

Soil Solarization in High Tunnels in the Semiarid Southwestern United States

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Abstract. High tunnels are unheated structures covered with polyethylene (PE) glazing to protect high-value crops from adverse weather. The objective of this study was to raise soil temperatures to determine the efficacy of soil solarization using clear mulch on the soil surface and glazing or no glazing on a high tunnel during the hottest months of the year in the semiarid southwestern United States. Solarization trials were conducted in May and June 2013 in two high tunnels in southern Arizona. Highest soil temperatures were reached with the combination of a high tunnel covered with glazing and the soil covered with PE mulch. Average daily soil temperatures were 48 and 47 °C and average degree hours (DH) per day (base temperature 45 °C) were over 14 at soil depths of 5 and 15 cm. The average daily maximum soil temperature at 5- and 15-cm depth was 63.4 and 52 °C, respectively. The second highest soil temperatures were reached when the soil was covered with PE mulch without high tunnel glazing, which resulted per day in 5.2 DH above 45 °C at 5 cm and less than one DH at 15-cm depth. Glazing on the high tunnel without covering the soil surface raised soil temperatures only at the 5-cm depth above 45 °C, but not further down. High tunnel producers in the low desert areas in the southwestern United States can complete solarization in less than 1 week, depending on the organism to be controlled, when the soil is fallow during the summer months with glazing on the high tunnel and on the soil surface.

Soil solarization uses solar radiation to disinfest the soil from pests detrimental to crop plants (Katan, 1981; Stapleton, 2000). Soil solarization is used most in areas with high solar radiation and temperatures during the summer season (Gill et al., 2009; Stapleton, 2000). It is used as an alternative to soil fumigation for pathogen and pest control either alone or in combination with fumigants (Elmore et al., 1997; Hartz et al., 1993). Disinfection is achieved by using solar radiation to passively heat moist soil covered with clear plastic sheeting for a period of a few weeks to increase soil temperatures to the point where they are lethal to soilborne organisms (Katan, 1981; Pullman et al., 1981; Stapleton, 2000). Higher soil moisture during solarization can increase the soil heat conductivity resulting in higher temperatures compared with soil that is less moist (Katan et al., 1976). Low-density PE film and ethylene vinyl acetate film have the best solarizing properties for increasing temperatures in production beds (D'Addabbo et al., 2010). Solarization is a strategy used to reduce the

soilborne pests and diseases such as *Verticillium dahliae* (verticillium wilt), *Fusarium* spp. (fusarium wilt), *Phytophthora cinnamomi* (Phytophthora root rot), *Meloidogyne incognita* (root knot nematodes) and weed species (Dahlquist et al., 2007; Stapleton et al., 2000). The elevated soil temperatures are also beneficial for soil physical and chemical structure, accelerating the release of minerals from decomposition and increasing soil aggregation (Elmore et al., 1997; Stapleton, 2000).

The effectiveness of solarization is based on the actual maximum soil temperature achieved under the plastic cover and the amount of time that this temperature can be sustained (Chase et al., 1999). Soil temperatures of 37 °C can be effective in controlling some pests and pathogens if they are maintained for 4 to 6 weeks (Elmore et al., 1997). The optimal temperature for the solarization process depends on which organisms are present in the soil and their susceptibility to high temperatures. Some organisms and their thermal thresholds for inactivation are listed in Table 1. Studies have shown a logarithmic relationship between temperature and pathogen mortality where less time is required to kill pests and disease-causing organisms as soil temperature increases (McLean et al., 1999; Pullman et al., 1981). In laboratory studies, pathogens such as *Verticillium dahliae*, *Pythium ultimum*, and *Thielaviopsis basicola* required 29, 18, and 33 d to kill 90% of propagules at 37 °C, respectively (Pullman et al., 1981). However, at 50 °C those times were reduced to 23, 33, and 68 min. Temperatures of 50 °C or greater dramatically

reduce the amount of time required to inactivate various pest organisms (Dahlquist et al., 2007; Mihail and Alcorn, 1984; Pullman et al., 1981; Stapleton et al., 2000).

Solarization in a greenhouse or high tunnel structure will yield higher soil temperatures than in fields or gardens (Elmore et al., 1997). Using PE mulch inside a greenhouse will further increase the effectiveness of the soil solarization process (Maher et al., 1987), especially in cooler coastal climates (Larson, 2007). Although temperatures in soils covered with PE mulch will be highest in a glass house, a structure with PE glazing will also be effective in raising soil temperatures above mulched soil exposed to open air conditions. Soil solarization in a Mediterranean climate using PE mulch for 7- to 9-week intervals was successful in raising soil temperatures at 15-cm depth between 37 and 50 °C in beds used for strawberry (*Fragaria xananassa* Duch.) cultivation under plastic tunnel conditions (Iapichino et al., 2008). Solarization in a high tunnel in Costa Rica increased the soil temperature of covered soil to ≈60 °C compared with 30 °C for uncovered soil (Santos et al., 2008). A double-tent system within a greenhouse facilitated structural solarization by raising temperatures to 60 °C and resulted in effective inactivation of *Fusarium* sp. (Shlevin et al., 2004). The same temperature was effective in killing weed species in containers filled with soil and exposed to solarization in a double tent (Stapleton et al., 2002). At present there are no studies for the semiarid southwestern United States region comparing solarization inside and outside of a high tunnel. One goal of this study was to provide growers using high tunnels with information that may be beneficial to protecting their crops from weed and other pest populations.

The semiarid climate in southern Arizona is ideal for soil solarization as a result of high solar radiation. June is the optimal time for solarization because the daily solar radiation can reach 30 MJ·m⁻² and temperatures are higher for this month than others [Arizona Meteorological Network (AZMET), 2013; Mihail and Alcorn, 1984]. In Tucson, AZ, daily fluctuations in temperature are typically 8 to 17 °C with June average highs and lows of 38 °C and 21 to 27 °C, respectively (AZMET). Although these are averages, temperatures can reach extreme highs such as 47 °C in June of 1990. Low relative humidity during early summer months combined with high temperatures and high solar radiation provides growers with an opportunity for using solarization when production areas are fallow. The objective of this study was to determine the efficacy of clear PE mulch on the soil surface and glazing on a high tunnel to raise soil temperatures to solarize the soil during the hottest time of the year in the semiarid southwestern United States.

Materials and Methods

Two high tunnels with the dimensions of 4.3 m width, 12.8 m length, and 2.1 m height

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Table 1. Temperature and time period required for the inactivation of some pests.

Organism		Treatments to inactivate organism	Literature citation
<i>Amaranthus albus</i>	Tumble pigweed	1 h at 60 °C 20 min at 70 °C	Stapleton et al., 2000
<i>Aphanomyces cochlioides</i>	Black leg	72 h at 45 °C	Dyer et al., 2007
<i>Botrytis cinerea</i>	Grey mold	20 min at 46.4 °C 2 min at 49 °C	Lichter et al., 2003
<i>Echinochloa crus-galli</i>	Barnyard grass	15 h at 46 °C 9 h at 50 °C 15 min at 60 °C	Dahlquist et al., 2007
<i>Macrophomina phaseolina</i>	Charcoal rot	72 h at 45 °C 48 h at 50 °C 24 h at 55 °C	Mihail and Alcorn, 1984
<i>Meloidogyne incognita</i>	Root knot nematode	1 h at 45 °C	Wang and McSorely, 2008
<i>Pythium ultimum</i>	Pythium root rot	20 min at 46 °C	Baker and Cummings, 1943
<i>Phytophthora cactorum</i>	Blight, damping off	30 min at 45 °C	Juarez-Palacios et al., 1991
<i>Phytophthora capsici</i>	Phytophthora blight	22 h at 45 °C 4.7 h at 50 °C 1 h at 53 °C	Ettxeberria et al., 2011
<i>Phytophthora cinnamomi</i>	Blight, damping off	20 min at 45 °C	Juarez-Palacios et al., 1991
<i>Phytophthora megasperma</i>	Blight, damping off	2 h at 45 °C	Coelho et al., 2000
<i>Phytophthora nicotianae</i>	Raspberry root rot	52 h at 35 °C	Pinkerton et al., 2009
<i>Phytophthora rubi</i>	Common purselane	3 h at 60 °C 20 min at 70 °C	Stapleton et al., 2000
<i>Portulaca olerace</i>	Stem and Stolon Canker	5 min at 50 °C	Sherwood, 1970
<i>Sclerotium cepivorum</i>	Sclerotinia rot	48 h at 40.7 °C 24 h at 41.9 °C 12 h at 45.2 °C 6 h at 47.4 °C	McLean et al., 1999
<i>Sclerotium rolfsii</i>	Southern blight	12 h at 45 °C 6 h at 50 °C 3 h at 55 °C	Mihail and Alcorn, 1984
<i>Solanum nigrum</i>	Black nightshade	2 h at 60 °C 20 min at 70 °C	Stapleton et al., 2000
<i>Solanum nigrum</i>	Black nightshade	213 h at 46 °C 71 h at 50 °C 2 h at 60 °C	Dahlquist et al., 2007
<i>Sonchus oleraceus</i>	Annual sowthistle	4 h at 50 °C 15 min at 60 °C	Dahlquist et al., 2007
<i>Verticillium dahliae</i>	Verticillium wilt	40 min at 47 °C	Nelson and Wilhelm, 1958

located at the Campus Agricultural Center in Tucson, AZ, were used for this experiment. Each structure had two growing beds with dimensions of 1.2 m × 11.5 m divided by a path along the center. The growing beds were amended with compost in 2012 and raised soil organic matter to ≈3.5%. Glazing (152.4 µm IR/AC polyethylene; GreenTek, Visalia, CA) was kept on each of the two high tunnels from 24 May 2013 through 5 June 2013 for solarization of the beds. Each high tunnel was constructed with end walls with working doors and vent windows that were kept closed during solarization. One half of each of the beds was covered with 25.4 µm solid, clear PE mulch, which contained an ultraviolet stabilizer that prevented degradation from solar radiation for 180 d (Water Tech, Charlotte, NC) and the other half remained uncovered. Each bed was thoroughly irrigated using six drip tapes per bed with 10-cm spacing of emitters at a rate of 0.60 L·h⁻¹ for each dripper for 1 h (Jain Irrigation Inc., Watertown, NY). The water was allowed to drain through the beds for 1 h after which the cycle was repeated. The irrigation lines were removed from the beds before covering the soil surface with the PE mulch.

The 25.4-µm PE mulch was placed directly on the beds keeping the film smooth

against the soil surface to eliminate any air pockets. Edges of the film were held down with lumber to prevent any air from entering underneath and drying the soil in the beds. Thermocouples were placed in each covered and uncovered soil area in each high tunnel at depths of 5 cm and 15 cm to record the temperature every 15 min (HOBO U12 4-Channel External Data Logger; Onset Corp., Bourne, MA). One temperature sensor was placed 15 cm above the soil at the center of each tunnel to record the air temperature every 15 min. This sensor was not shielded and aspirated and higher recorded air temperatures may be the result of exposure to long wave radiation. Solar radiation data and ambient outside air temperature were collected from sensors 1.5 m above the soil at the AZMET station located ≈200 m from the experimental site. Solar radiation is measured and reported as average Langley's per hour. These units were converted to average hourly and average daily MJ·m⁻². On 31 May 2013, the PE mulch was removed from the beds. Irrigation lines were redeployed and the irrigation process was repeated before replacing the thermocouples. The beds were covered again with the PE mulch and the solarization process was repeated from 1 June to 6 June 2013.

On 10 June 2013, the glazing was removed from one of the high tunnels for a comparison of temperatures in a high tunnel with glazing with open-field conditions. This was done to compare soil temperatures in the same soil conditions as in the hoop house because no comparable soil was available outside the hoop houses. The same methods as described were used for soil irrigation and soil solarization. Soil and air temperatures were collected from 11 to 17 June and from 18 to 23 June 2013. On 17 June, the PE mulch was removed, irrigation applied, and the soil covered again with PE mulch. Treatments were designated as high tunnels with the glazing on or glazing off and soil covered with PE mulch or soil uncovered.

Temperatures collected during a time period at the same soil depth of two replicate beds within a tunnel under each solarization treatment were averaged and the DH above 45, 50, or 55 °C were determined for each 24-h period. Temperature differences between covered and uncovered soil were calculated. A regression was calculated between the soil temperatures at 5-cm and 15-cm depth in soil covered with PE mulch in a glazed tunnel as a function of the ambient temperature.

Results

The hourly solar radiation for two periods during the month of June 2013 is shown in Figure 1. From 1 to 6 June, high solar radiation levels prevailed as a result of clear skies. From 11 to 16 June, cloud cover decreased solar radiation levels on some days.

Soil solarization with the glazing on the high tunnel and the beds covered with a PE mulch resulted in the highest temperatures for the longest duration at 5 cm and 15 cm (Table 2; Fig. 2). From 24 May 2013 through 23 June 2013, the soil at a depth of 5 cm and 15 cm reached on average 14.8 DH per day over 45 °C (Table 2). Figure 2 shows daily air and soil temperature fluctuations for a 5-d period when glazing covered the high tunnels. Outside air temperatures reached up to 40 °C and air temperatures in the covered high tunnel climbed to 70 °C (Fig. 2A). Similar AZMET and air temperatures in the closed tunnel were monitored during the second week of June (Fig. 3A). During the entire study, diurnal air temperature fluctuation outside was 20 °C and inside the tunnel 50 °C (Figs. 2A and 3A). Daily soil temperatures oscillated ≈30 °C at 5-cm depth in covered soil and 20 °C in uncovered soil (Fig. 2B). Less fluctuation was observed at 15-cm depth with the least change in soil temperature in uncovered soil (Fig. 2B). Covering the soil in the glazed high tunnel raised temperatures at 5-cm depth between 15 and 18 °C during the warmest part of the day compared with uncovered soil and ≈13 to 14 °C at 15-cm depth (Fig. 2C).

A linear regression equation predicted the soil temperature at 5-cm depth in a tunnel with glazing and with soil covered with PE

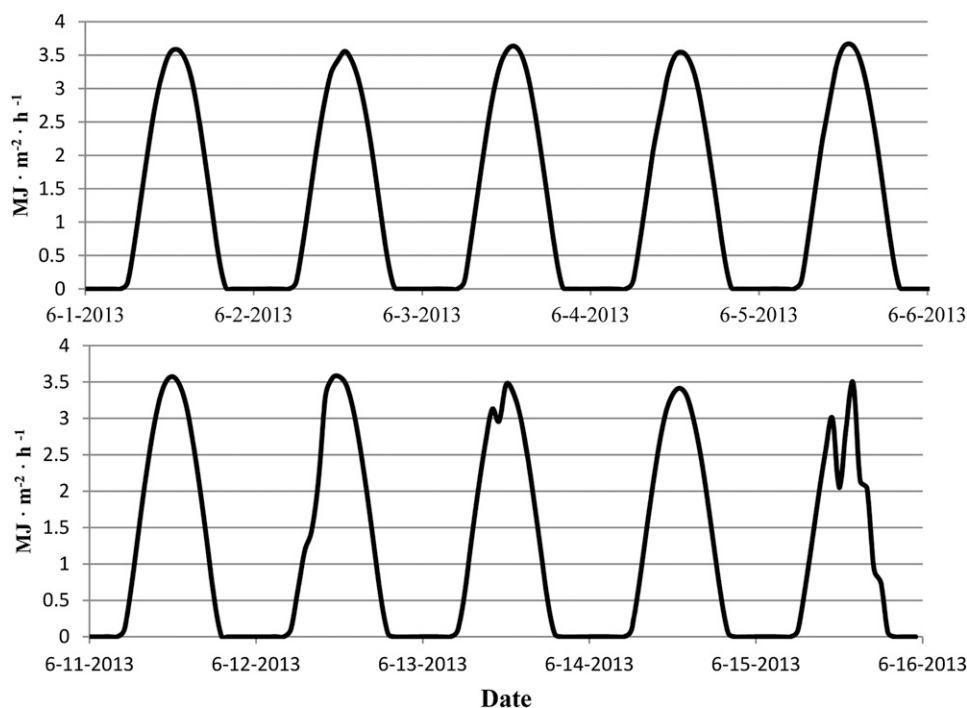


Fig. 1. Solar radiation from 1 to 5 June 2013 and 11 to 15 June 2013.

Table 2. Daily maximum and average soil temperatures and degree hours above 45, 50, and 55 °C in high tunnels with or without glazing and in soil covered with plastic mulch or without from 24 May to 23 June 2013.

High tunnel glazing	Soil glazing	Soil depth (cm)	Avg daily maximum temp (°C)	Avg daily temp (°C)	Degree hours		
					>45 °C	>50 °C	>55 °C
On	On	5	63.4	48.0	14.7 (0.33) ^a	10.6 (0.27)	7.8 (0.20)
On	On	15	52.0	47.0	14.9 (0.13)	6.3 (0.12)	0
On	Off	5	48.2	40.5	5.2 (0.14)	0.2 (0.17)	0
On	Off	15	41.0	37.7	0	0	0
Off	On	5	54.3	41.4	8.2 (0.28)	5.5 (0.17)	0.3 (0.23)
Off	On	15	44.2	40.4	0.7 (0.13)	0	0
Off	Off	5	40.7	32.3	0	0	0
Off	Off	15	35.5	33.3	0	0	0

^aAverage (SE).

mulch as a function of the ambient air temperature as follows:

$$\begin{aligned} \text{Soil temperature (°C) at 5 cm depth} \\ = 10.86 + 1.27 \\ \times (\text{ambient AZMET temperature (°C)}) \\ (R^2 = 0.77) \end{aligned}$$

A linear regression of soil temperature at 15-cm depth under the same conditions resulted in a poor fit (data not presented).

Solarization with the high tunnel glazing off and mulch covering the beds sustained temperatures above 45 °C. Results showed an average of 8.2 DH a day over 45 °C at a depth of 5 cm but less than one DH a day at 15-cm depth (Table 2). The highest soil temperature achieved at 5 cm was 55.8 °C (data not shown). Degree hours above 50 and 55 °C were 5.5 and 0.3 at 5 cm but PE mulch on the soil alone did not raise temperatures above these values at 15-cm depth (Fig. 3B). Covered and uncovered soil temperatures in open air conditions fluctuated $\approx$ 20 and 10 °C daily

at 5-cm and 15-cm depth (Fig. 3B). Plastic mulch on the soil raised temperatures at 5-cm depth between 6 to 17 °C (Fig. 3C).

Leaving the glazing on the high tunnel and no PE mulch on the soil surface resulted only in 5.2 DH over 45 °C at 5 cm and 0 h at 15-cm depth (Table 2). Daily maximum temperatures at 5 cm were almost 15 °C less than when high tunnel glazing and soil glazing were installed and only up to 8 °C warmer than in bare soil.

Bare soil without glazing on the high tunnels and the beds uncovered did not reach soil temperatures of 45 °C at any depth (Fig. 3B). At 5-cm depth the highest temperature was 42.8 °C and the average temperature was 32.3 °C.

Discussion

The most effective solarization strategy was to keep the glazing on the high tunnels in conjunction with a 25.4- μ m PE cover on the well-irrigated beds. When daily solar radiation averaged 29.8 MJ·m⁻² and outside temperatures reached 38 °C, the soil at 5-cm

depth exceeded 45 and 55 °C for almost 15 h and 8 h, respectively, each day. This treatment resulted in a significant period each day when temperatures exceeded the thresholds to effectively kill many soil pathogens, pests, and weeds in a relatively short time (Katan, 1981; Mihail and Alcorn, 1984; Pullman et al., 1981). Maintaining the glazing on high tunnels was especially beneficial for raising the soil temperature at 15-cm depth where temperatures above 45 °C were maintained for almost 15 h daily and thus control potential pathogens or pests to a greater depth. Although monitored only for a total of 20 d, AZMET temperatures during the hottest part of the year could be used to predict soil temperatures at a depth of 5 cm in covered beds in a hoop house with glazing.

Solarization in a clear plastic tunnel in coastal California raised soil temperatures significantly and led to improved weed control compared with solarized soil without the tunnel (Larson, 2007). Solarization under plastic tunnels in Italy raised soil temperatures above 45 °C at 15-cm depth for 72 cumulative hours over a period of 50 d from

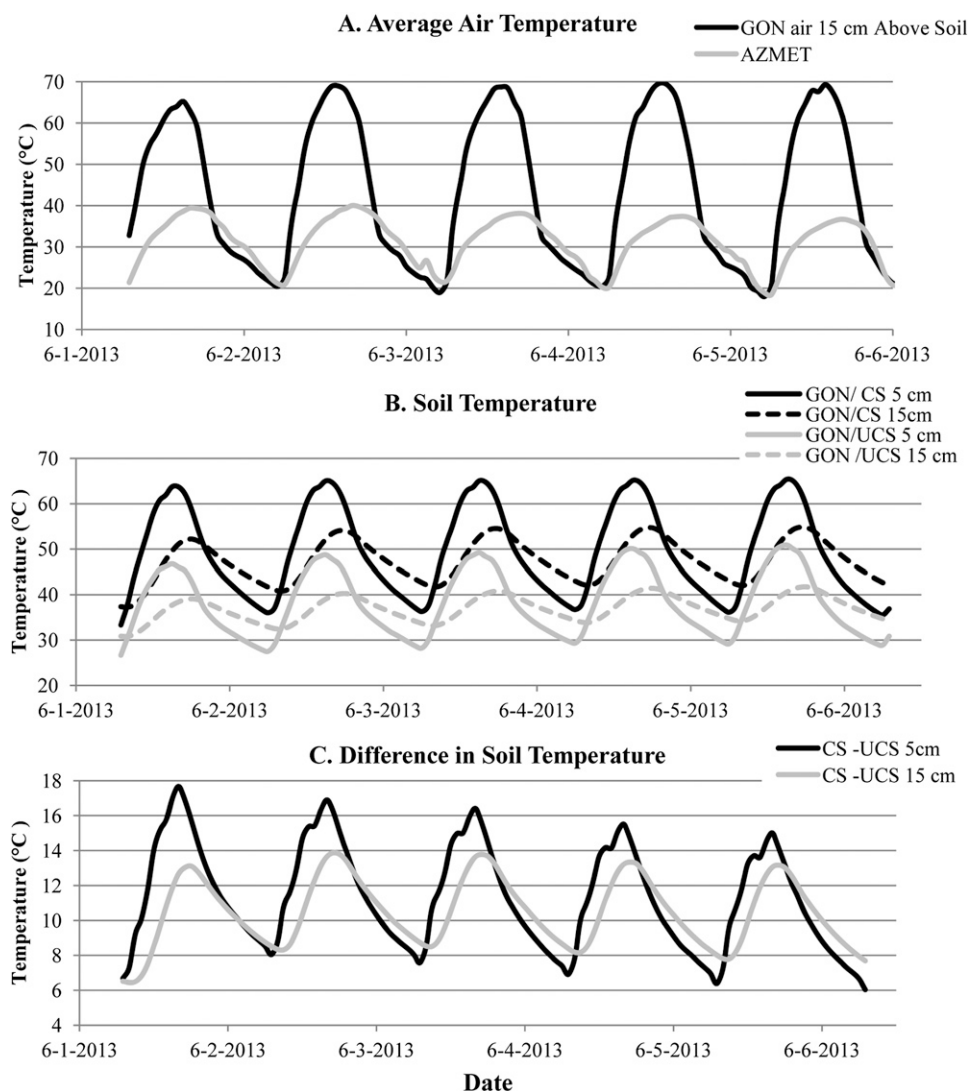


Fig. 2. (A–C) Air and soil temperatures in high tunnels with glazing and soil covered with polyethylene (PE) mulch or uncovered from 1 to 5 June 2013. GON = glazing on high tunnel; CS = covered soil; UCS = uncovered soil. AZMET is the outside air temperature from an adjacent weather station.

June through September (Iapichino et al., 2008). Solarization in Costa Rica under high tunnels where soil temperatures reached 60 °C resulted in 100% weed control in beds used for hot pepper cultivation (Santos et al., 2008).

The second most effective treatment to raise the soil temperature was the conventional use of PE mulch on moist soil. Previous studies at the University of Arizona Campus Agriculture Center during the month of June resulted in maximum average temperatures of 49 and 50 °C at 15-cm depths in 1981 and 1982 in plots covered with a 50.8- μ m PE tarp (Mihail and Alcorn, 1984). These average temperatures were 3 to 4 °C higher than those we collected when only the soil was covered with plastic mulch. Thinner PE films are found to be more effective at producing higher temperatures and less expensive than thicker films (Stapleton and Devay, 1986). However, lower soil temperatures during solarization can result from previously amending the soil with compost to improve soil structure as thermal conductivity decreases in soil when pore space between

aggregates increases (Usowicz et al., 2013). Contrary, the addition of 10% compost to soil before solarization increased soil temperatures during solarization compared with unamended soil (Simmons et al., 2013). A maximum soil temperature of 48 °C at 5-cm depth was reported at 5 cm in Pakistan, which is lower than those we collected in covered beds in an open field (Usmani and Ghaffar, 1982). These lower temperatures likely resulted from the drip lines being left between the soil and the plastic creating more air space and reducing the solar heating potential. Other potential causes for lower temperatures could be the result of the physical properties of the solarization film, climate, and soil structure. Absorption of radiation and heating of the soil is best when air space between the soil and the plastic is kept at a minimum (Shlevin et al., 2004). Maximum temperatures in covered beds in Australia and in covered and uncovered beds in California were comparable to those that we collected in covered and uncovered beds in an open field (Pullman et al., 1981). Temperatures collected in covered beds at

the Campus Agriculture Center in Tucson at 5-cm depth were higher than those collected in Yuma, AZ, during the months of July through September when solar radiation levels are lower than in June (AZMET, 2013; Matheron and Prochas, 2010). Soil heating by solarization is affected by a number of factors including soil moisture, solar irradiation, air temperature, soil properties, color and aggregate size, wind, the size of the air gap between the soil and the glazing, and the properties of the glazing material (Ozores-Hampton et al., 2005; Shlevin et al., 2004; Stapleton, 2000; Usowicz et al., 2013). Clear and transparent PE is used as a result of its low cost and high strength. Mulch made from coextruded low-density polyethylene/ethylene-vinyl acetate or ethylene vinyl acetate raises soil temperatures at depths greater than 10 cm in a greenhouse over 50 °C for a longer duration than low-density PE (Candido et al., 2011).

Keeping the glazing on the high tunnel without covering the beds raised soil temperatures up to and over 45 °C at 5-cm depth but not at 15-cm depth. This strategy would

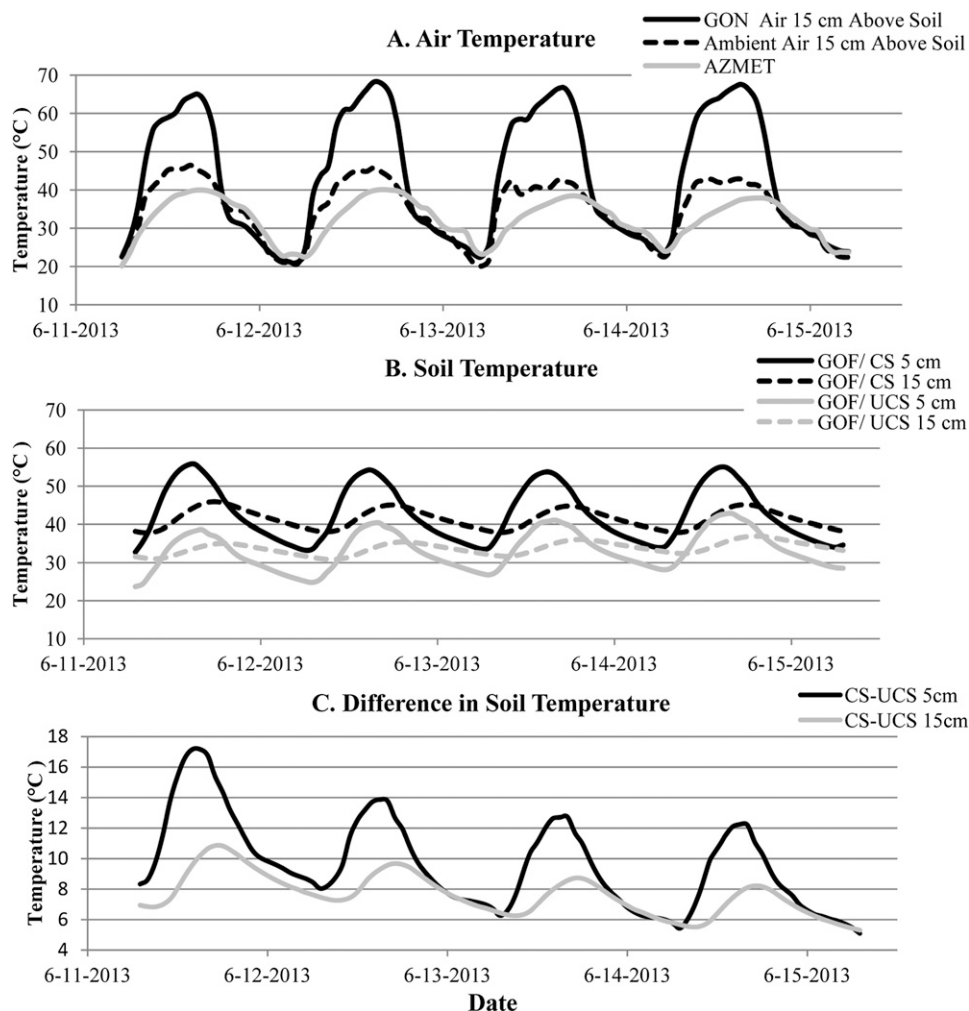


Fig. 3. (A–C) Temperature for air and soil in a high tunnel without glazing, but with soil covered with polyethylene (PE) mulch or uncovered from 11 to 15 June 2013. GOF = glazing off high tunnel; CS = covered soils; UCS = uncovered soil. AZMET is the outside air temperature from an adjacent weather station. Air temperature GON (A) is the temperature in the high tunnel with glazing.

require the glazing to be left on the high tunnels for extended periods of time compared with a treatment with the glazing and PE mulch in place. The high tunnel glazing alone was less effective in raising soil temperatures than the conventional PE mulch on the soil surface under open air conditions. The high tunnels had small gaps around the door frame, which allowed air movement inside the tunnels from outside. It is possible that without the structure being airtight, the soil dried more quickly, which would reduce the potential for higher soil temperatures. Without soil mulching, maximum temperatures at 5- and 15-cm depth were ≈ 15 or 11 °C lower than with soil mulching in a covered high tunnel and effective temperatures to control pests were reached at the shallow depth but not at 15 cm. This might reduce the efficacy of the process depending on the pathogen and pest pressure in the production beds.

Lower soil temperatures for parts of this study may be the result of several factors. On some days solar radiation was obstructed by cloud cover during the experimental period and reduced the amount available for thermal heating. Although held down tight with the lumber, the PE mulch was not buried around

the bed and possibly had small breaks in the seal, allowing air to enter and possibly dry the soil. Air entering the high tunnels through small gaps around the door frame might also have contributed to soil drying.

Soil solarization is often carried out for several weeks in field situations (Stapleton, 2000). The goal of our study was to determine the soil temperatures that can be obtained during the hottest time in the southwestern United States. A previous study demonstrated that a 1-month solarization where soil temperatures at 5-cm depth reached 47 and 49 °C had the same efficacy in controlling fusarium wilt of lettuce (*Fusarium oxysporum* f. sp. *lactucae*) as a 2-month solarization in Yuma, AZ (Matheron and Prochas, 2010). The higher soil temperatures that were obtained in our study suggest the potential to shorten the duration of solarizing soil in the southwestern United States during times of highest solar irradiation and clear days.

Soil solarization can be an effective method to control soil pathogens and pests in southern Arizona from late spring through summer when high tunnels are not used for production. During the study period from 24 May through 23 June 2013 soil temperatures

to 15-cm depth increased such that disinfection for many undesirable organisms would be completed in less than 1 week (Table 1). Soil solarization with PE mulch alone would require a longer duration. Solarization with glazing alone was least effective in raising soil temperatures and may not control organisms with a higher temperature tolerance, especially at lower soil depths. High tunnel producers in the low desert areas in the southwestern United States can take advantage of solarization when the soil is fallow during the summer months.

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