0.0039	< 0.0001	0.0032	0.1415	0.0002
Mar 17	**wilcox**	0.0745	0.0556	0.0002	0.2222	0.0001	0.2222	0.6905	0.0079
	t-test	0.3304	0.0543	0.0001	0.4507	0.0001	0.4251	0.9799	0.0096

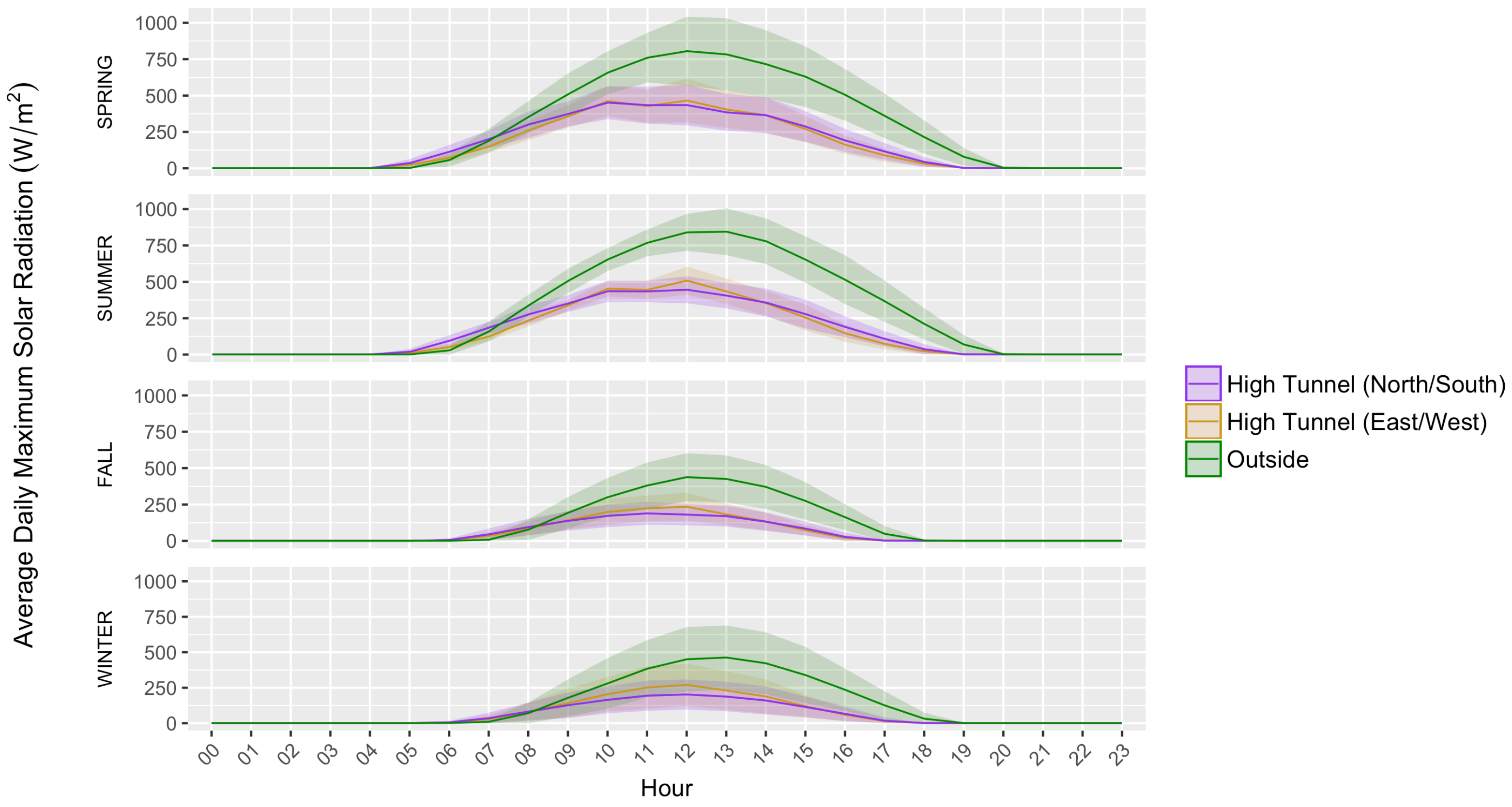

Fig. 1. Hourly average of solar radiation at DFI. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

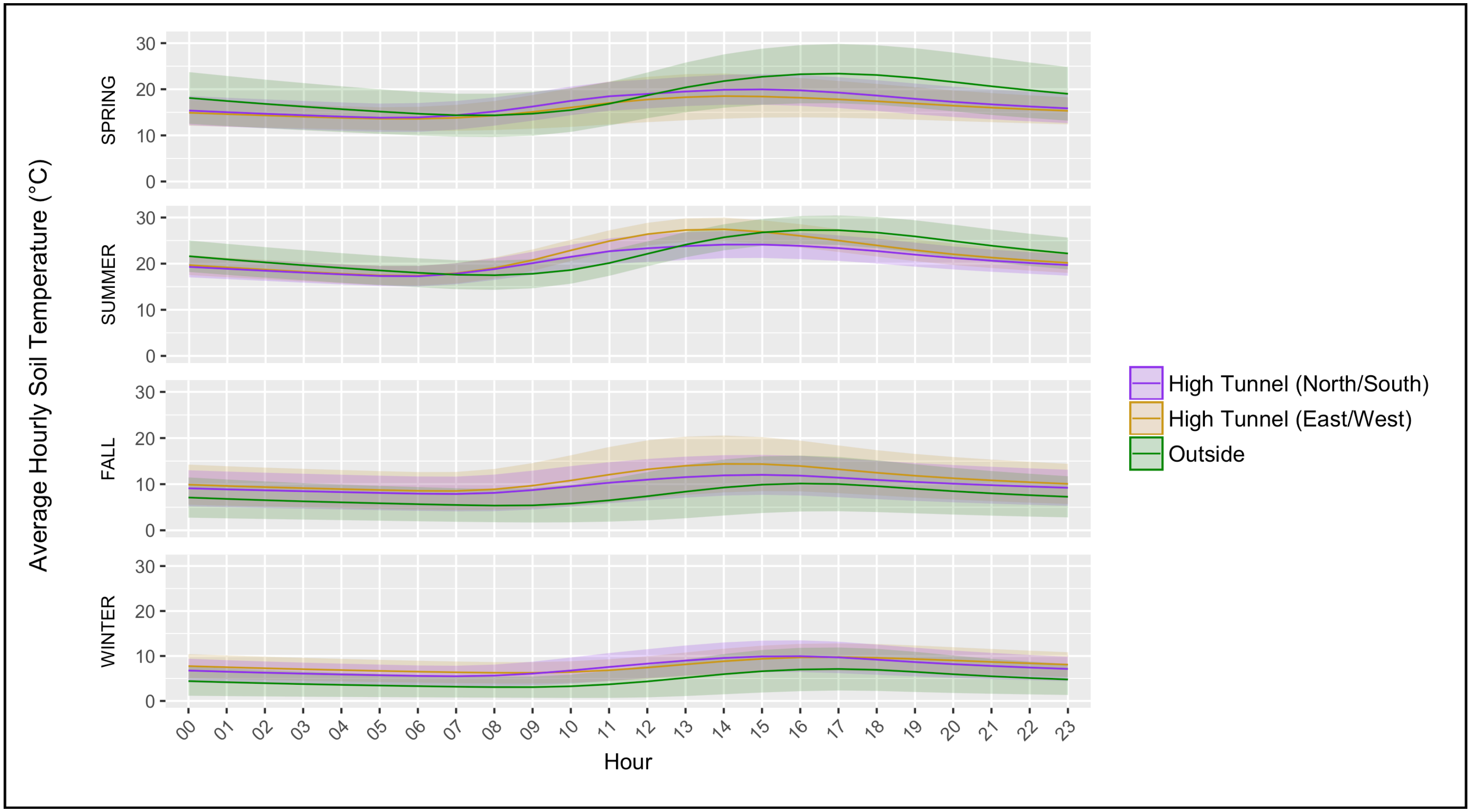

Fig. 2. Hourly average of soil temperature at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

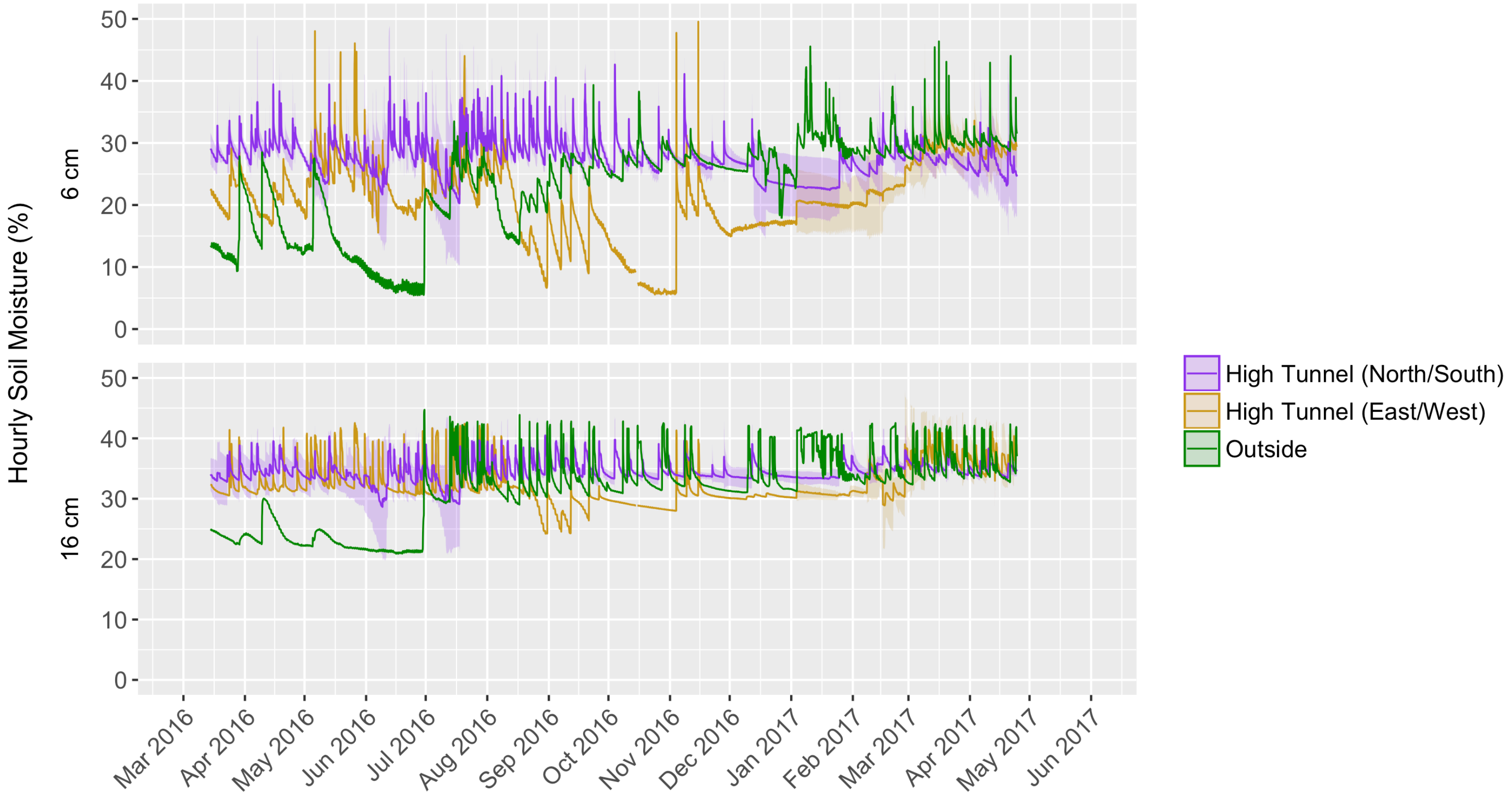

Fig. 3. Hourly soil moisture at DFI. Shading shows the standard deviation across sensor. The outside plot had no replicate. The East/West high tunnel had replicates only for January through April due to sensor and high tunnel failures.

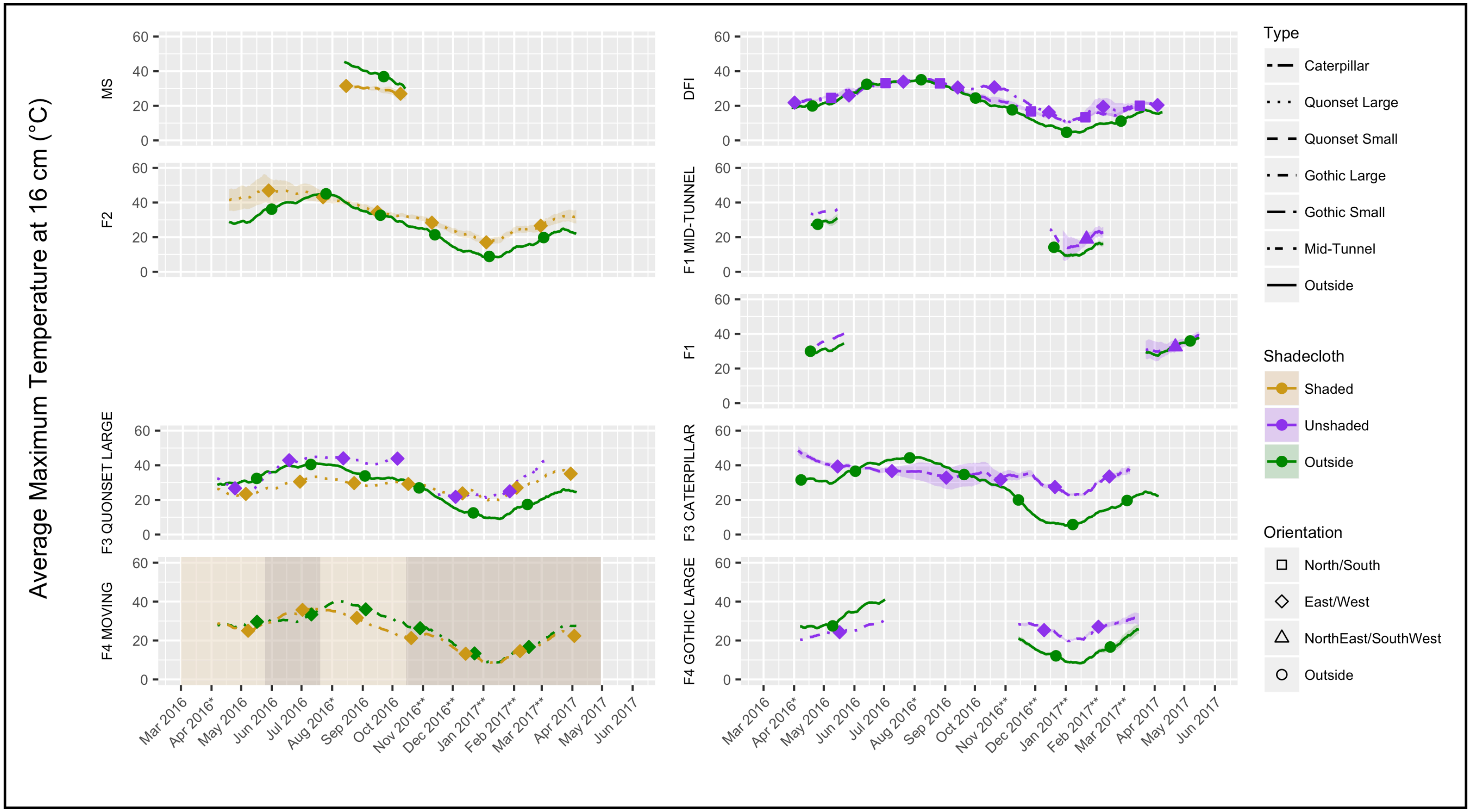

Fig. 4. The 31-day moving average of maximum air temperature at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

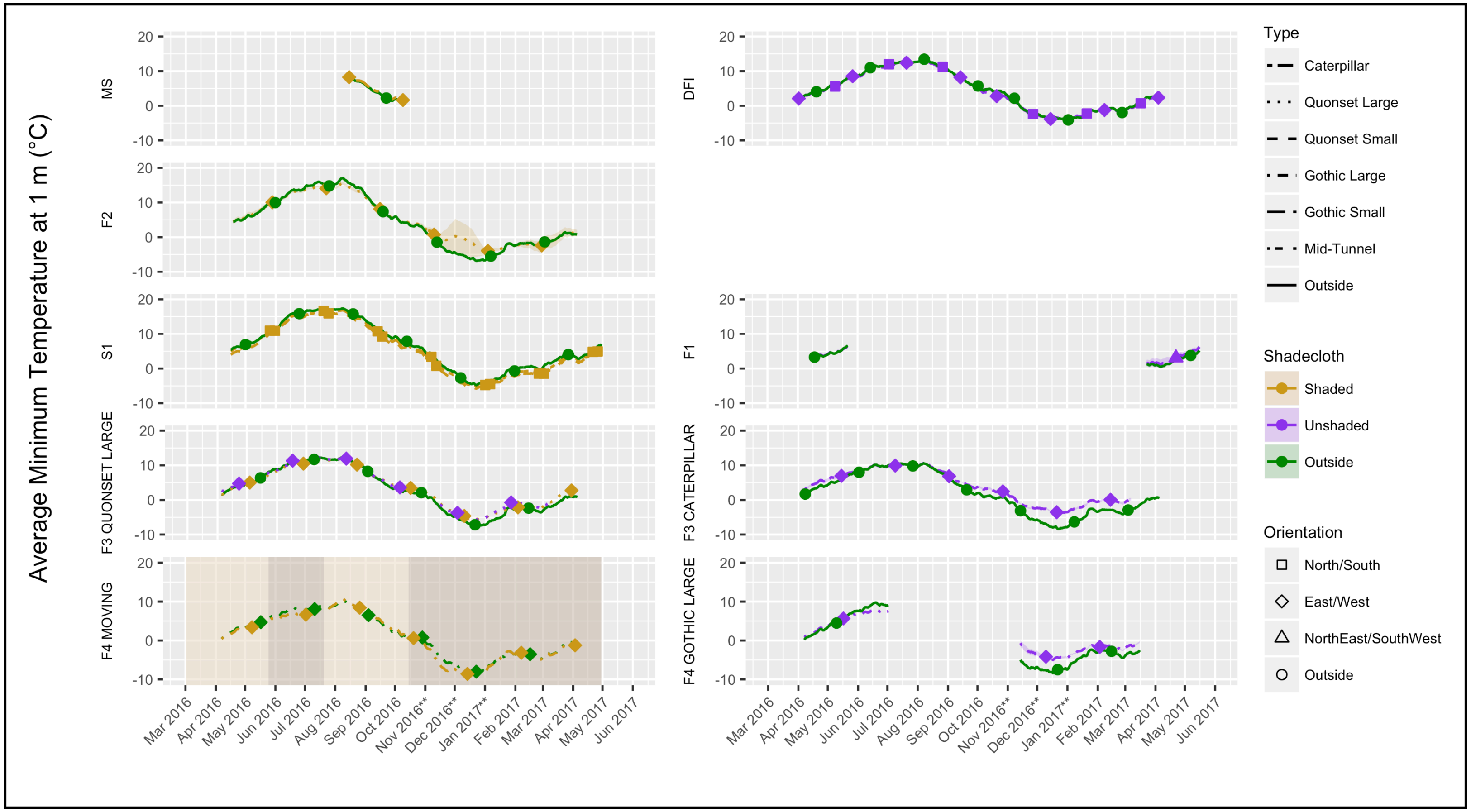

Fig. 5. The 31-day moving average of minimum air temperature at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

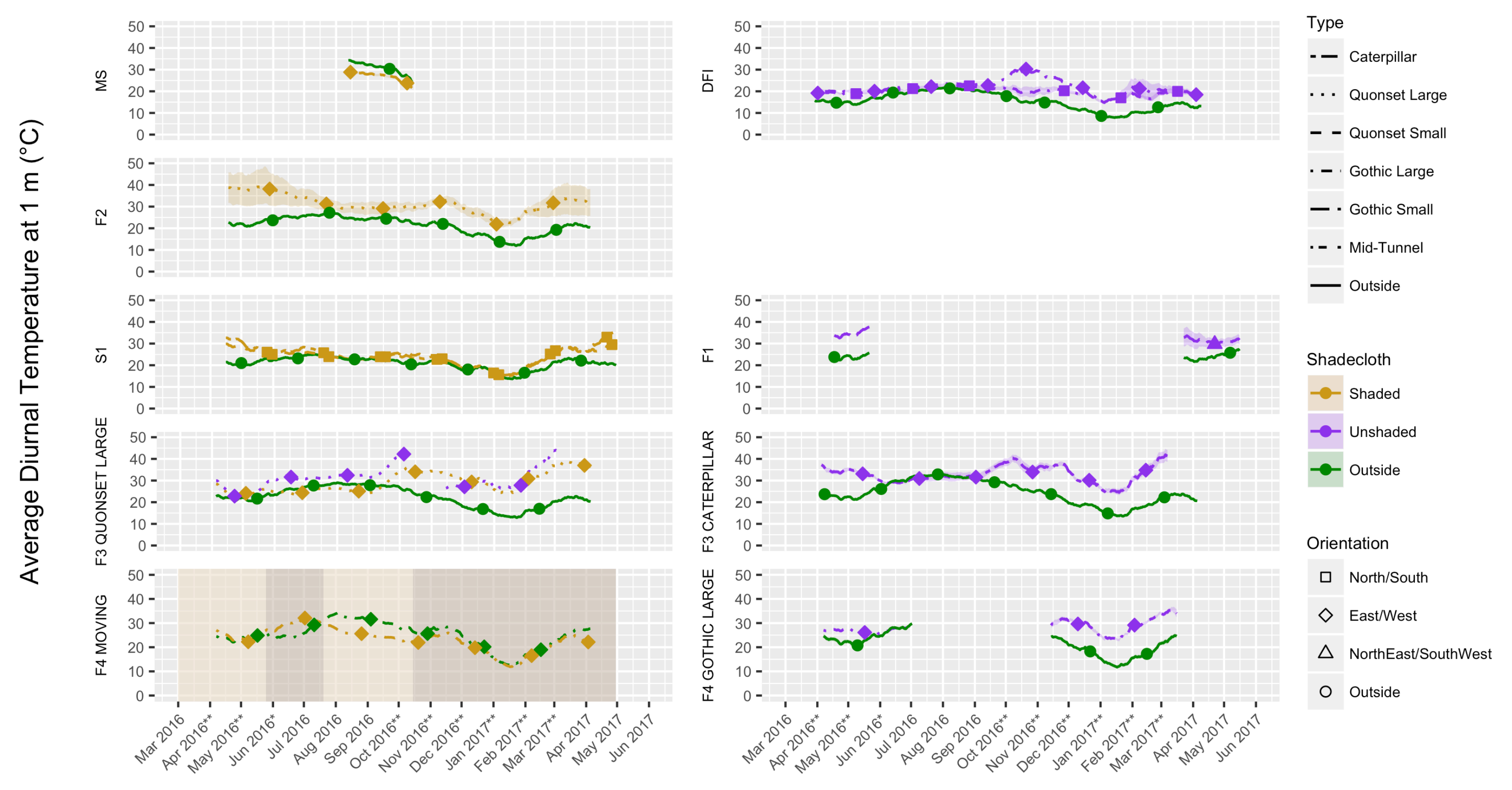

Fig. 6. The 31-day moving average of diurnal air temperature at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

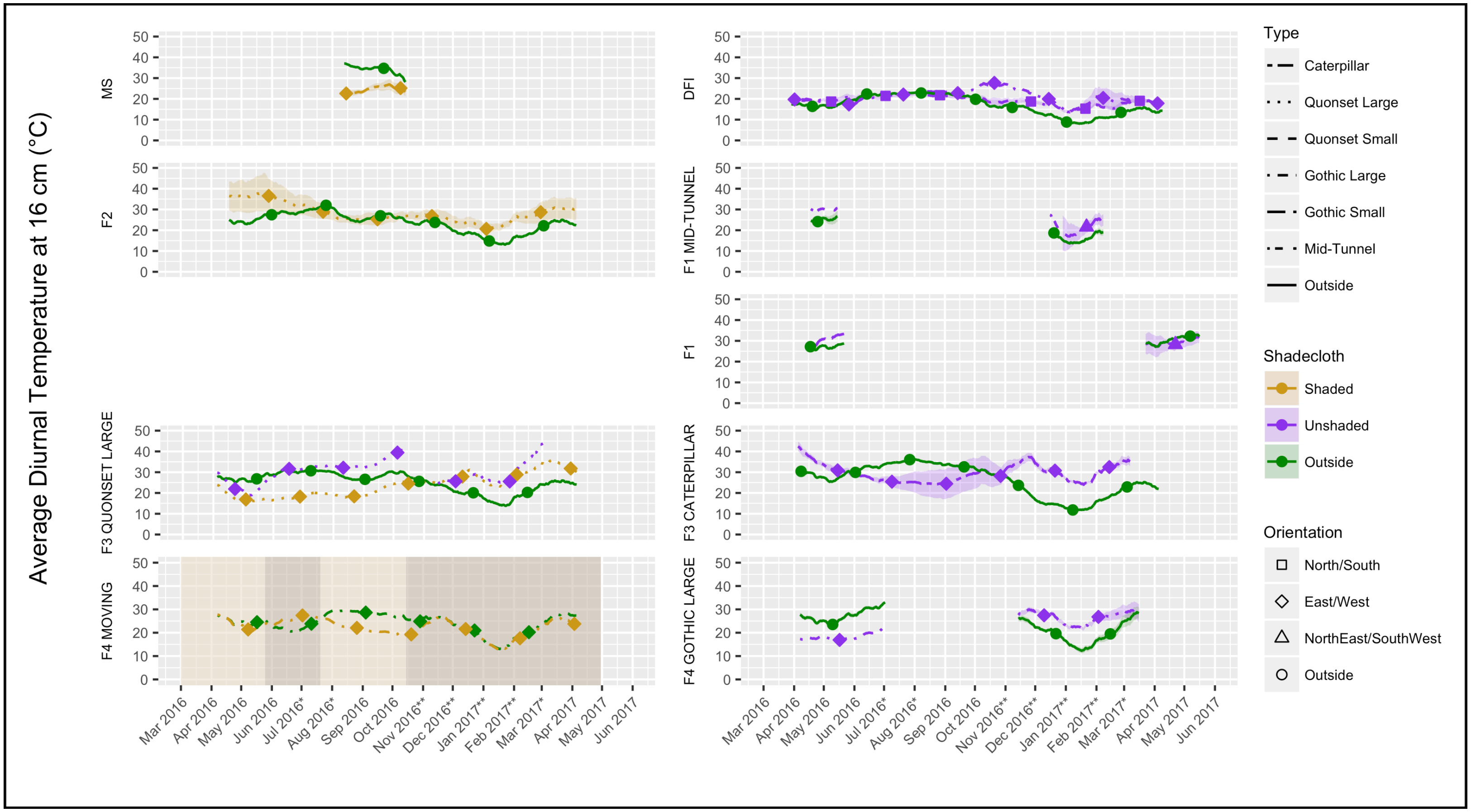

Fig. 7. The 31-day moving average of diurnal air temperature at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

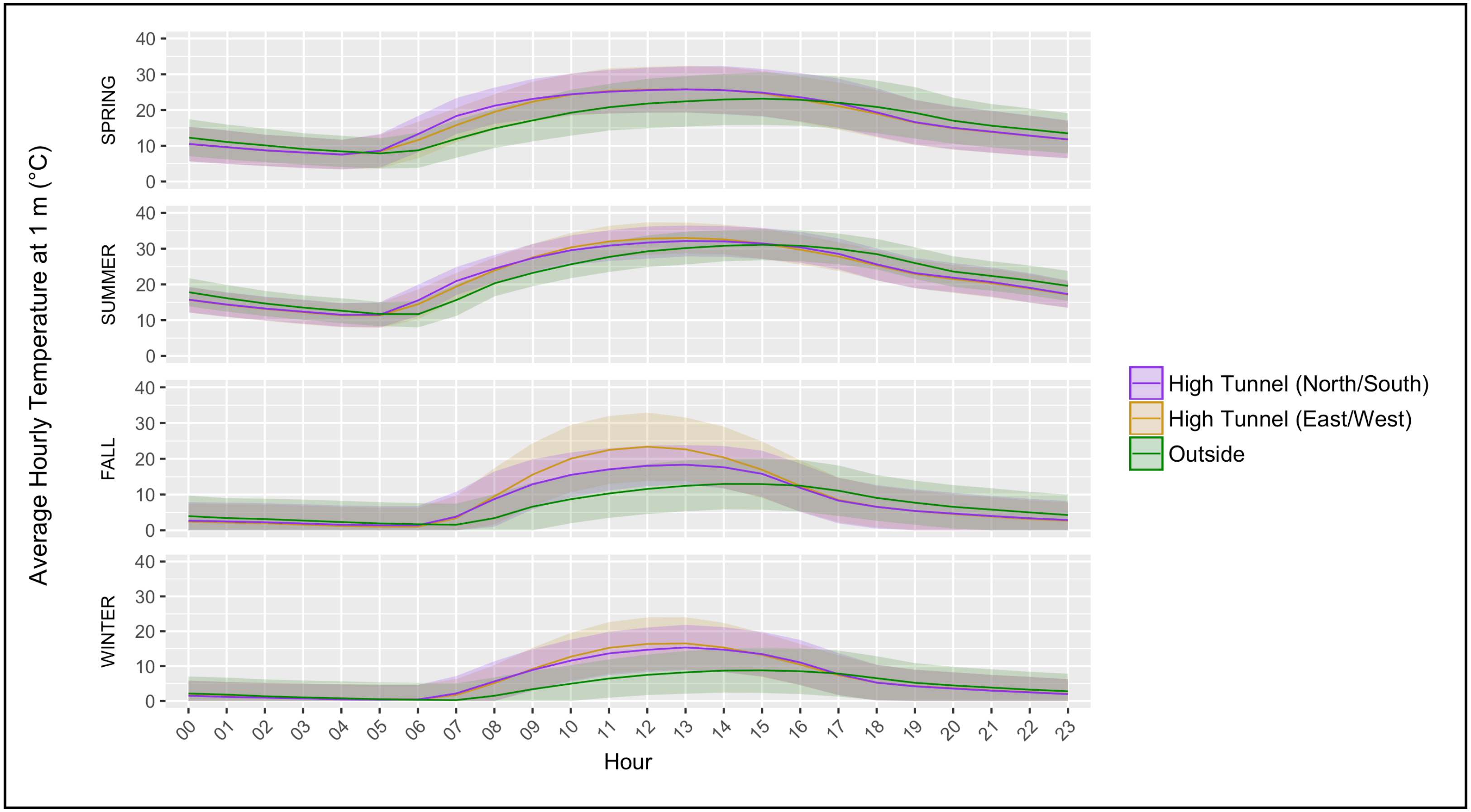

Fig. 8. Hourly average of air temperature at 1 m at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

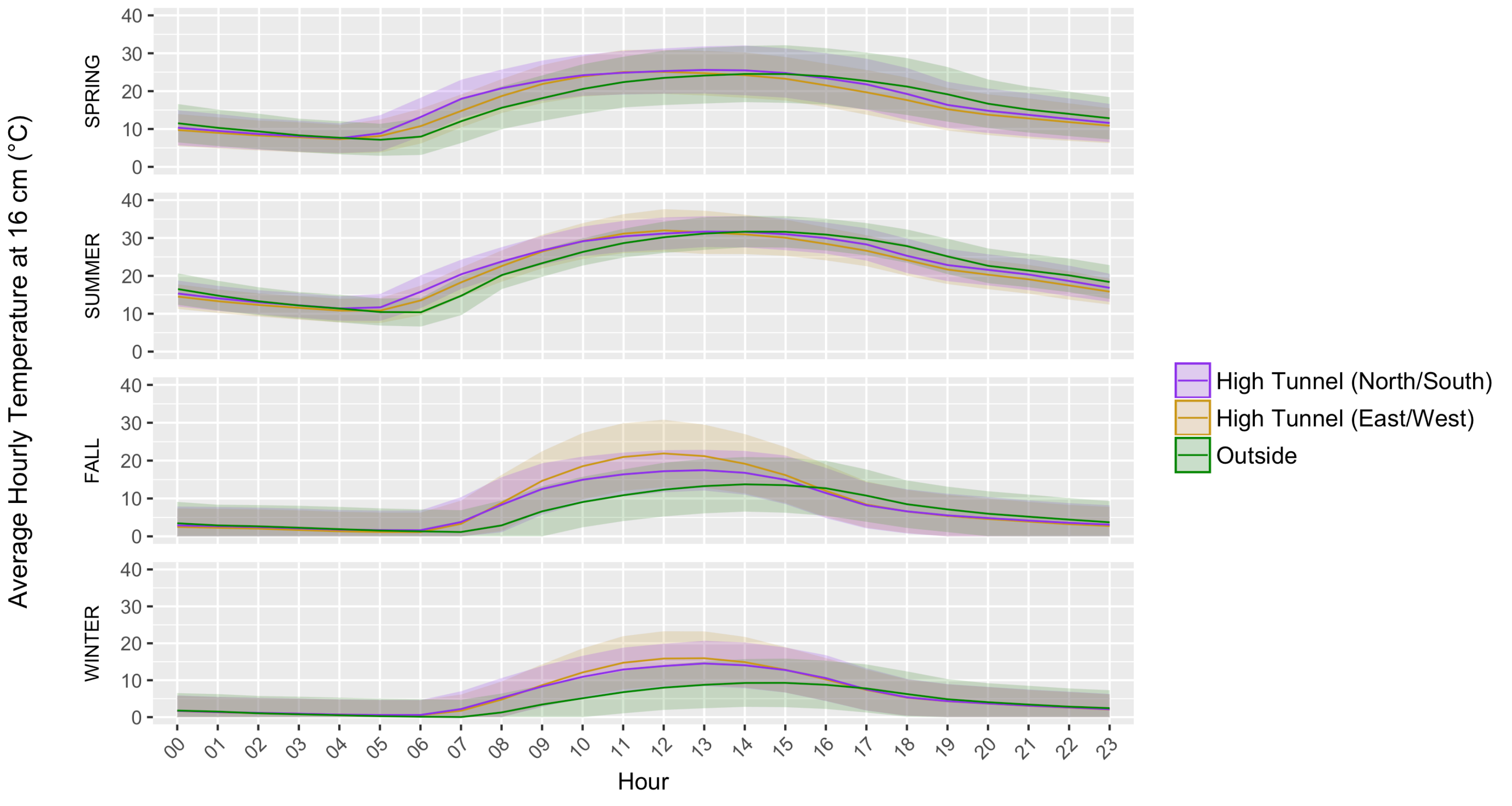

Fig. 9. Hourly average of air temperature at 16 cm at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

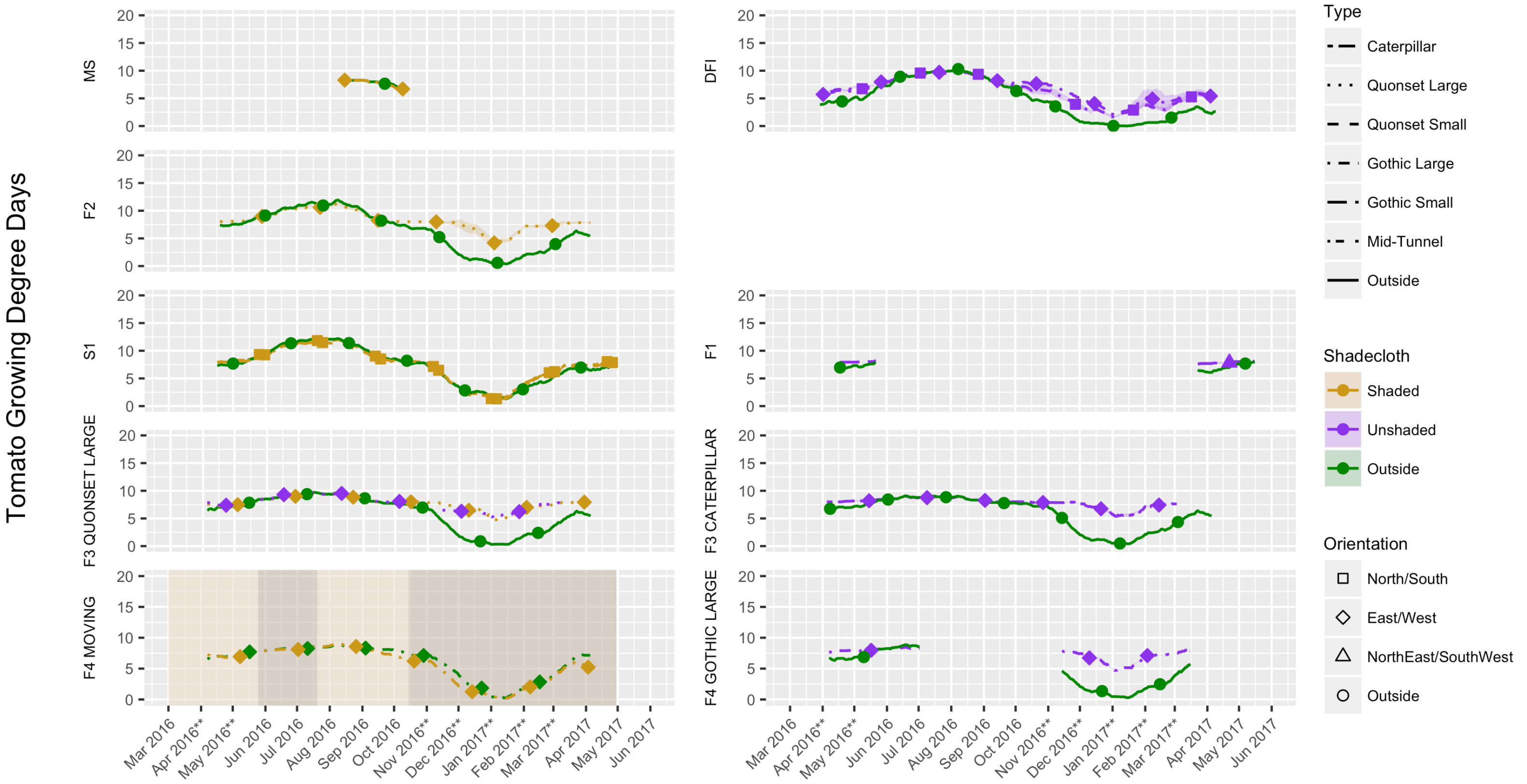

Fig. 10. The 31-day moving average of tomato growing degree days. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

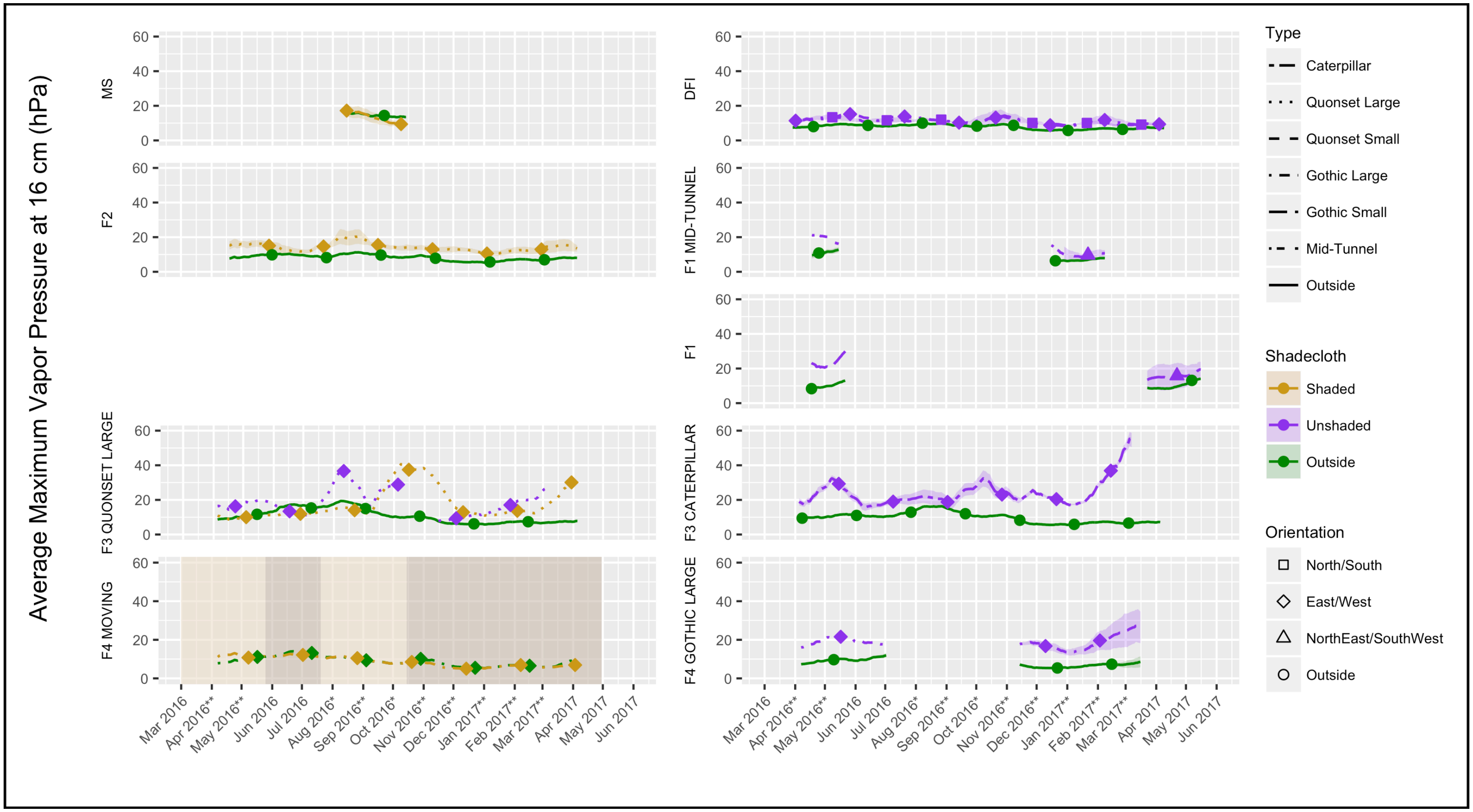

Fig. 11. The 31-day moving average of maximum vapor pressure at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

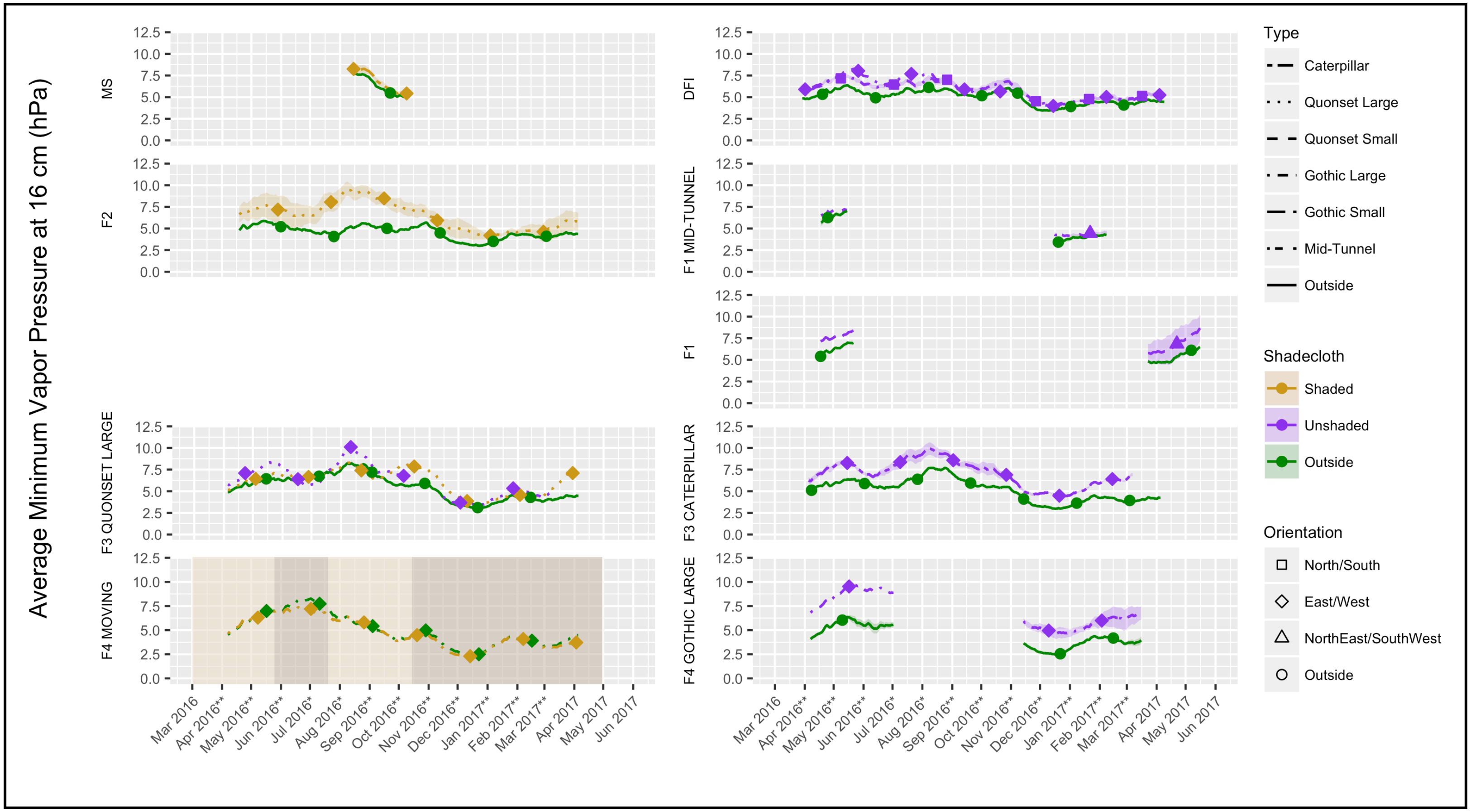

Fig. 12. The 31-day moving average of minimum vapor pressure at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

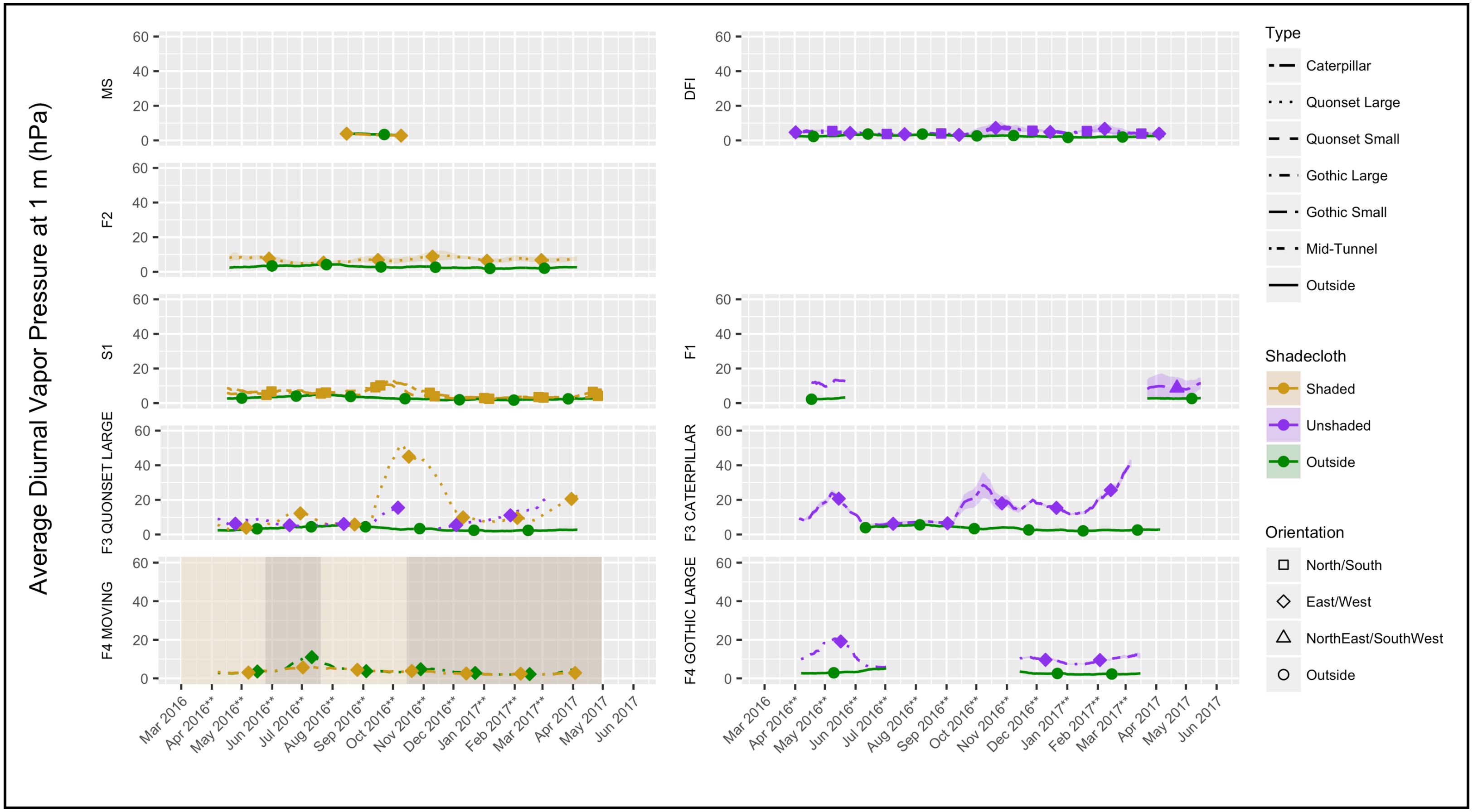

Fig. 13. The 31-day moving average of diurnal vapor pressure at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

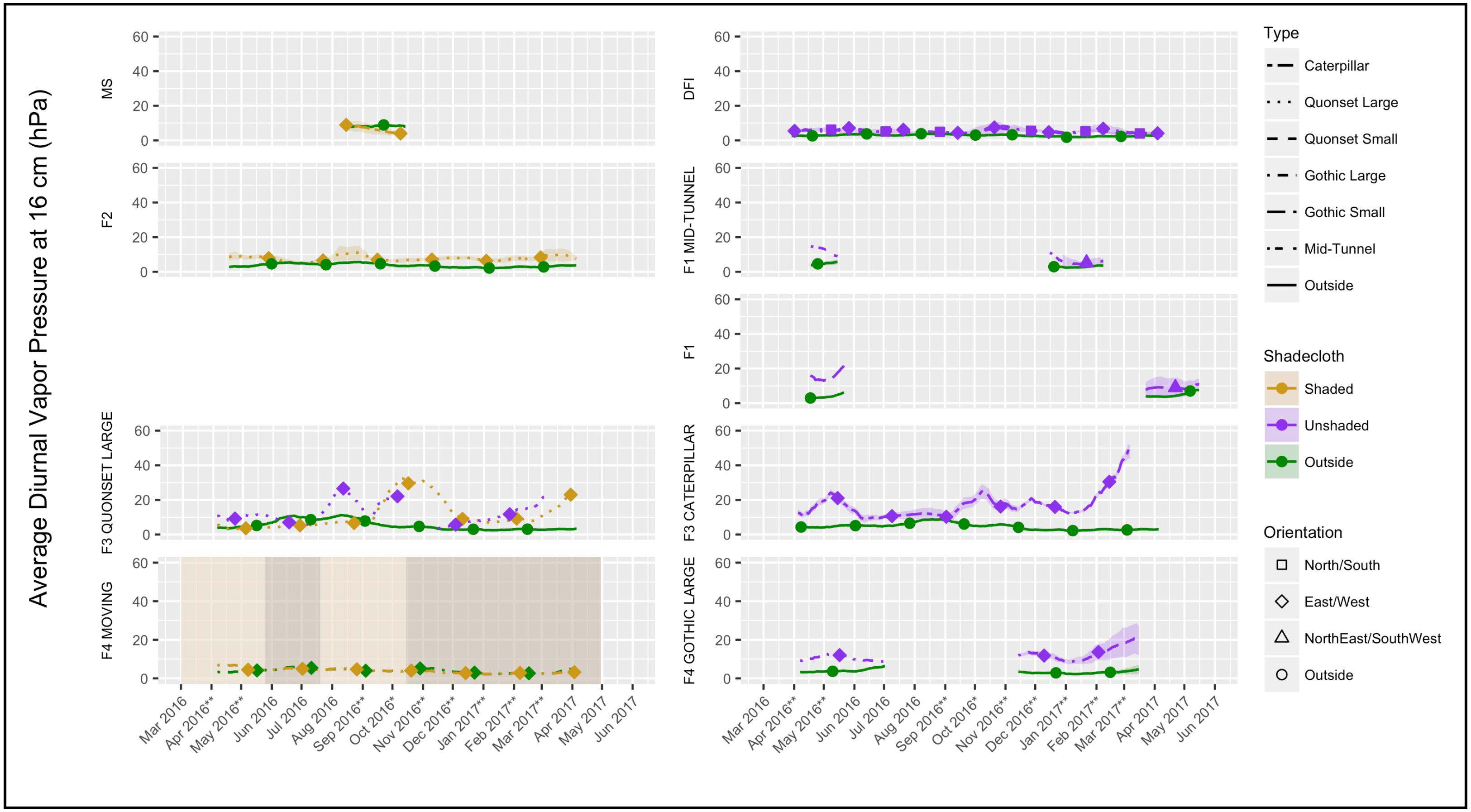

Fig. 14. The 31-day moving average of diurnal vapor pressure at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

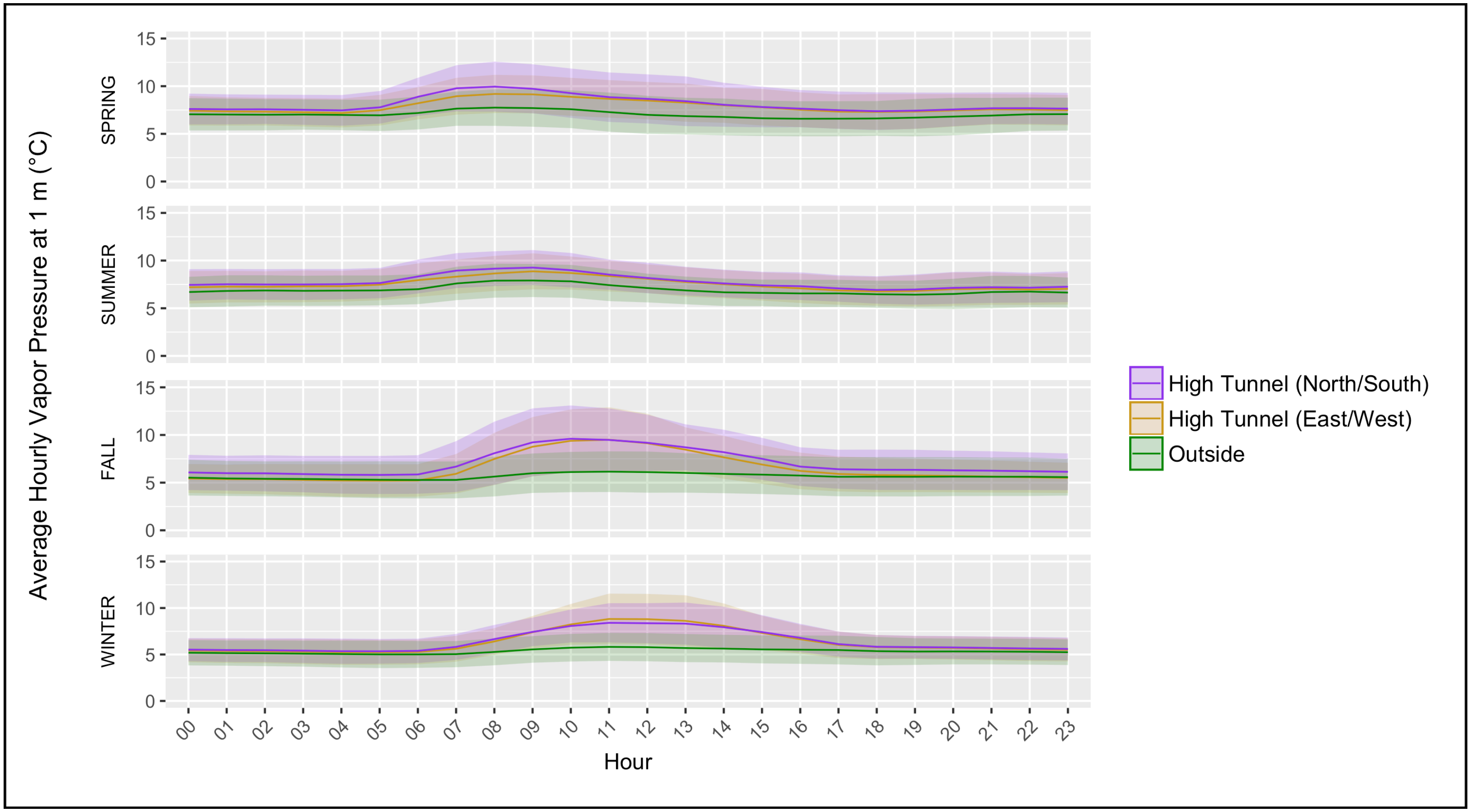

Fig. 15. Hourly average of vapor pressure at 1 m at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

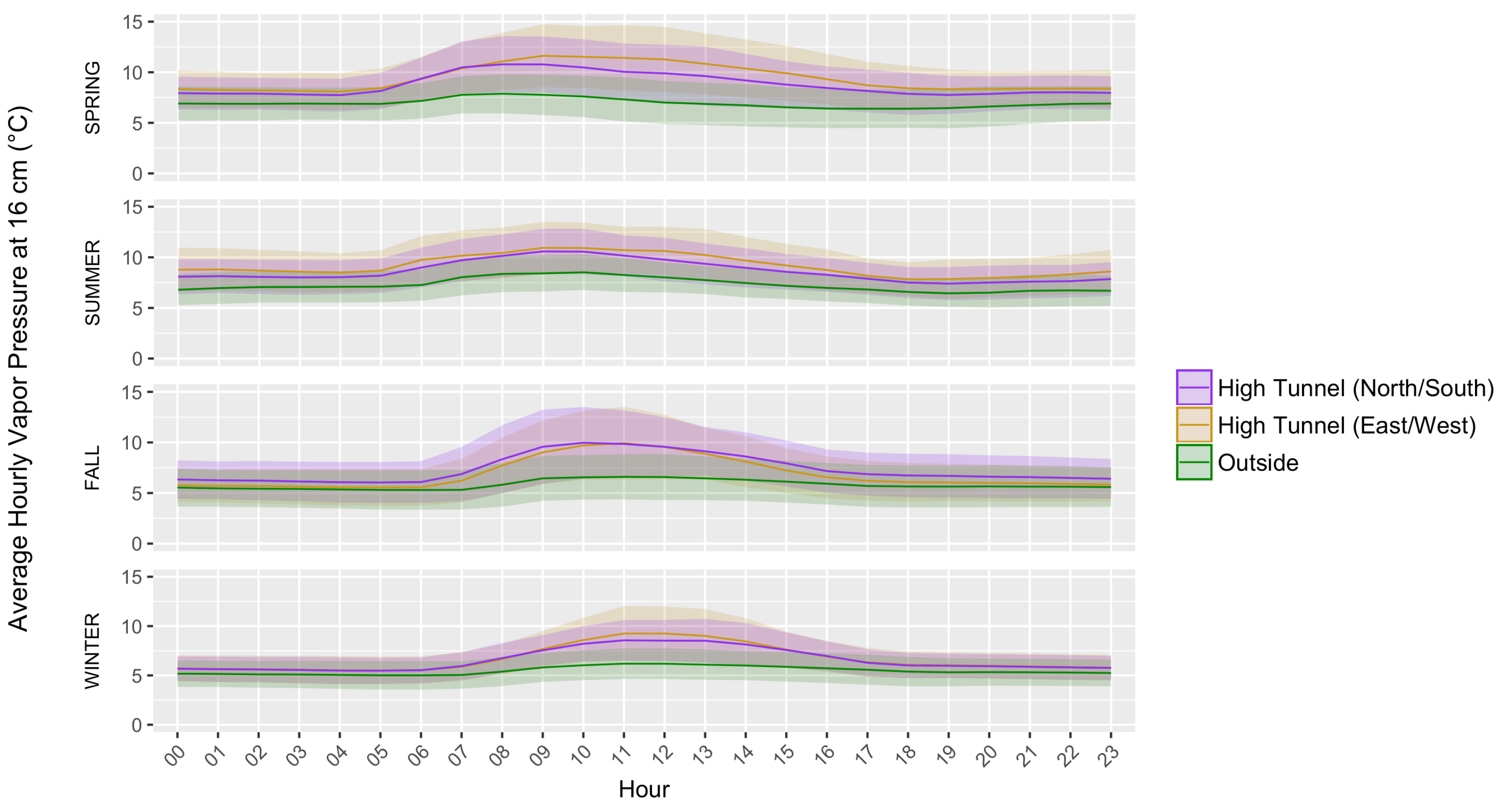

Fig. 16. Hourly average of vapor pressure at 16 cm at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

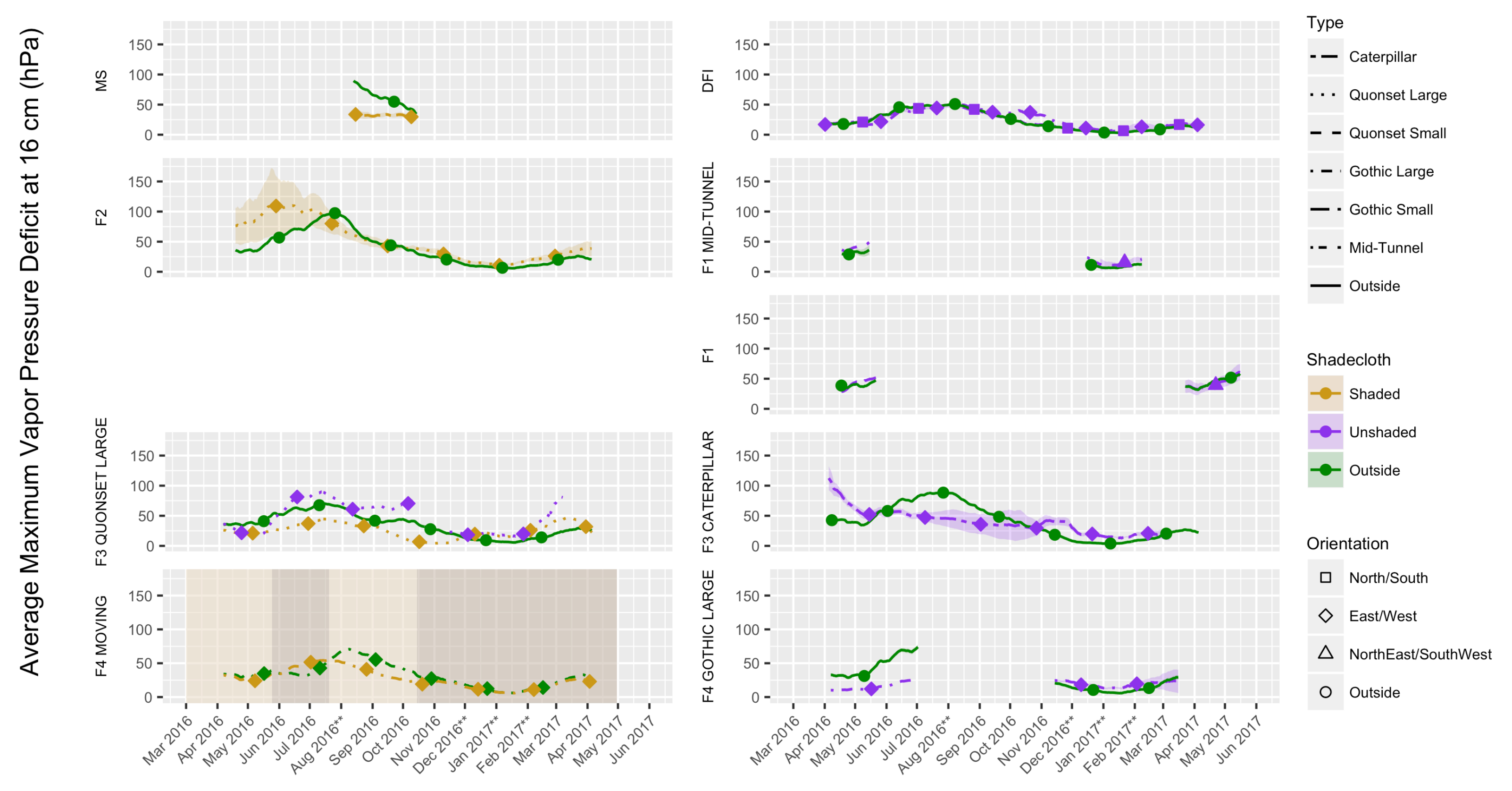

Fig. 17. The 31-day moving average of maximum vapor pressure deficit at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

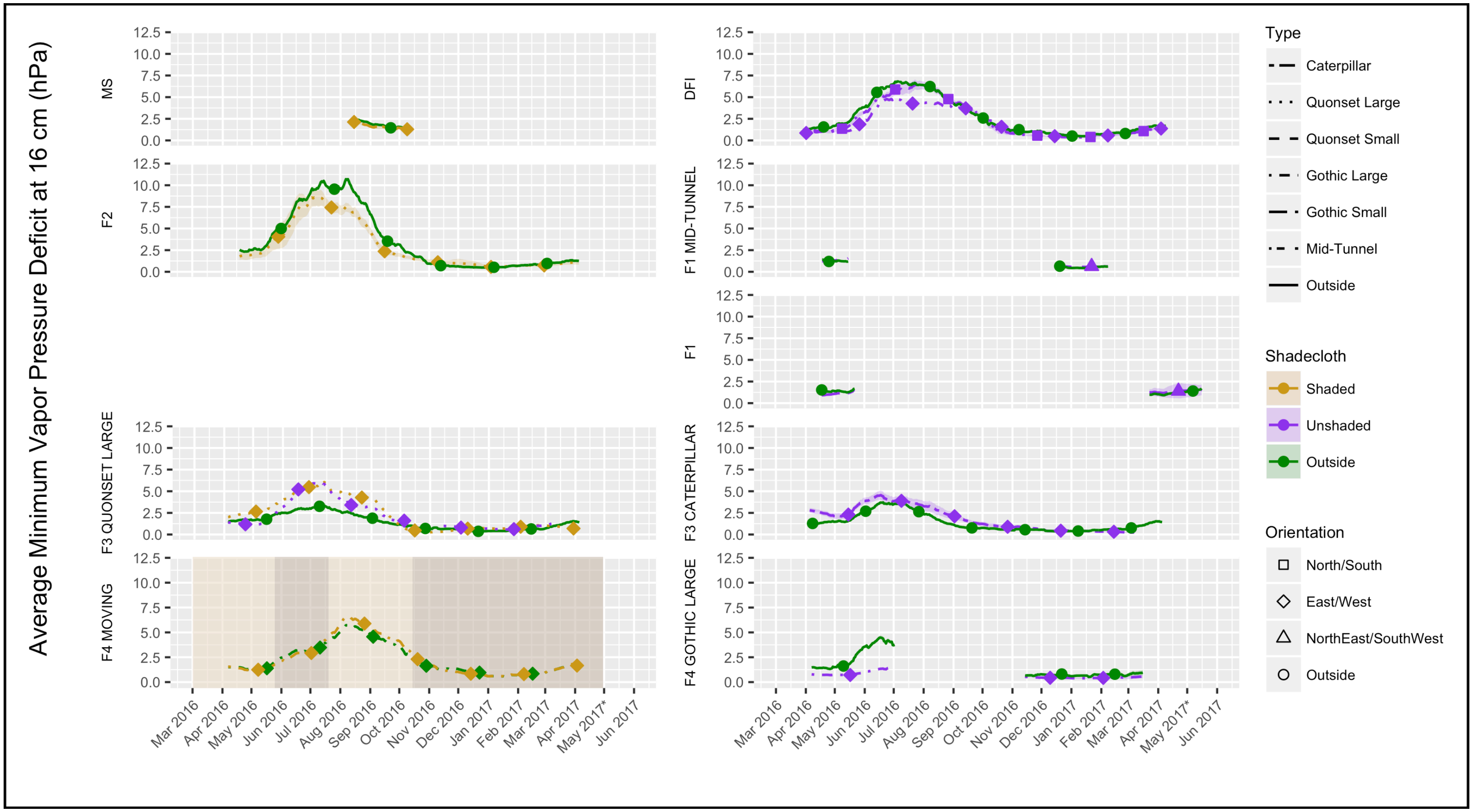

Fig. 18. The 31-day moving average of minimum vapor pressure deficit at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

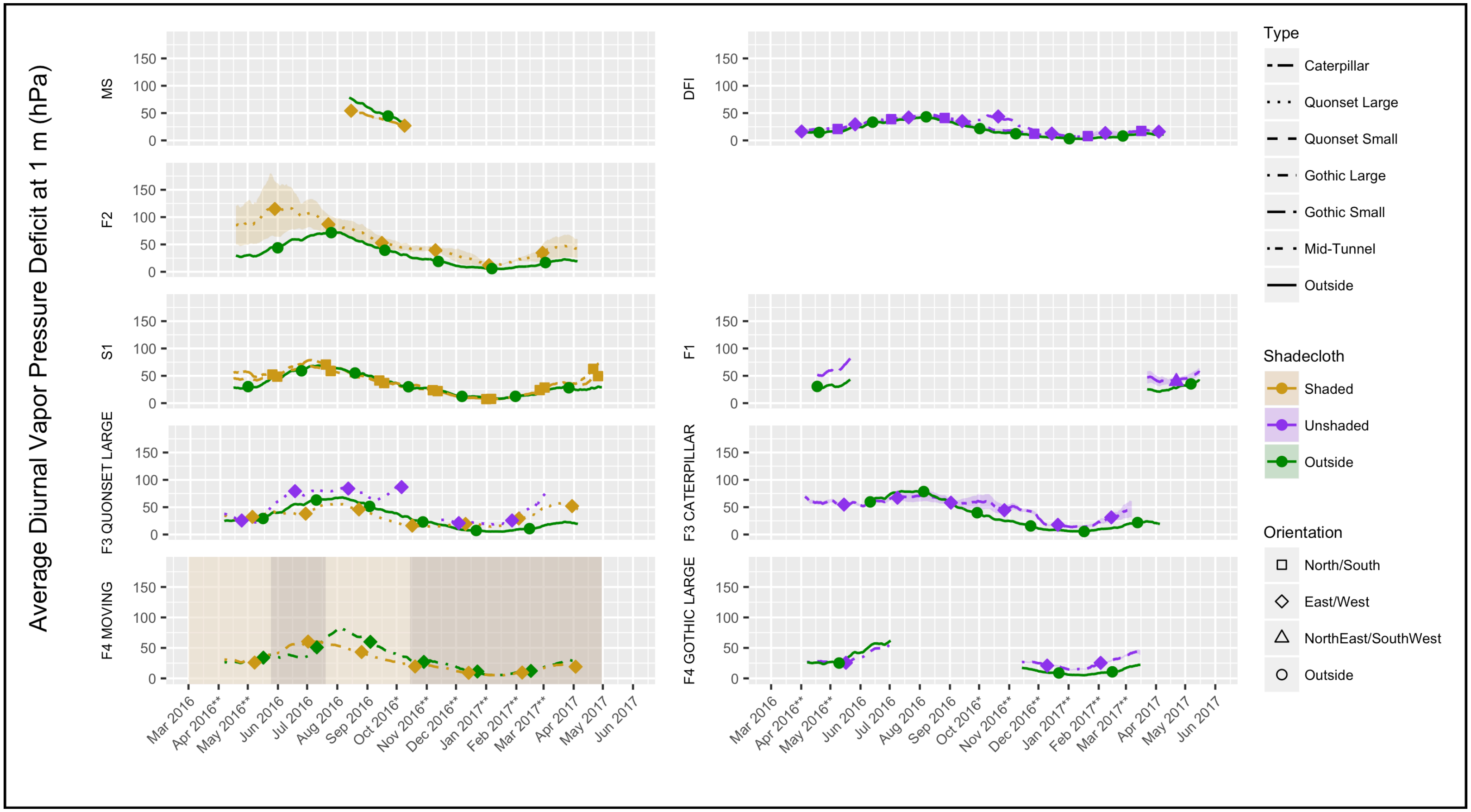

Fig. 19. The 31-day moving average of diurnal vapor pressure deficit at 1 m. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

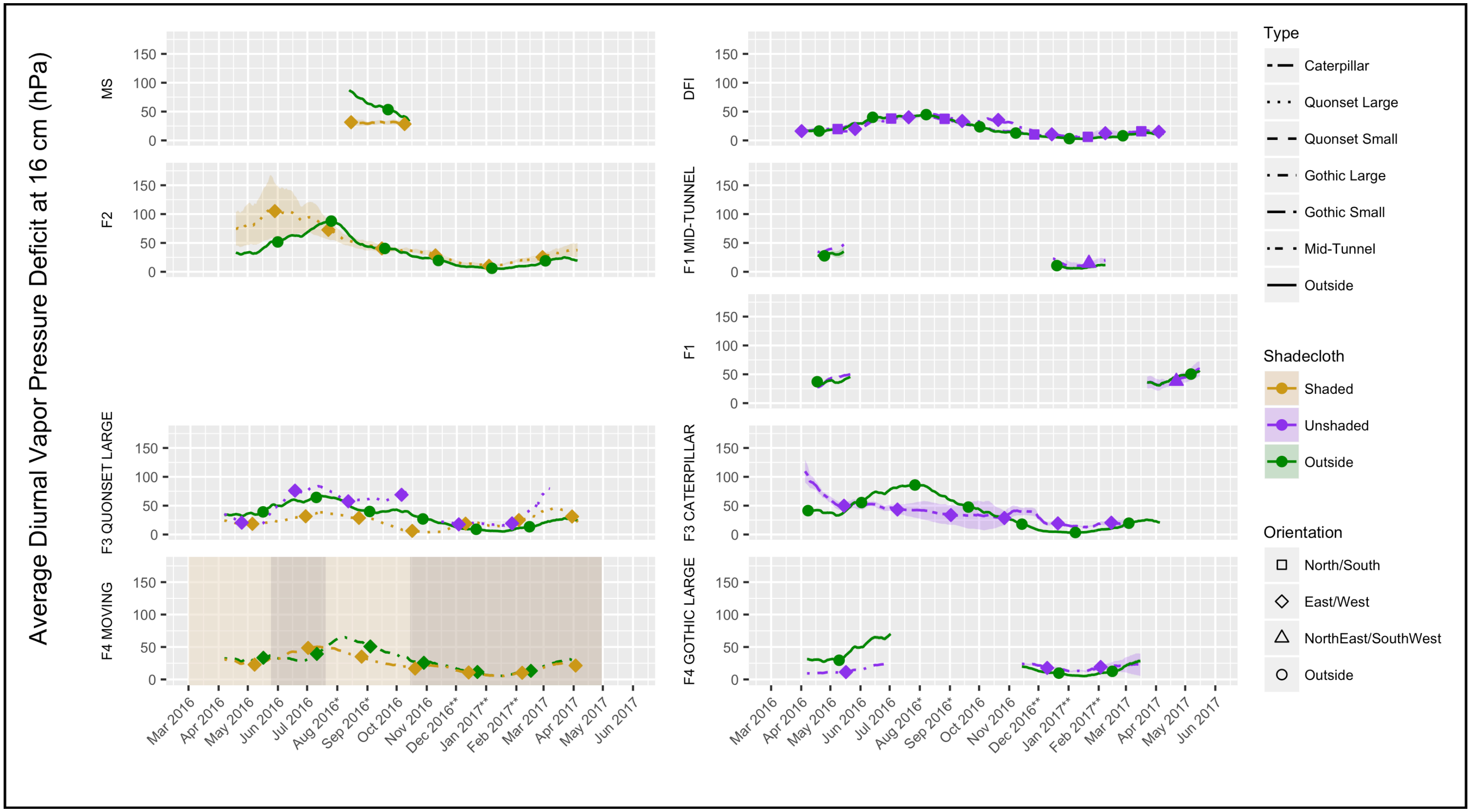

Fig. 20. The 31-day moving average of diurnal vapor pressure deficit at 16 cm. Values are plotted against the center date. Two HTs with the same construction, similar crops and management were averaged together. Shading shows the standard deviation across HTs. DFI temperature data were collected with a different sensor in a different type of shielding, so they are not directly comparable to other farms. Farm 4 HT moves are indicated by shading. Light tan indicates when the orange line was covered by the HT, while dark tan indicates when the green line was covered by the HT. Dates of moves are approximate. Months with one asterisk indicate a statistical significance of 0.10, and months with two indicate a statistical significance of 0.05. See Table 7 for further details and a description of y-axis codes.

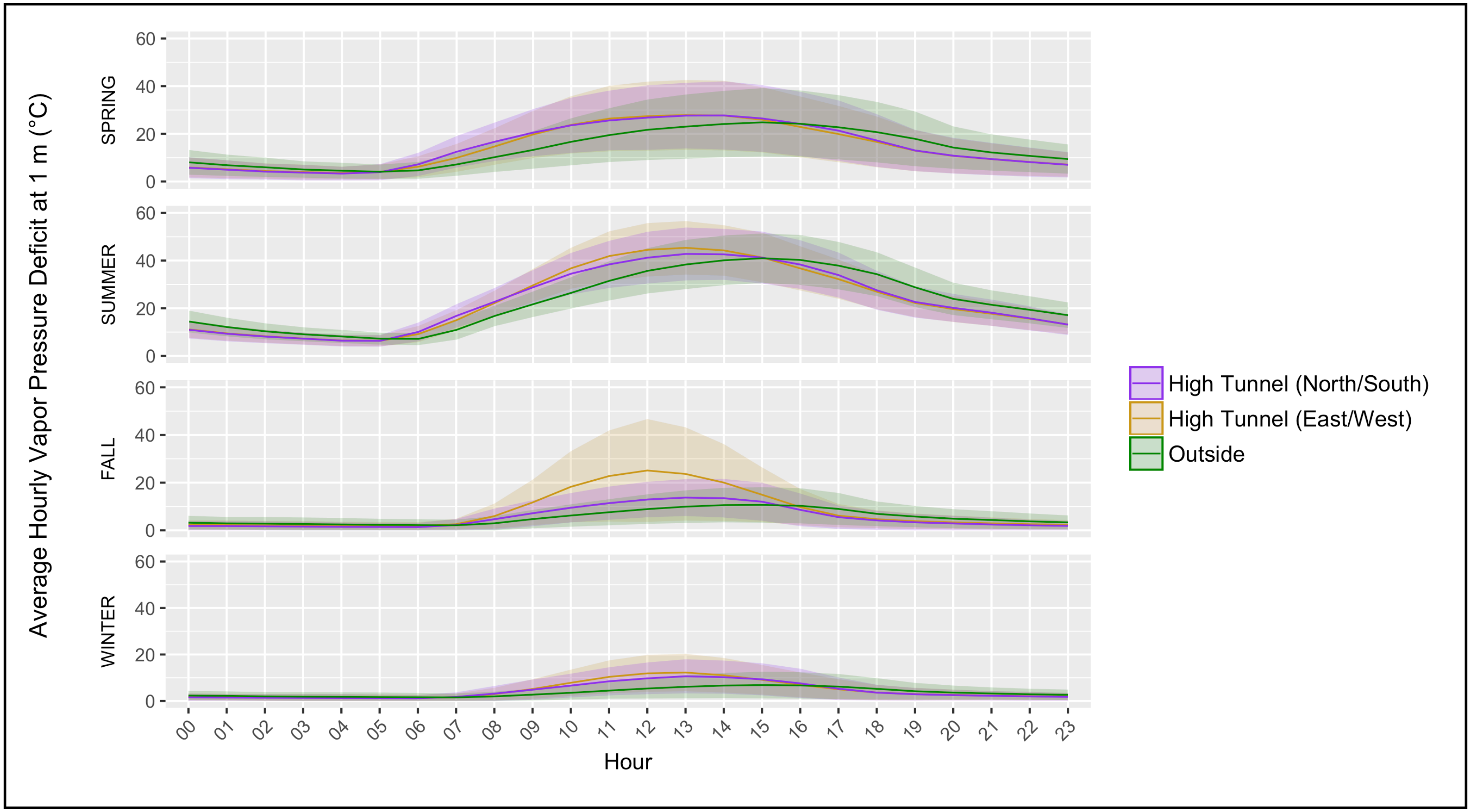

Fig. 21. Hourly average of vapor pressure deficit at 1 m at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

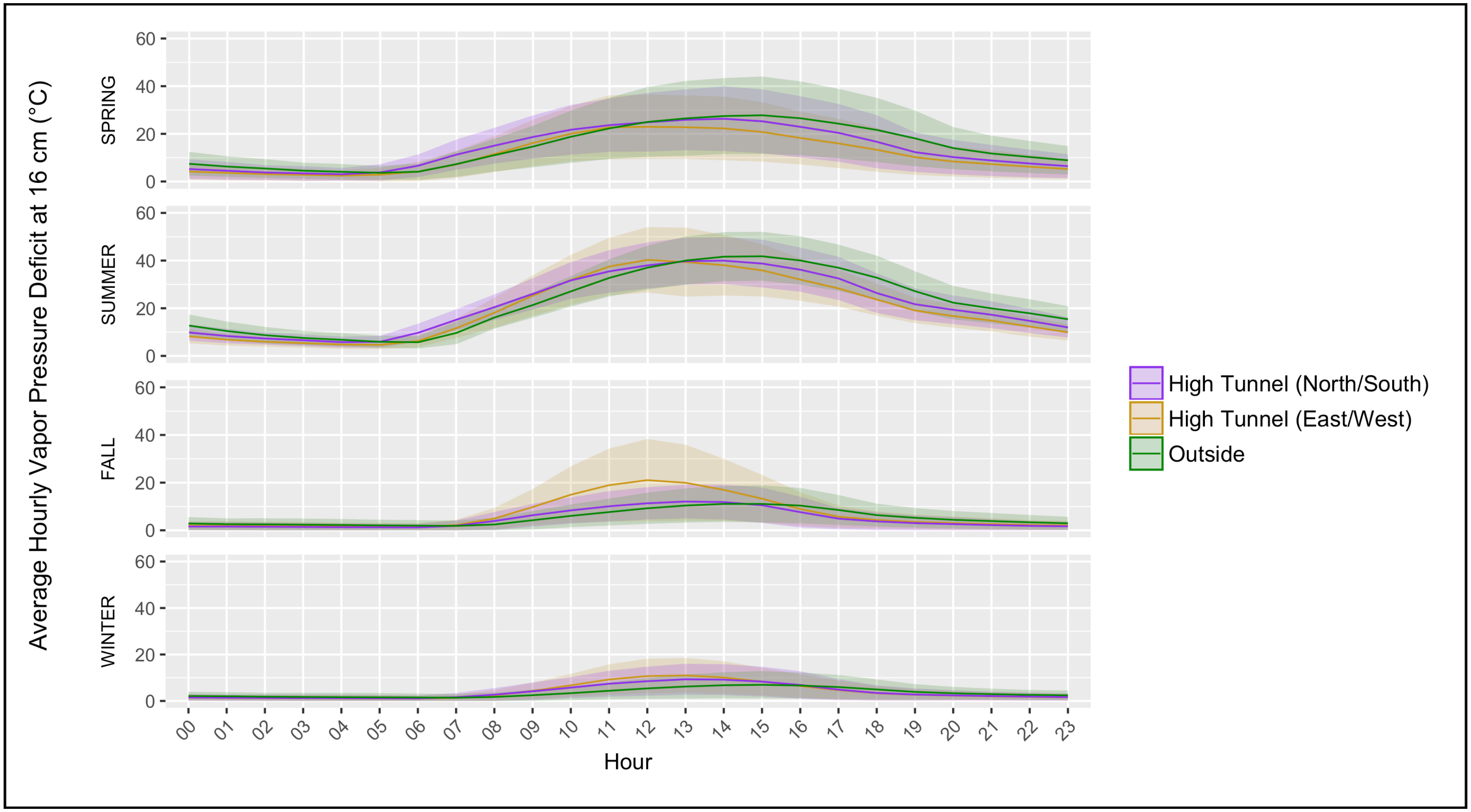

Fig. 22. Hourly average of vapor pressure deficit at 16 cm at DFI. Values are plotted against the center date. Shading shows the standard deviation across sensor and day. Standard deviation has been truncated at zero. Winter is January, February and March. Fall is October, November and December. Summer is July, August and September. Spring is April, May and June.

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