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Climate Modification Using High Tunnels in Western Nevada

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Growers in the high desert are increasingly turning to high tunnels or hoop houses to extend their production season and protect their plants. This study reports on how high tunnels alter the temperature, wind and solar radiation experienced by plants in northwestern Nevada.

Summary

Farmers in the Great Basin are investing in inexpensive low-tech greenhouses, known as high tunnels, but little is known about how high tunnels alter the climate conditions that crops experience inside of high tunnels. We examined the effect of high tunnels on temperature, humidity—as measured by vapor pressure deficit (VPD)—wind speed and solar radiation by measuring each variable inside and outside of high tunnels for a full year. Maximum temperatures were higher inside high tunnels than outside in spring, autumn and winter, when they were not vented. However, high tunnels did little to increase minimum temperatures, and we occasionally measured colder minimum temperatures inside the high tunnel than outside. Because high tunnels were effective in raising daytime temperatures but did not always moderate nighttime temperatures, crops inside the high tunnels could experience larger daily swings in temperature than those outside of a high tunnel, except very near the soil surface. Vapor pressure deficit patterns were similar to temperature, with higher vapor pressure deficits (lower relative humidity) inside high tunnels during the day owing to warm temperatures. High tunnels reduced the amount of solar radiation compared to outside. The degree of reduction varied seasonally, with larger decreases in the summer. Wind speeds were substantially reduced, even when the high tunnels were partially vented. Despite high tunnels not increasing minimum temperatures relative to outdoor plots, they have the potential to extend the growing season and increase the number of crops grown in the high desert by increasing maximum temperatures during the cooler seasons of the year. They may also be effective in reducing radiation and wind damage.

Figure 1. Crops inside a high tunnel at the Desert Farming Initiative in Reno, Nevada. Photo credit: S. Heckler.

What are high tunnels and why do growers use them?

High tunnels, like that shown in Figure 1, are single or multi-bay greenhouse-like structures, usually unheated and covered by one or two layers of greenhouse plastic film, in which temperature and humidity are managed by some combination of roll-up side vents, end-wall vents and fans. The type of structure varies by location, based on the farmers' needs and local climate concerns, such as wind, rain and snow load (Blomgren and Frisch, 2007; Lamont et al., 2002). In the United States, high tunnel adoption has increased as local food movements across the country have led to greater demand for fresh, local produce (Carey et al., 2009). In general, high tunnels are used for growing high-value specialty crops, such as berries, tree fruit, cut flowers and a wide variety of vegetables (Lamont, 2009). Although research results and educational resources about growing crops in high tunnels are available (Carey et al., 2009), additional 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) as high tunnels grow in popularity.

One of the main proposed benefits of high tunnels is the ability to manipulate the microclimate, the climate conditions immediately around the plants, to improve crop growth. Because most high tunnels use passive heating and cooling, they are highly influenced by local climatic conditions and management practices. In particular, high tunnels have grown in popularity in places with short and variable growing seasons, such as high deserts. Most high tunnel research has focused on crop growth and yield, so little information is available comparing microclimates inside and outside high tunnels, especially in high-desert regions.

Research in other environments

Although relatively few researchers have undertaken comprehensive assessments designed to compare multiple aspects of the microclimates inside and outside of high tunnels, numerous studies tracking crop growth or insect, pest and pathogen activity measured some aspects of microclimate. All of the studies reviewed showed that high tunnels reduce solar radiation (Borrelli et al., 2013; Both et al., 2007; Bumgarner et al., 2012; Cowan et al., 2014; Lang, 2009; Lang 2014; Lang et al. 2011; Olberg and Lopez, 2016; Owen et al., 2016; Reiss et al., 2004; Rom et al., 2010; Thompson et al., 2009; Zhao and Carey, 2009) and wind speed (Cowan et al., 2014; Lang, 2009; Wallace et al., 2012; Zhao and Carey, 2009) within the high tunnel relative to outside of the high tunnel.

Despite reductions in the amount of solar radiation, most studies have documented higher maximum temperatures inside high tunnels than outside (Cowan et al., 2014; Gent, 2002; Gu et al., 2017; Kadir et al., 2006; Lang, 2014; O'Connell et al., 2012; Ogden and van Iersel, 2009; Ogden et al., 2011; Rader and Karlsson, 2006; Rogers and Wszelaki, 2012; Rogers et al., 2016; Shiwakoti et al., 2016; Vescera and Brown, 2016; Wallace et al., 2012; Zhao and Carey, 2009; Zhao et al., 2014). In the few cases where maximum or daytime temperatures were not higher in high tunnels than surrounding areas, it was typically because the high tunnel was covered with shade cloth (Rowley et al., 2011; Zhao and Carey, 2009). Two studies focused on winter or spring, however, found conditions within high tunnels to be similar (Santos and Salame-Donoso, 2012) or even cooler (Wallace et al., 2012) than outside.

The effect of high tunnels on minimum temperatures was not as clear. A number of studies documented higher minimum temperatures inside than outside of high tunnels, although many of those increases were relatively modest (Both et al., 2007; Cowan et al., 2014; Gent, 2002; Gu et al., 2017; Kadir et al., 2006; Martin and Sideman, 2012; O'Connell et al., 2012; Rader and Karlsson, 2006; Rowley et al., 2014; Santos and Salame-Donoso, 2012; Santos et al., 2014; Shiwakoti et al., 2016; Ward and Bomford, 2013; Zhao and Carey, 2009; Zhao et al., 2014). A substantial minority of studies, however, found that temperatures inside high tunnelss were similar to or even cooler than outside of the structures (Ogden and van Iersel, 2009; Ogden et al., 2011; Rogers and Wszelaki, 2012; Rogers et al., 2016; Vescera and Brown, 2016; Vescera and Brown 2011; Wallace et al., 2012).

Although there has been extensive work on the topic of high tunnel microclimates, little research has targeted the use of high tunnels in high- or cold-desert environments. Moreover, microclimatic monitoring in those environments appears to be accessory to production evaluations in the few available studies. For example, Rowley et al. (2011) measured air temperature as part of a study evaluating strawberry success inside and outside of high tunnels in northern Utah. Likewise, Shiwakoti et al. (2016) monitored high tunnel air temperature as part of a study focused on the yield and quality of several common kitchen herbs in Wyoming. Winter air temperatures inside and outside of high tunnels in Idaho and eastern Washington were presented as supporting information for research focused on the growth of salad and cooking greens (Borrelli et al., 2013). Wallace et al. (2012) conducted a study on lettuce production using high tunnels located in Lubbock, Texas, which is arid, but substantially warmer than western Nevada. Consequently, this is one of the first studies documenting the results of comprehensive microclimate monitoring within high tunnels in the Intermountain West. The objective of our study was to examine temperature, vapor pressure deficit (VPD), wind speed and solar radiation inside and outside high tunnels in the Great Basin region of western Nevada to provide baseline information about the impact of high tunnels on microclimate in the high desert.

Figure 2. Weather stations installed outside (left) and inside (right) high tunnels. Photo credit: S. Heckler.

Research design

We conducted this work at the Desert Farming Initiative (DFI, 39.5384°N, 119.8049°W, elevation 4493 ft.) in the University of Nevada, Reno Experiment Station on Valley Road in Reno, Nevada from March 2016 to April 2017. We used existing gothic-style high tunnels (FarmTek GrowSpan Gothic Premium High Tunnels, Dyersville, Iowa) constructed from triple-galvanized structural steel tubing with a 0.3 mm woven polyethylene fabric covering (PolyMax® 5.2 oz.,12 mil Clear Woven Greenhouse Covering, 85% light transmission when new) and manual roll-up sides. Onset® weather stations (U30-NRC, Bourne, Massachusetts) were installed in two 26-foot by 124-foot high tunnels oriented east-west, two 26-foot by 96-foot high tunnels oriented north-south, and in a nearby outside plot. Crops growing inside the high tunnels at various times during the data collection period were leaf lettuce, carrot, radish, bell pepper and tomato. The farm manager determined fertilizer plans, irrigation scheduling, pest control and planting schedules.

Inside, weather stations were placed in the center crop bed, 12.5 m and 9.8 m from the high tunnel entrances (Figures 1 and 2). Outside, one weather station was located in the center crop bed in the center of the plot (Figure 2). Each weather station had a temperature and relative humidity sensor covered in a solar radiation shield (S-THB-M002, RS3, Bourne, Massachusetts) positioned at 1 m and 16 cm above the soil surface to account for microclimates of crops of differing heights. The sensor recorded temperature with an accuracy of ± 0.2 degrees C and a measurement resolution of 0.02 degrees C between -40 degrees C and 75 degrees C and humidity with an accuracy of ± 2.5% and measurement resolution of 0.1% between 10 and 90%, with accuracies closer to 5% under very dry and very humid conditions. A silicon pyranometer (S-LIB-M003, M-LBB, M-LLA, Bourne, Massachusetts) recorded incoming solar radiation with an accuracy of ± 10 W/m^2. An anemometer (S-WSET-B, M- CAA, Bourne, Massachusetts) measured wind speed with an accuracy of ± 1.1 m/s at approximately 1.5 m. Weather stations recorded measurements every 15 minutes.

Sensors were tested for precision by deploying them for 24 hours in a controlled setting to confirm that they produced similar measurements before they were installed in the field. Data collected on October 10, 2016 in one of the east-west high tunnels were removed from the study because supplemental heating was brought in for a farm-to-table dinner. One of the east-west high tunnels only had data from January 2017 to April 2017 because the high tunnel cover blew off and sensors malfunctioned. For data from all sensors, measurements made every 15 minutes were averaged to hourly. Daily maxima and minima were isolated from the hourly averaged data for each complete 24-hour period starting at midnight Pacific Daylight Time (PDT). The diurnal temperature range was calculated using the daily maximum and minimum temperatures. Relative humidity was converted to vapor pressure, and saturation vapor pressure was calculated from temperature using the Clausius-Clapeyron equation in the humidity package (Cai, 2016) in R (R Core Team, 2017). Vapor pressure was subtracted from saturation vapor pressure to calculate the vapor pressure deficit (Abtew and Melesse, 2013). Because of the small numbers of replicates (one weather station outside of the high tunnels and only one or two measurements within each high tunnel), it was not possible to conduct any robust statistical analyses. Making additional measurements to provide more replication was not feasible due to cost limitations and the desire to minimize impacts on operations at Desert Farming Initiative.

Reduced solar radiation inside high tunnels

Solar radiation inside all high tunnels was reduced relative to outside in all seasons. This was expected, as even new, the high tunnel cover allows only 85% light transmission, and the cover likely had been in place for three to four years. Moreover, the amount of reduction varied depending on the orientation of the high tunnel and the time of year (Figure 3). Annually, the north-south high tunnels experienced greater reductions in solar radiation than the east-west high tunnels. Early in the season, maximum solar radiation rose quickly inside the high tunnels, similar to trends outside the high tunnel. Solar radiation in our high tunnels leveled off from May to July, irrespective of high tunnel orientation, before decreasing in August. It is possible that the summertime plateau in radiation is related to the style of high tunnels at Desert Farming Initiative. The amount of incoming solar radiation that the high tunnel cover transmits varies with the angle of the sun relative to the angle of the high tunnel roof. While Quonset-style high tunnels generally transmit the most solar radiation in the summer, when the sun is highest in the sky (Blomgren and Frisch, 2007), gothic-style high tunnels, such as those at Desert Farming Initiative, 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 high tunnel roof. This effect is often increased in east-west oriented gothic-style high tunnels (Blomgren and Frisch, 2007), as we observed at Desert Farming Initiative.

Regardless of high tunnel orientation, however, the light transmitted through the high tunnel cover was adequate to meet plant photosynthesis requirements during the growing season (Figure 3). The light saturation point, indicated by the dashed line on the graph, shows the point at which an increase in solar radiation above the line does not result in an increased plant photosynthetic rate, assuming adequate CO_2 and optimal temperatures. Below about 200 W/m^2, lack of light may limit plant growth. During this time (December and January), high tunnel production could focus on plant propagation by seeds or cuttings.

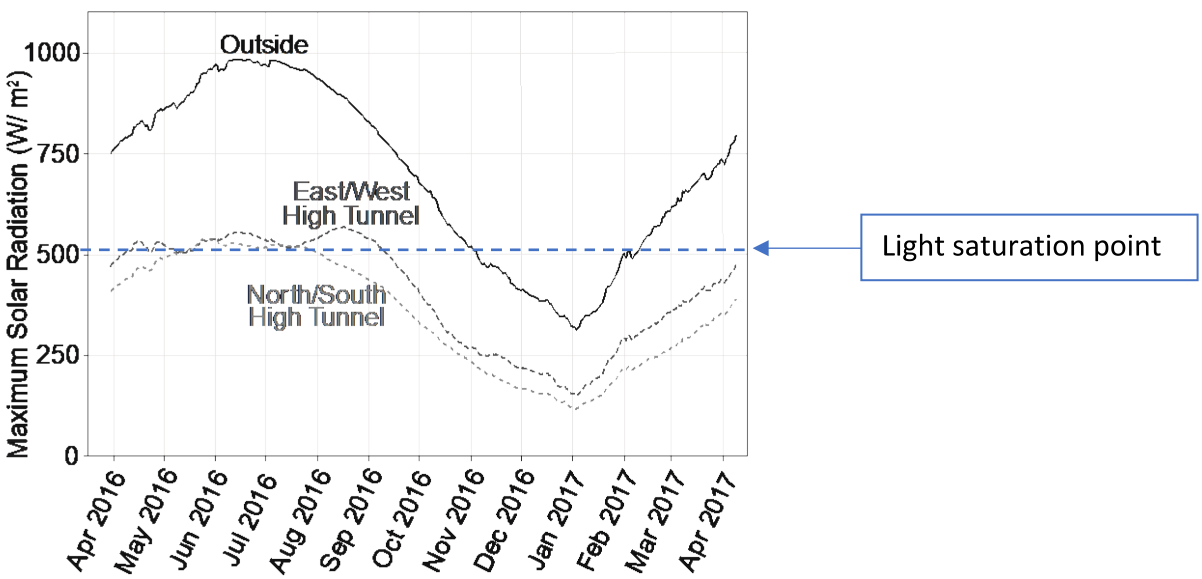

Figure 3. The 31-day moving average of maximum solar radiation within and outside of high tunnels at the Desert Farming Initiative. Values were plotted against the center date. The light saturation point is the point at which an increase in light intensity does not increase the rate of plant photosynthesis.

Significant reductions in wind speed inside high tunnels

Windspeeds were substantially lower inside high tunnels than outside (Figure 4). During the winter, when the high tunnels were often entirely closed, no wind was measured inside the high tunnel. However, maximum wind speeds were lower even when the high tunnel was vented.

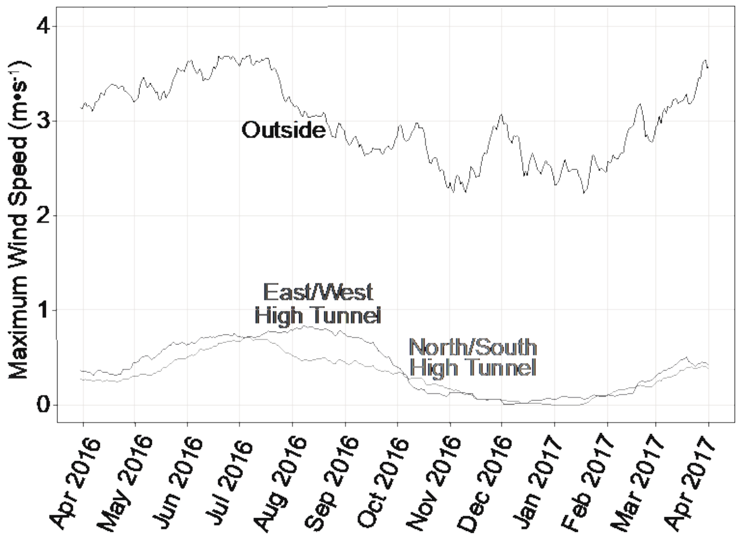

Figure 4. The 31-day moving average of maximum wind speed within and outside the high tunnels. Values were plotted against the center date.

Higher daytime maximum temperatures inside high tunnels

High tunnels increased maximum temperature during the spring, autumn and winter, but during the summer, inside temperatures were closer to or lower than outside temperatures (Figure 5A and B). The seasonal pattern of temperature change was similar at 1 m and 16 cm. This seasonal variation was likely a function of increased manual ventilation in the summer. High tunnels are often vented more in the summer to keep them from reaching extremely high temperatures (Kadir et al., 2006; Reiss et al., 2004). Previous research has found several factors that influence the magnitude and direction of maximum air temperature differences between the inside and outside of high tunnels. Maximum air temperatures rise more inside high tunnels on sunny days than on cloudy days (Ogden et al., 2011; Powell et al., 2014). Increases in air temperature inside high tunnels are reduced and often become negligible with greater ventilation (Lang, 2014; Ogden and van Iersel, 2009; Powell et al., 2014; Rogers et al., 2016; Thompson et al., 2009; Wien, 2009). Maximum air temperatures can also be effectively lowered inside high tunnels, often below that of outside, using shade cloth (Rowley et al., 2011; Zhao and Carey, 2009). Gothic-style high tunnels have the potential to reduce summer maximum temperatures because, depending on the orientation and location of the high tunnel, incoming solar radiation can be reduced (Blomgren and Frisch, 2007). We did not observe substantial differences in maximum temperature between the east-west and north-south oriented high tunnels until late summer or early fall (Figure 5A and B), even though higher levels of incoming solar radiation were measured in the east-west oriented high tunnel throughout most of the year.

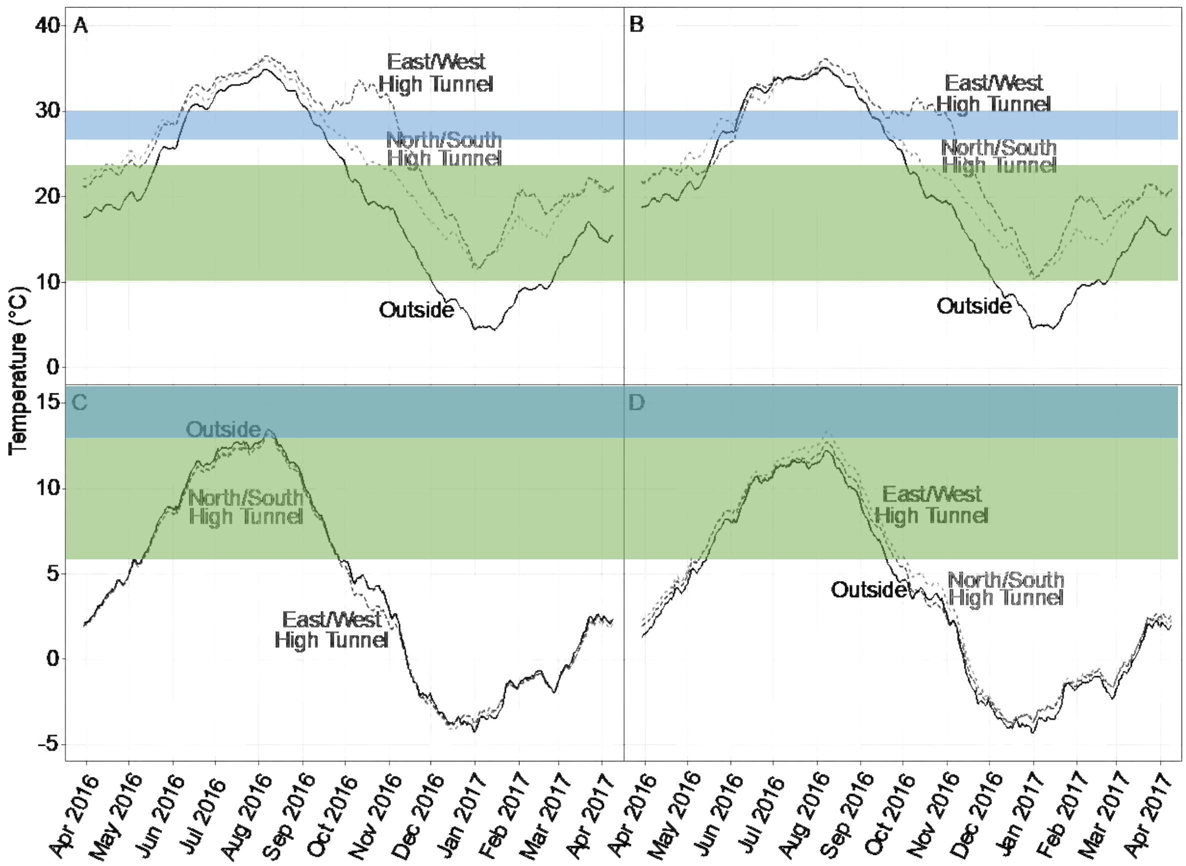

Figure 5. The 31-day moving average of maximum air temperature at 1 m (A) and 16 cm (B). The 31-day moving average of minimum air temperature at 1 m (C) and 16 cm (D). Values were plotted against the center date. The blue shaded areas indicate optimal maximum (A and B) or minimum (C and D) temperatures for fruiting crops. The green shaded areas indicate the optimal maximum (A and B) or minimum (C and D) temperatures for leafy green crops.

Little difference in nighttime minimum temperatures inside and outside of high tunnels

Minimum temperatures were less influenced by the high tunnel than maximum temperatures. In this study, minimum temperatures were similar inside and outside in all seasons. At 1 m, minimum temperatures in the high tunnel were very similar to those outside. At 16 cm, minimum temperatures were almost always higher inside the high tunnel than outside, but the average increase was typically < 1 degree Celsius (Figure 5C and D). Because of the very small effect of the high tunnels on minimum temperature, the influence of high tunnel orientation was likewise small. Other studies have found that minimum air temperatures inside high tunnels can slightly exceed (Ogden and van Iersel, 2009; Rogers and Wszelaki, 2012), be the same as (Ogden and van Iersel, 2009; Ogden et al., 2011; Rogers and Wszelaki, 2012; Rogers et al., 2016), or be lower than outside air temperatures (Ogden et al., 2011; Wallace et al., 2012). Nonetheless, high tunnels can provide protection from air temperatures below freezing (O'Connell et al., 2012). In some cases, crops inside high tunnels benefit from an increase in both minimum air temperature and minimum soil temperature, buffering extreme low temperatures (Zhao et al., 2014).

Several processes inside high tunnels can lead to air temperatures lower than outside. Because of reduced air movement inside high tunnels, especially when they are closed (Figure 4), warmer air from outside does not mix with the air inside, and less air movement leads to more stratification; this pattern is especially pronounced on clear nights (Ogden et al., 2011). Additionally, some plastic coverings radiate more longwave radiation than the ground or crops, creating a thermal inversion effect (Montero et al., 2005; Ogden et al., 2011), although it is not clear whether the specific coverings used at Desert Farming Initiative do so. Two potential passive solutions to the lower minimum temperatures have been suggested in the literature. One is to cover high tunnels in an infrared-blocking greenhouse plastic to hold heat in. However, summer nighttime air temperatures inside infrared-blocking high tunnels remained just above those outside (Both et al., 2007; Wien, 2009), while winter nighttime air temperatures inside high tunnels dropped below outside air temperatures (Wien, 2009). Another solution is to use low tunnels or floating row covers made of plastic or woven fabric that cover one row of crops either with small hoops to hold the covers just above the crops, or placed directly on the crop, inside high tunnels, as seen on the right-hand side of Figure 1. Low tunnels have been effective at increasing minimum air temperatures inside high tunnelss by several degrees (Martin and Sideman, 2012; Santos et al., 2014; Ward and Bomford, 2013). Because of the variable results among seasons, the impact of different plastic coverings on minimum temperature warrants further research.

Figure 5 shows the optimal ranges for maximum (A and B) and minimum (C and D) temperatures for fruiting crops (blue shaded area) and leafy green crops (green shaded area). Our data indicate that fruiting crops, such as tomato, bell pepper and cucumber, may spend most of their life outside of their optimal maximum and minimum temperature ranges and, without employment of strategies to further cool the microclimate within high tunnels, decreased yields may result. Leafy greens (e.g., leaf lettuces), however, could be grown between October and April, with use of row covers or heating devices to keep crops from falling below recommended temperature levels.

Larger daily swings in temperature inside high tunnels than outside

Consistent with previous studies (Bumgarner et al., 2012; Ogden et al., 2011; Wien, 2009), we found that daily temperatures tended to increase and decrease faster inside high tunnels as compared to outside. As discussed, high tunnels do little to increase minimum temperatures, but they do increase maximum temperatures, especially in the spring, autumn and winter when high tunnels are typically not ventilated. Because minimum temperatures were similar in both high tunnels but maximum temperatures increased more in the east-west oriented high tunnels than in the north-south high tunnel, the diurnal temperature range (DTR)—the difference between the highest and lowest temperatures—tended to be larger in the east-west high tunnel. Similar to the results found by Li et al. (2014), the diurnal temperature range was generally increased inside the high tunnels at both 1 m and 16 cm for much of the year. However, in the spring and summer, the diurnal temperature range was sometimes lower inside than outside at 16 cm (Figure 6A and B). This pattern occurred when maximum temperature in the high tunnel was lower than it was outdoors due to ventilation of the high tunnel coupled with reduction in incoming radiation by the plastic cover.

Rather than moderating diurnal temperature range and decreasing large temperature swings, the high tunnels increased them most of the time. This result may seem counter-intuitive to improved crop growth. However, lower minimum temperatures at night limit the resources plants expend on respiration (Nelson, 2003), unless temperatures fall below the crop's optimal range, which could cause stress or damage to the crop. 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 range, which differs by crop species. Nevertheless, plants inside high tunnels are still subject to temperature extremes that could negatively impact crop growth (Gatzke, 2012; Olberg and Lopez, 2016; Rowley et al., 2011; Wien, 2009). Crops could be buffered from temperature extremes by increased soil moisture inside high tunnels (Montri and Biernbaum, 2009). While high tunnels provide a buffer to field climatic conditions, it is more difficult to maintain optimum temperatures for crops in high tunnels than in it is traditional greenhouses (O'Connell et al., 2012), in which more environmental control is possible.

However, low-growing crops may experience less extreme temperature swings than taller plants. Because air exchange with outside is limited and there is less air movement within the high tunnels, stratification may occur inside high tunnels, especially at night as air temperature drops (Ogden et al., 2011). Soils may also moderate air temperature very near the surface, by acting as a heat source or sink or by retaining moisture and allowing for greater partitioning of energy into latent heating. During the day, as air temperature increases and warm air begins to rise, high tunnels tend to increase temperatures more with height. Crops closer to the ground experience less temperature variability with slightly higher temperatures at night and slightly lower temperatures during the day inside high tunnels than outside. 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.

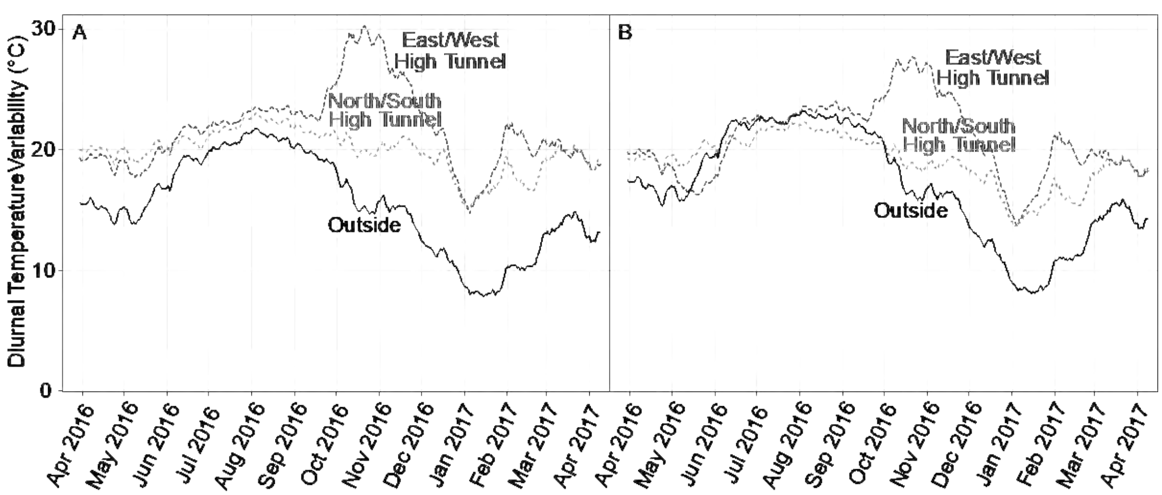

Figure 6. The 31-day moving average of diurnal temperature variability at 1 m (A) and 16 cm (B). Values were plotted against the center date.

Similar plant water loss potential inside and outside of high tunnels

Although crop productivity in high tunnels is influenced by both air temperature and relative humidity (Konopacki et al., 2018), vapor pressure deficit is a more effective measure of the influence of these factors on crop growth and health, because it accounts for the temperature-dependence of relative humidity and is a more accurate way of expressing potential impact on plant water loss to the atmosphere (Shamshiri et al., 2018). Extremely low vapor pressure deficits (0 hPa to 3 hPa) protect plants from water loss but can make some crops more susceptible to diseases. Extremely high vapor pressure deficits (above 16 hPa) equate to a greater potential for excessive water loss from plant leaves to the atmosphere, shutting down leaf pores, inhibiting photosynthesis and plant growth, and putting crops at greater risk of heat-related tissue damage.

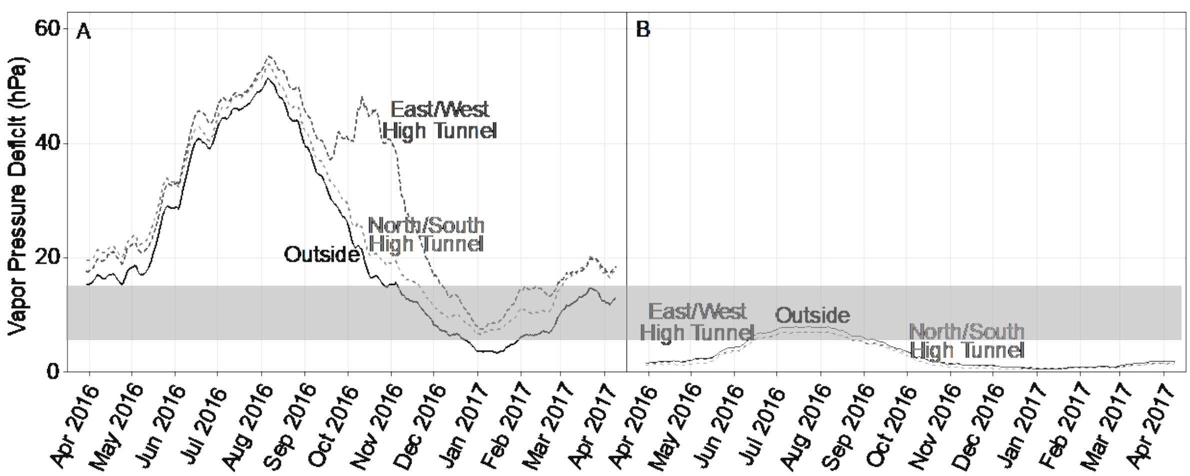

Figure 7. The 31-day moving average of maximum (A) and minimum (B) vapor pressure deficit at 1 m. Values were plotted against the center date. The shaded area indicates the acceptable vapor pressure deficit range for most crops.

In our study, maximum vapor pressure deficit (Figure 7A) closely tracked maximum temperature (Figures 5A and B), displaying similar seasonal patterns and high tunnel orientation effects. Perhaps due to the higher maximum temperatures, maximum vapor pressure deficit was higher inside high tunnels than outside, suggesting that plants inside the high tunnels might experience higher peak moisture stress. Further, by increasing ventilation in the high tunnel to moderate maximum temperatures, farmers introduced potentially drier air from outside the high tunnel. Minimum vapor pressure deficit was variable across the growing season, increasing from May through September but remaining near zero between October and April (Figure 7B). During the summer, minimum vapor pressure deficit was slightly higher outside of the high tunnels than inside, but the difference was on the order of only 1 hPa. Vapor pressure deficit levels within the high tunnels were likely a function of temperature, evaporation from irrigated soils and evapotranspiration from crops. In this study, we monitored conditions at a working farm rather than experimental plots, so irrigation volumes likely differed between high tunnels and inside versus outside the high tunnels, depending on crop type and perceived plant moisture stress.

Crops growing in the high tunnels during the time frame of our study included cucumber, bell pepper and tomato during the warm season and carrot, leaf lettuces and radish during the cooler seasons. Studies have indicated the optimal range of vapor pressure deficit for most crops in protected culture is between 3 hPa and 10 hPa (Shamshiri et al., 2018), with lower vapor pressure deficits within this range more conducive to rooting young plants and higher vapor pressure deficits promoting increased photosynthetic rates and higher yield during finishing. The shaded area in Figure 7 shows the optimal range of vapor pressure deficit for most crops. Maximal vapor pressure deficit levels were optimal for crops from November through March, while minimum vapor pressure deficit levels were optimal June through October.

The range of vapor pressure deficits in our study varied from close to 0 hPa in winter to as high as nearly 60 hPa in the heat of summer. Because temperatures spike quickly once the sun rises in our climate, and the effect is amplified inside high tunnels, crops grown in high tunnels in our region have the potential to experience vapor pressure deficits outside of their optimal range from May until September. We tracked the number of hours per 24-hour day that vapor pressure deficit was between 2 and 14 hPa (Table 1) and found that, in July and August and again in December and January, only 7 hours per day (29.2% of the time) were within the optimal vapor pressure deficit range, most of those hours likely occurring during darkness. This effect was less pronounced during that time period at 16 cm than at 1 m inside the high tunnels (data not shown), suggesting lower-growing crops, or those at an earlier stage of development during that time, could be less negatively affected. Higher than optimal vapor pressure deficit levels, during a time when cucumber, tomato and bell pepper are at critical developmental stages of growth, could affect their fruit development and yield. For example, Omafra (2005) found that tomato photosynthesis and nutrient uptake was optimal at vapor pressure deficits of 4 hPa to 8 hPa, and vapor pressure deficit levels between 16 hPa and 22 hPa reduced tomato fruit fresh weight and fruit water content, affecting fruit yield and quality (Leonardi et al., 2000). Konopacki et al. (2018) assumed an optimal range of 4 hPa to 14 hPa for cultivation of cucumber in their study.

Table 1. Average number of hours per 24-hour day when the vapor pressure deficit inside high tunnels was between 2 hPa and 14 hPa at 1 m above the soil surface.

Mar 2016	Apr 2016	May 2016	Jun 2016	Jul 2016	Aug 2016	Sep 2016	Oct 2016	Nov 2016	Dec 2016	Jan 2016	Feb 2017	Mar 2017	Apr 2017
Average number of hours per day vapor pressure deficit is between 2 hPa and 14 hPa (optimal range for most crops)*													
15	15	14	13	7	7	14	13	14	7	7	13	15	16

*Assume 8 to 12 hours occurred during periods of darkness when plants are physiologically less active.

Growers in high-desert climates need to evaluate the range of crops they can grow and market successfully, matching crop production cycles and developmental stages to seasonal microclimatic conditions. Depending on the market value of the crop, they might consider strategies to lower vapor pressure deficit levels. For example, Harel et al. (2014), studying protected cultivation of tomato in a Mediterranean climate, found that a fogging system was useful in reducing heat and increasing humidity levels to improve tomato fruit set. Ghani et al. (2019) describe a variety of technologies that have been used to control heat and humidity in protected culture, including shading, ventilation, fogging and evaporative cooling. Although these systems are more common in greenhouse structures, electrification of high tunnels to provide for easier deployment of these strategies is gaining popularity (Mefferd, 2017).

Because of the uncontrolled nature of this study, it is difficult to draw further conclusions from our data about the effects of high tunnels on vapor pressure deficit. Future research could investigate specific crops in high tunnels to determine whether they spend more time in their optimal vapor pressure range and how vapor pressure deficit varies with irrigation inside and outside of high tunnels.

Conclusions

Reduction in solar radiation and wind provided by the structure of the high tunnels played an important role in modifying the temperature and vapor pressure deficit inside our high tunnels. The reduction in wind speed and solar radiation provided by high tunnels, coupled with farmers' ability to further modify conditions through ventilation and shading, moderated seasonal variability rather than daily variability. Specifically, we found that maximum temperatures were higher inside closed high tunnels than outside, but that high tunnels were not effective in significantly raising minimum temperatures. Further minimum temperature moderation could likely be achieved in other ways. Variation in temperature with height was also found within the high tunnel, such that plants close to the ground might receive more benefits of climate modification than taller plants. Combined, these modifications will make high tunnels a popular investment for high-desert farmers, particularly those interested in season extension. Further research could examine how solar radiation and wind speed modification influence temperature and vapor pressure deficit at different heights in different types of high tunnels.

Although the woven polyethylene fabric used on these particular high tunnels is not the most common covering, it is a clear material with reasonable light transmission similar to other polyethylene films and to that used in some other studies (Li et al. 2014; Wallace et al. 2012). Farmers at Desert Farming Initiative felt it was appropriate for the high-desert environment. Other growers in the region would likely value its durability as well. Because of its general similarities to other coverings presented here, results will be useful to growers, if not directly applicable to high tunnels using other coverings

A limitation of this study is that the information provided is not readily adaptable to specific crops, as data were collected in working high tunnels, with different crops rotating in and out as the season progressed. However, the data do provide insights into the microclimate dynamics inside high tunnels, and can be used by Nevada growers wanting to try growing vegetables using high tunnels for season extension.

Recommendations for Nevada growers

- Propagate seedlings early in the year when light levels are lower, or in lower-light areas of your high tunnel.
- Use row covers within high tunnels during late winter to early spring to prevent overnight freeze damage to crops.
- Choose lower-growing crop species or varieties to prevent crop damage from excessive heat and water stress during the summer.

- Choose crops for high tunnels that can be harvested before July to prevent crop damage from excessive heat and water stress during the summer.
- Space crops closer together during the hottest months of the year to create a more humid microclimate around the plants, reducing the potential for excessive water loss and resulting growth inhibition.
- Electrify high tunnels to allow use of humidifying technologies when growing high-value crops during the hottest months of the year.

Acknowledgments

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