Active Solarization as a Nonchemical Alternative to Soil Fumigation for Controlling Pests

S.R. Yates*
D.J. Ashworth
USDA-ARS
U.S. Salinity Lab.
450 W. Big Springs Rd.
Riverside, CA 92507

M.D. Yates
Dep. of Civil and Environ. Eng.
Pennsylvania State Univ.
University Park, PA 16802

Lifang Luo
Dep. of Environmental Science
Univ. of California
Riverside, CA 92521

Deterioration of soil, water, and air resources by soil fumigants represents a serious threat to agricultural production in semiarid regions due to their high volatility and high emission rates. New pest control methods are needed that do not rely on fumigant chemicals. Soil heating via solarization has been proposed as a nonchemical alternative to soil fumigation but has not found wide acceptance due to limitations in soil temperatures and heating depth, especially in cooler environments. We have developed a new soil heating method, termed *active solarization,* to increase the soil temperature and heating depth in the root zone. An experiment was conducted to compare heating for bare soil, standard (i.e., passive) solarization, and active solarization methodologies. A cumulative heat stress index, CHT_{30}, was computed and has been shown to be related to plant-pest survival. After 15 d of heating, passive solarization increased at the 10- and 20-cm depths by 263 and 65°C h, respectively, compared with leaving the soil bare. For active solarization, CHT_{30} increased by 387 and 105°C h , respectively, compared with bare soil. After 30 d of passive solarization, CHT_{30} at 10 and 20 cm was 345 and 66°C h, respectively, and for active solarization CHT_{30} was 755 and 252°C h. The results indicate that active solarization increases soil temperatures and heat stress on plant pests. Based on published pest survival information, observed CHT_{30} after active solarization would provide better control of a plant pest (nematode) than passive solarization. Active solarization may offer a suitable nonchemical alternative to soil fumigation.

The availability of pesticides has been essential in the production of an abundant, nutritious, and low-cost food supply. The use of pesticides in agricultural production has also resulted in contamination of the atmosphere and soil and water resources. In particular, soil fumigants are highly volatile and are prone to rapid diffusion in soil. While this helps promote a uniform soil distribution and effective pest control, high volatility also leads to large atmospheric emissions (Yates et al., 2003).

Air emission inventories conducted in California have demonstrated that pesticides, and predominately fumigants, are a significant source of air pollution. In Fresno County from 1976 to 1995, about 17 Mg of pesticides were emitted into the atmosphere each day (Air Resources Board, 1978, 1997a,b). This represents 4% of the total organic gas emission and 16% of the reactive organic gas emission in this region. Ambient air quality problems caused by inappropriate application of an agricultural fumigant, 1,3-dichloropropene, prompted a 4-yr suspension in California between 1990 and 1994 (California Department of Food and Agriculture, 1990). Also, the agricultural fumigant methyl bromide was scheduled for phase-out in the year 2005 due to its potential for depleting stratospheric ozone (United Nations Environment Programme, 1992, 1995; Federal Register, 2000).

A primary environmental risk associated with the use of fumigants and other pesticides is the release of toxic volatile organic compounds into the atmosphere.

The use of trade, firm, or corporation names in this publication is for the information and benefit of the reader. Such use does not constitute an official endorsement or approval by the USDA-ARS of any product or service to the exclusion of others that may be suitable.

Soil Sci. Soc. Am. J. 75:9–16
Posted online 29 Nov. 2010
doi:10.2136/sssaj2009.0379
Received 2 Oct. 2009.
*Corresponding author (scott.yates@ars.usda.gov).

The problems of bystander exposure and near-surface ozone production have been identified as regulatory concerns.

The concern about fumigant emissions and toxicological risks has led investigators to search for nonchemical pest control alternatives. To date, nonchemical methods have not been widely adopted as replacements for agricultural fumigants in preplant production systems (Noling and Becker, 1994; United Nations Environment Programme, 1995; Noling, 2002; Ajwa et al., 2003). Several nonchemical pest management methods have been studied, which include: solarization (Katan, 1981; Hartz et al., 1993; Gallo et al., 2007), steam sterilization (Awuah and Lorbeer, 1991; Luvisi et al., 2006), biocontrol agents (Jayaraj and Radhakrishnan, 2008), and the use of soil amendments such as *Brassica* spp. (Matthiessen and Kirkegaard, 2006), which can produce natural isothiocyanates and aldehydes that impart some level of pest control.

Soil heating (e.g., soil solarization) is based on observations showing that many pests are sensitive to prolonged exposure to temperatures above a threshold level (Katan, 1981; Heald and Robinson, 1987; Wang et al., 2002). While the temperature and exposure time necessary for adequate pest control varies by organism, the results from these studies indicate that soil temperatures in the treatment zone should be raised in excess of 40°C for several tens of hours to achieve some level of control.

Current solarization technology is characterized by high temperatures at the soil surface and, often, insufficient temperature at depths >25 cm, potentially compromising pest control (Katan, 1981; Dahlquist et al., 2007). This is a possible reason for slow adoption in U.S. agriculture. The transport of heat downward is limited by soil thermal diffusion, relatively large soil heat capacity, and large energy losses that occur during nighttime hours when the energy gradients are directed toward the atmosphere (Katan, 1981). To reduce heat loss at night, thermal barrier (i.e., thermic) films have been developed that reduce the long-wave radiation from the soil to the atmosphere (Chase et al., 1999; Espí et al., 2006).

Most of the current methods to heat soil can be classified as passive processes because soil heating is accomplished by direct input of solar energy and the energy is then transported into the soil via thermal diffusion. Success using this approach relies heavily on factors that affect soil heating, such as soil structure, color, and moisture, air temperature, and solar radiation.

There appears to be very little research reported in the literature investigating new methods to improve soil heating. For example, one potential approach to disinfest soil, termed here *active solarization*, uses solar energy to heat recirculated irrigation water before delivery to the soil via a drip irrigation system. This approach is analogous to solar heating systems for residential pools. The approach was designed to satisfy several constraints, including: (i) the use of common materials and technology currently available to agricultural production systems (e.g., pumps, plastic films, tubing, laterals, and valves), (ii) negligible energy costs, achieved by using solar panels to provide electricity to recirculation pumps and valves, (iii) no additional C emissions from burning fossil fuel to heat water (i.e., steam sterilization), and (iv) the ability to provide soil heating in a targeted manner (e.g., depth and position of the drip line).

A study was conducted to test the hypothesis that active solarization increases soil temperatures and improves soil temperature penetration depth compared with passive solarization. A primary study goal was to determine the merits of this approach and to gain experience with active solarization that would lead to future enhancement in thermal efficiency and future studies of the effect of increased temperatures on plant pests.

The performance indicator used to compare methods was the cumulative thermal time (i.e., a temperature–time index), which has been shown to be correlated with the control of plant pests (Wang and McSorely, 2008). The cumulative heat stress index provides a means of comparing treatments while at the same time providing a reference to the potential to control a plant pathogen. While this approach may have limitations for sublethal temperatures, it provides a first-order approximation that can be used for comparative purposes. If the methodology can be successfully integrated into crop production systems, this technology could provide a cost-effective approach to heat soil and could become an effective nonchemical alternative to soil fumigation.

MATERIALS AND METHODS

Field Site

The field experiment was conducted at the University of California–Riverside's Agricultural Experiment Station. The soil type was an Arlington sandy loam (a coarse-loamy, mixed, active, thermic Haplic Durixeralf), consisting of 64% sand, 29% silt, 7% clay, and 1.3% organic matter, with a pH of 7.2. Several weeks before starting the experiment, the soil was repeatedly irrigated and plowed to bring the moisture content and soil tilth to typical agricultural conditions before soil fumigation; this continued until a few days before the tarp was placed. The initial water content was a fairly uniform 0.08 ± 0.01 m^3 m^{-3} below 0.1 m and 0.04 ± 0.01 m^3 m^{-3} in the surface layer (6 cm). The bulk density was 1.42 ± 0.05 g cm^{-3} in the upper 16 cm of soil and 1.57 ± 0.07 g cm^{-3} below 16 cm.

Four days after installation of the temperature sensors, a plastic film was laid in the field. The experiment began on 30 Sept. 2008, ended on 31 Oct. 2008, and the start time, $t = 0$ d, was defined as 0000 h. Figure 1 shows a schematic of the experimental configuration.

Temperature Sensors

Temperature sensors were installed in triplicate at several depths and distances from the centerline of the plot (see Fig. 1). A narrow trench was excavated and a small rod was inserted about 5 to 10 cm horizontally into the soil at each sensor location. A Type-E (chromel-constantan) thermocouple temperature sensor was then inserted into the channel; pressure was applied to firmly seat the probe into undisturbed soil, and the small hole was backfilled. After installing all of the sensors, the trench was refilled and packed to restore the soil profile.

Plot Construction

The heat recirculation tubing (3.8-cm [1.5-inch] blue lay-flat style vinyl irrigation line) was placed near the edge of the active solarization plot so that the tubing would be covered by the plastic film. A drip irriga-

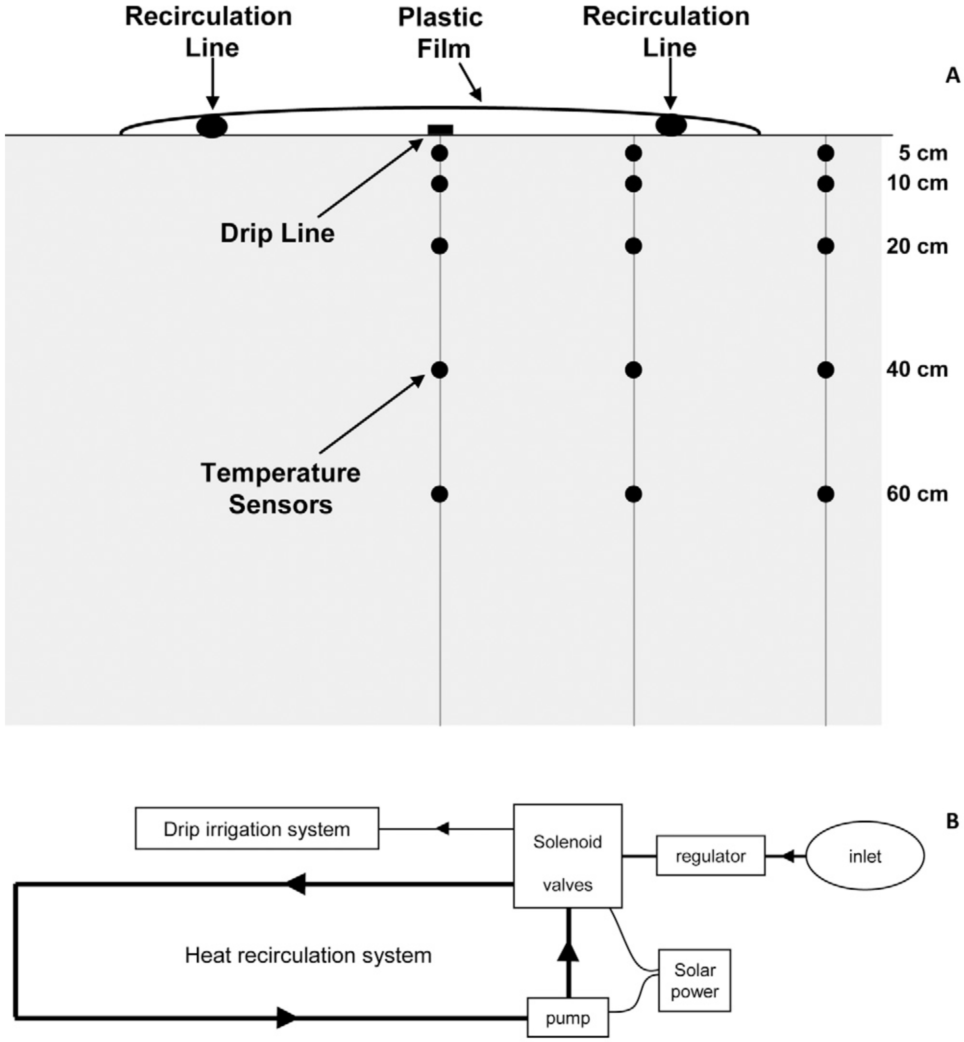

Fig. 1. Schematics of (A) the active solarization plot including the placement of the temperature sensors, plastic film, recirculation lines, and drip irrigation line in a soil cross-sectional view, and (B) the heat recirculation system. The passive solarization plot did not have the drip line or recirculation system; the control plot did not have irrigation, recirculation, or the plastic film.

tion line (2.5 L m^{-1} h^{-1}; 20-cm hole spacing) was placed on the soil surface at the centerline of the plot. Once the irrigation lines were in place, standard high-density polyethylene film was placed on the soil surface and the edges were buried. This produced a 50-m-long by 1-m-wide plot. The passive solarization plot was prepared in a similar manner but did not include the recirculation or drip irrigation lines. The control plot did not include recirculation or drip lines and the soil surface remained bare.

Irrigation and Heat Recirculation

The irrigation system used the field station pressurized water supply. The temperature of the supply water was 26°C and a pressure regulator was installed to provide approximately 83 kPa to the experimental site. Three landscape irrigation valves (Model 075-DV, Rain Bird Corp., Azusa, CA) fitted with latching solenoids (Model TBOSPSOL, Rain Bird Corp.) and a solar-powered recirculation pump (Model D5-38 Vario, Laing Thermotech, Fresno, CA) were used to control the flow of water in the recirculation system. The system was powered by a solar panel and therefore the valves and pumps operated only during sunlit hours. A datalogger was used for control and event timing and to monitor the system water temperature. During sunlit hours, water was either recirculated to increase the water temperature via solar gain or flowed through the drip system to heat the soil in the active solarization plot. When the recirculation system was operating, the master solenoid at the inlet of the pressurized water supply turned on every 30 min, and then turned off 1 min later, to ensure the system would remain pressurized. For the first 8 d of the experiment, the drip system turned on when the recirculated water exceeded 40°C. Afterward, the set point was reduced to 35°C to allow irrigated heating during time periods with reduced solar radiation and cooler air temperatures.

A second test of the solar collector was conducted in July 2009 to determine the heat recirculation during hot summer months. This experiment utilized a configuration similar to that shown in Fig. 1 and used the same valve and pump components. In an attempt to improve performance, several changes were made including the use of a thermic plastic film (Pliant Corp., Schaumberg, IL), which is reported to retain heat better than high-density polyethylene film. Furthermore, a 3.175-cm (1.25-inch) black polyethylene lay-flat tubing was used for the recirculation lines and were placed on top of a layer of 0.1016-mm (4-mil) black polyethylene instead of laying the tubes directly on the soil. Solar collector temperatures were recorded for several days, at which time the solenoid

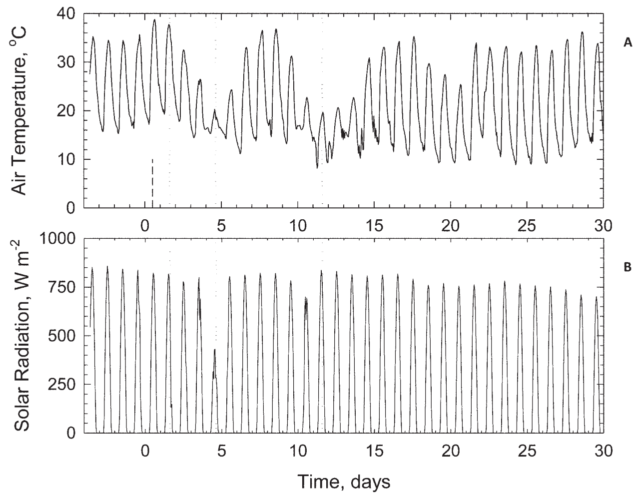

Fig. 2. Air temperature and global solar radiation during the experiment. Dotted lines indicate times for which the cumulative heat stress index was determined. At *t* = 1.6 d, air temperature and solar radiation were high. At *t* = 4.6 d, the air temperature and solar radiation were low and the skies were cloudy. At *t* = 11.6 d, air temperature was low and the solar radiation was high. The dashed line indicates when placing the plastic film on the soil was completed.

valve controlling the irrigation lines failed due to the observed temperatures exceeding the manufacturing limits of the solenoid valve.

Heat Stress Index

To provide a first-order approximation of the potential control of plant pest organisms, a comparison of solarization treatments with respect to their potential to control citrus nematode (*Tylenchulus semipenetrans*) was obtained. Using the data of Xue et al. (2000), the control of citrus nematode could be inferred from data collected during laboratory experiments when the organism was exposed to a temperature of 20 to 45°C for 6 to 24 h. This provided a relatively simple reference point to compare the performance of the solarization treatments.

A pest organism is acclimated to specific environmental conditions. When conditions deviate significantly, the organism's survival may decrease. Once an upper threshold exposure level has been obtained, i.e., where survival is not impacted but any increases in temperature will lead to increased mortality, an environmental heat stress index, $HT_{T_o}(t)$ can be defined as (Wang and McSorely, 2008)

$$HT_{T_o}(t)=\begin{cases}0, & T<T_o\\ \left[T(t)-T_o\right]\Delta t, & T\geq T_o\end{cases} \quad [1]$$

where T_o is the threshold level and Δt is the time interval. Integrating over time produces the cumulative heat stress index (°C h):

$$CHT_{T_o}(t)=\int_0^t HT_{T_o}(\tau)d\tau \quad [2]$$

where τ is an integration variable. This index was used to provide a simple means to evaluate an organism's exposure to soil heat based on the soil temperatures observed in each treatment. From the nematode data presented by Xue et al. (2000), a value of 30°C was used for T_o because the survival of nematodes began to decrease when this temperature was exceeded. It was also determined that 90 to 120°C h would lead to 100% mortality of the citrus nematode (Xue et al., 2000).

RESULTS

Figure 2 shows the air temperature and solar radiation, R_{in}, during the October 2008 experiment. The vertical dashed line at t = 0.5 d (Fig. 2A) indicates the completion time for the installation of the plastic tarp in the field. At the start of the experiment, temperatures were generally warm, with daytime highs several degrees above 30°C and nighttime lows generally <18°C. Two relatively cool periods were observed during the experiment, with durations from 3 to 4 d. On t = 4.6 and 11.6 d (dotted vertical lines) the midday temperatures were between 19 and 20°C, representing the lowest observed during the experiment. The dotted line at t = 1.6 d marks the end of a relatively long warm period. There were 36 daily-peak air temperatures recorded during the experiment; the maximum, average, and minimum values were 38.8, 31.1, and 19.7°C, respectively. The minimum temperature observed during the entire experiment was 8.1°C and the average of all recorded temperatures was 21.2°C.

Solar radiation is a measure of the incoming energy available for heating. Heating of the water in the recirculation system is a result of thermal diffusion and radiative heat transport. At the start of the experiment, R_{in} tended to produce a fairly consistent pattern, with peak radiation levels in excess of 800 W m^{-2} and an average of 218 W m^{-2}. The daily-peak solar radiation maximum, the average of the peaks, and the minimum peak value were 858, 768, and 430 W m^{-2}, respectively.

The three dotted lines in Fig. 2 indicate times that were used to illustrate the potential of active solarization as an improved solarization methodology. At t = 1.6 d, warm temperatures and clear skies occurred leading to high temperatures in the recirculation water (54.8°C). At t = 4.6 d, cool temperatures and cloudy skies were observed and the temperature of the water in the recirculation system (28.6°C) never rose high enough to switch to irrigation mode, therefore, no water was added to the plot. At t = 11.6 d, even though the air temperature was relatively cool, the skies were clear leading to significant warming of the recirculation water (39.4°C), although not as high as observed on warm days. These time points were used to explore the effectiveness of the active solarization system.

Figure 3A shows the temperature of the water at the outlet of the solar collector throughout the 2008 experiment. The daily peak temperatures were routinely >50°C during the first 8 d, with maximum and minimum peak values of 54.9 and 33.2°C, respectively. After 8 d, the set-point temperature was reduced to 35°C and the daily peak values were from 40 to 45°C. During the experiment, the average of the 32 peak temperatures was 43.9 (±4.7) °C.

Shown in Fig. 3B are the solar collector outlet temperatures observed during a solar-collector test conducted in July 2009. The daily peak R_{in} was observed to be about 20% higher and the total daily solar radiation flux was about 40% higher than the October 2008 experiment, which led to higher collector temperatures. The daily peak temperatures were routinely at or above 60°C (i.e., the set-point temperature). The maximum, average, and minimum peak temperature values were 69.9, 60.8 (±3.8), and 49.0°C, respectively.

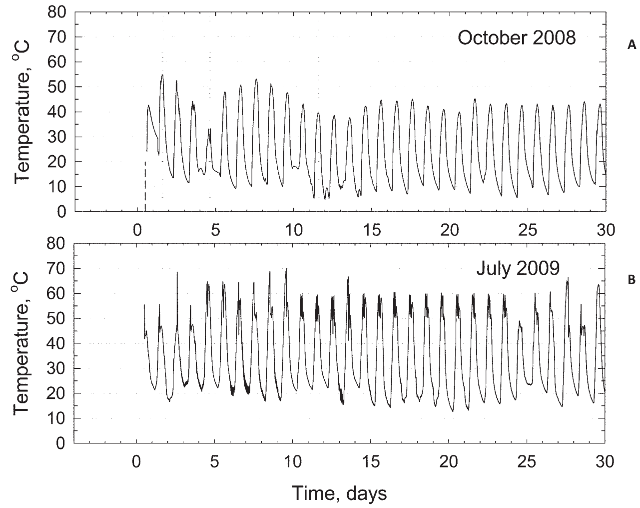

Fig. 3. Temperature of the water (A) at the solar collector outlet during the experiment, and (B) during July 2009 from a solar collector using 3.175-cm (1.25-inch) black polyethylene lay-flat tubing.

Figure 4 provides a cross-sectional view of the soil temperature pattern in the three plots for warm and sunny (Fig. 4A, t = 1.6 d), cool and sunny (Fig. 4B, t = 11.6 d), and cool and cloudy (Fig. 4C, t = 4.6 d) conditions in October 2008. For all three cases, the active solarization plot had higher maximum temperatures than the passive and control plots. Even when air temperatures were relatively cool, the active solarization plot experienced a significant temperature increase in the region near the drip line. Under cloudy conditions, residual heat buildup and reduced heat loss produced slightly higher temperatures compared with passive solarization.

The increase in the average daily maximum soil temperatures at 5, 10, and 20 cm for the passive and active solarization are shown in Table 1 for several 4-d periods during the experiment. Also shown are the averaged maximum bare soil temperature, the air temperature, and R_{in} values. The 4-d average solar radiation decreased from 804 to 641 W m^{-2} during the experiment. Passive solarization produced soil temperature increases of as high as 8°C at 5 cm and 3.8°C at 10 and 20 cm compared with bare soil. Active solarization produced even larger increases in temperature compared with bare soil: 10.8°C at 5 cm, 6.1°C at 10 cm, and 7.5°C at 20 cm.

Shown in Fig. 5 are the cumulative heat stress index, CHT_{30}, values during the experiment at three depths in the active solarization, passive solarization, and control plots. Because the soil temperature exceeded 30°C for short periods during a day, the CHT_{30} curve increases in a stair-step fashion. The use of plastic film to cover the soil surface increased soil heating compared with the bare surface (i.e., the control plot). After 30 d of passive solarization, the 5-cm depth zone experienced CHT_{30} values that exceeded 900°C h, compared with approximately 100°C h for the control plot.

For active solarization, the CHT_{30} increased to nearly 1500°C h after 30 d and was 63% higher than the passive solarization plot. Active solarization also had higher values at the 10-cm (114%) and 20-cm (284%) depths compared with passive solarization. The spatial pattern of CHT_{30} after 30 d is shown in Fig. 6. This figure gives a cross-sectional view for the active solarization, passive solarization, and control

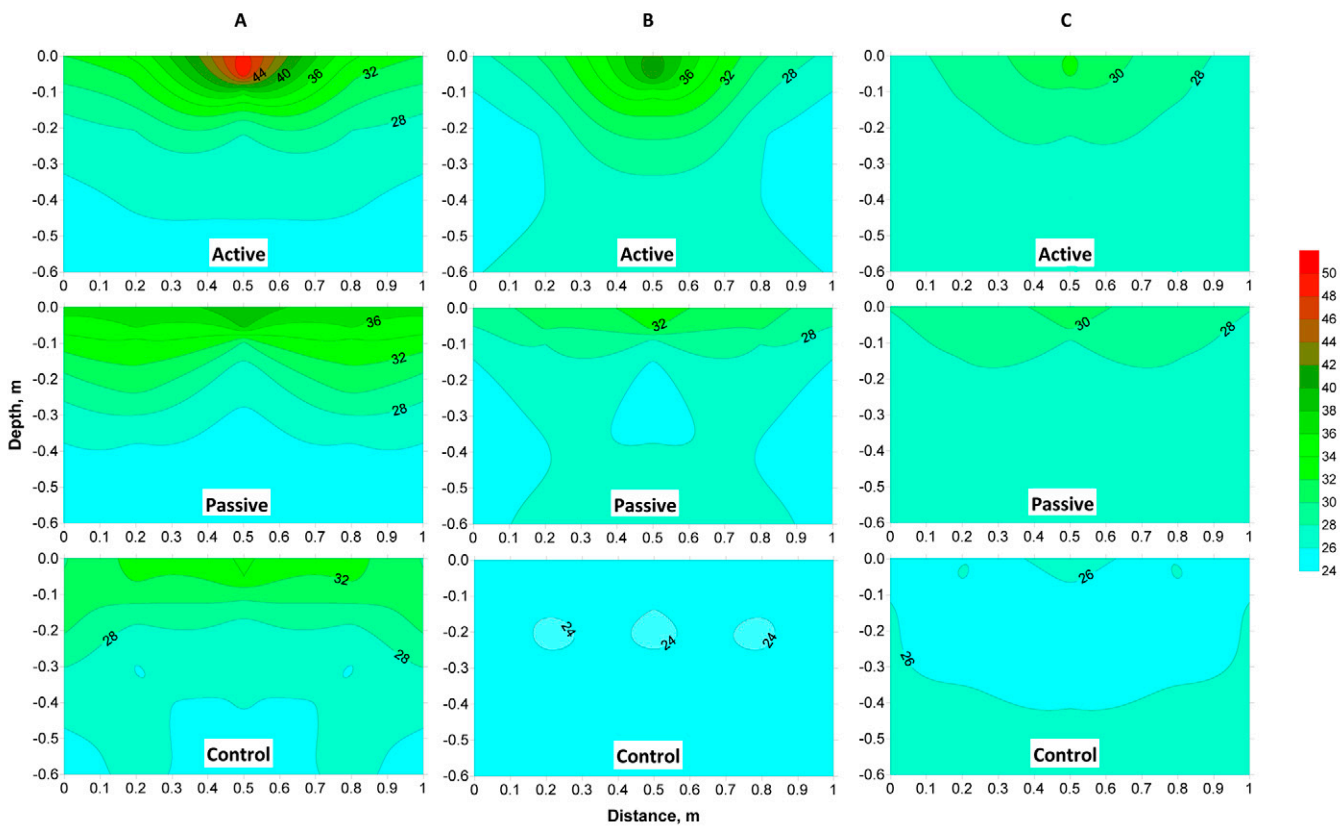

Fig. 4. Soil temperature (°C) cross-sections for the active solarization, passive solarization, and control plots: (A) warm temperature and clear sky conditions (t = 1.6 d); (B) cool temperatures and clear skies (t = 11.6 d); and (C) cool temperatures and cloudy conditions (t = 4.6 d). The sampling positions were the same for all plots, but for clarity, the positions are only shown in C(active). Rotational symmetry along the line (0.5, 0.0; 0.5, −0.6) has been assumed.

Table 1. Comparison of soil temperature at the 5-, 10-, and 20-cm depths after active and passive solarization. Solar radiation was collected at the field site. Temperature increases are relative to the bare soil plot. Day 0 began on 30 Sept. 2008 and values are the averages of the four daily maxima during each time period.

Time period	Daily max. temperature increase						Daily max.		
	Passive solarization			Active solarization			Bare soil temp.	Air temp.	Solar radiation
	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm			
	°C								W m^{-2}
Days 0–3	7.8	2.3	3.5	9.0	3.5	3.5	31.0	34.3	804
Days 10–13	8.0	3.8	3.4	10.4	6.1	5.6	25.6	21.9	796
Days 20–23	7.6	2.6	3.8	10.8	5.9	7.5	26.8	31.4	767
Days 28–31	6.2	1.8	3.0	9.3	5.5	6.6	26.5	32.3	641

plots. As shown in Fig. 1, temperature probes were installed in half of the plot, so this figure was prepared by assuming rotational symmetry around a vertical line at the drip line.

DISCUSSION

Soil Temperatures

It has been long known that solarization can be effective for increasing soil temperatures in warm, semiarid regions. In general, the timing of a solarization coincides with maximum air temperature and solar irradiance. In the northern hemisphere, solarization is commonly conducted in June and July and continues for several weeks to months (Katan, 1981; Hartz et al., 1993). In the southern hemisphere, solarization has been shown to be effective when conducted in January (Porter and Merriman, 1985).

Mahrer (1979) found that soil covered with a plastic film increased the soil temperature by 9°C at 5 cm and approximately 6°C deeper in the soil (i.e., 10 and 20 cm). Likewise, Porter and Merriman (1985) observed increases in soil temperature after covering the soil with a 50-μm polyethylene film. At 5 cm, the solarized plots had an average increase in maximum soil temperatures of as much as 14°C. At 10 and 20 cm, solarization increased temperatures by as much as 12 and 9°C, respectively. Iapichino et al. (2008) found that the average daily soil temperatures measured at the 15-cm depth in solarized plots in each of 4 yr (2001–2004) led to soil temperatures that were 6.0, 8.1, 7.8, and 8.4°C higher, respectively, than the control.

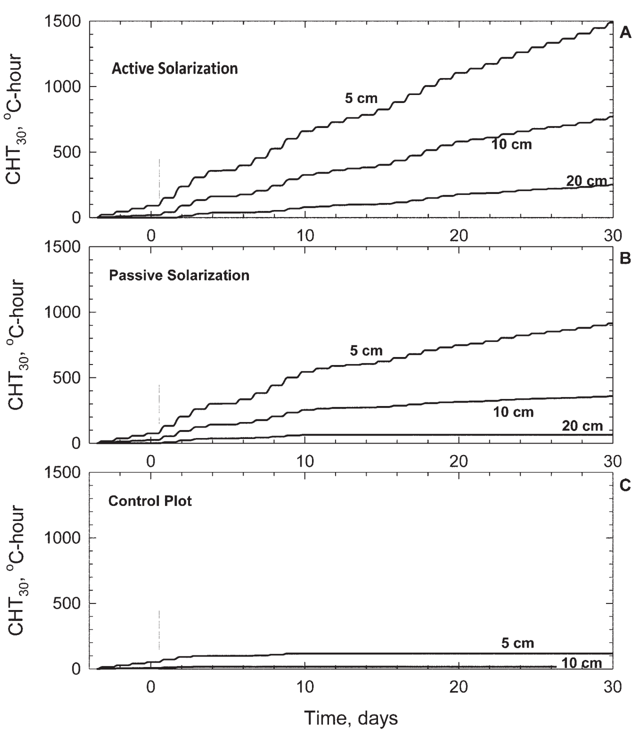

Fig. 5. Cumulative heat stress index, CHT$_{30}$, as cumulative degree hours >30°C at the 5-, 10-, and 20-cm depths for the (A) active solarization, (B) passive solarization, and (C) control plots. For the control plots, CHT$_{30}$ was 0 at the 20-cm depth at all times. The calculation for CHT$_{30}$ started as soon as the tarp installation was completed (dashed line). Day 0 was 30 Sept. 2008.

In some coastal settings that are strongly influenced by the marine environment (i.e., cloud cover, cool temperatures, etc.), solarization is often less reliable (Ajwa et al., 2003). Although site-specific characteristics determine the feasibility and reliability of the approach, successful solarization experiments have been conducted in these areas. For example, Hartz et al. (1993) observed soil temperature increases of as much as 9 to 12°C at shallow depth (i.e., 2–10 cm) and 6 to 9°C at deeper (i.e., 20–30-cm) depths during a 2-yr period, even though the mean daily maximum air temperature was relatively moderate (27–28°C).

These passive solarization studies reported similar results to our active solarization treatment, which, compared with the control, yielded soil temperature increases of 9.0 to 10.8°C at 5 cm, 3.5 to 6.1°C at 10 cm, and 3.5 to 7.5°C at 20 cm (Table 1). In addition, the soil temperature increases of 6.2 to 8.0°C at 5 cm, 1.8 to 3.8°C at 10 cm, and 3.0 to 3.8°C at 20 cm in the passive solarization plot were generally well below the values observed by others using the passive approach. It is significant, however, that in the current study, the timing of the active solarization experiment (October) was well after the yearly maximum in solar radiation (July). Therefore, a main goal of this study was to determine if improved heating of the soil profile occurs for active solarization under conditions of lower ambient temperature and solar radiation compared with traditional passive solarization under maximized ambient temperature and solar radiation. Moreover, the probable enhanced benefit from using active solarization during times of highest solar radiation is discussed below.

Solar Radiation

While ambient temperatures are often provided along with measurements of increased soil temperature during solarization, very few studies have reported solar radiation measurements. Solar radiation, R_{in}, drives the heating process in both the atmosphere and the soil and plays an important role in soil solarization (Mahrer,

Table 2. Estimated maximum solar radiation flux density (R_{in},) and the daily (24-h) total flux (Q_{in},) for several solarization experiments.

Location	Date	Estimated R_{in}	Measured R_{in}	Estimated Q_{in}
		W m^{-2}		MJ m^{-2}
Riverside, CA	27 Sept. 2008	844	859	20.6
Riverside, CA	28 July 2009	1017	1004	28.8
Rehovot, Israel (Mahrer, 1979)	16 May 1978	1039	–	29.0
Irymple, Australia (Porter and Merriman, 1985)	1 Feb. 1982	1067	–	29.8
Marsala, Sicily (Iapichino et al., 2008)	15 July 1999	1045	–	27.4
South Coast Field Station, CA (Hartz et al., 1993)	14 July 1989	1033	–	29.5

1979; Coelho et al., 1999). The downward transport of heat depends on many soil factors such as moisture content, soil type, albedo, the use of plastic film, the type of film material, etc., and differences in these factors lead to variable experimental results.

The effectiveness of solarization depends, in large part, on the R_{in}. When measurements are provided, this information can provide valuable insights into the heating process. During the October 2008 experiment, the daily maximum R_{in} decreased with time (Table 1) from 804 to 641 W m^{-2}, or in terms of 24-h total flux values, from 22 MJ m^{-2} to 16.4 MJ m^{-2}. These values are considerably lower than those reported by Katan (1981), who indicated that passive solarization is appropriate for locations that receive 25 to 27 MJ m^{-2} during a 24-h period. In terms of flux density values, this translates to a maximum R_{in} of approximately 900 to 1000 W m^{-2}, which commonly occurs in southern California during midsummer.

Tamietti and Vallentino (2006) conducted experiments where R_{in} was high during the experiment (daily peak values of 924–1046 W m^{-2}). They found that solarization increased the average soil temperature at 25 cm by as much as 13 to 16°C when the soil was covered with plastic film and then the entire plot was covered with a plastic tunnel. Adding the plastic tunnel probably increased soil temperatures by an additional 4°C due, in part, to increasing the air temperature above the plastic film. The temperature increase of approximately 12°C (plastic film only) at 25 cm is very large when compared with other studies reported in the literature. Relatively high inputs of solar energy probably helped to contribute to the deeper heating.

Using the method of Ryan and Stolzenbach (1972), a comparison of estimated daily maximum R_{in} can be made for those experiments that don't provide a direct measurement (Table 2). By comparing the measured and estimated R_{in} for Riverside, CA, the accuracy of the method can be established. The estimated R_{in} for several experiments reported in the literature had values that were approximately 25% higher than measured during the October 2008 experiment. The results from this experiment indicate that active solarization improves heat transport and leads to soil heating that is about the same as passive experiments conducted under nearly maximum R_{in} conditions.

Thermal Accumulation

While maximum temperatures in the soil are an important consideration in the efficiency of solarization, temperature alone may not always be sufficient for effective pest control, especially when maximum temperatures are in the sublethal range (Freeman and Katan, 1988). Under these conditions, a variety soil and environmental factors can influence survivability. Experiments have shown, however, that for sufficiently high temperatures and exposure times, temperature alone may be effective in controlling pest organisms (Luvisi et al., 2006; Fields, 1992). Nevertheless, the required temperature level and exposure time is specific to the pest organism.

An indicator that is commonly used to correlate organism survival to soil temperature uses the accumulation of thermal stress (Tamietti and Vallentino, 2006; Iapichino et al., 2008). The relationship between exposure time and temperature is important in determining the probable effectiveness of a treatment (Fields, 1992) and for distinguishing between temperatures that would probably

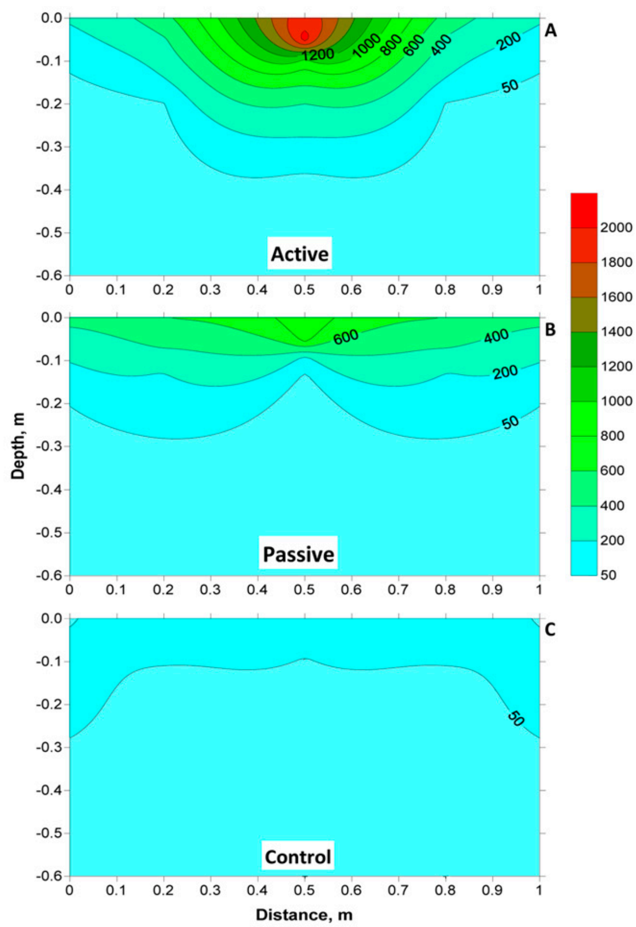

Fig. 6. Cumulative heat stress index, CHT_{30} (°C h), after 30 d (October 2008) for a soil cross-section of the (A) active solarization, (B) passive solarization, and (C) control plots. Below the 0.5-m depth in all plots, the CHT_{30} value was 0. The sampling positions were the same for all plots, but for clarity, the positions are only shown for the control plots. Rotational symmetry along the line (0.5, 0.0; 0.5, −0.6) has been assumed.

be lethal or sublethal. This information provides a guide to the temperatures needed to yield control under normal circumstances.

For active solarization, using a 30°C temperature threshold, the measured cumulative heat stress index increased to values in excess of 1500°C h near the irrigation line and dropped to about 400°C h at a depth of 20 cm (Fig. 6). This compares with approximately 600°C h for passive solarization near the surface and about 100°C h at 20 cm. Based on the results of Xue et al. (2000), citrus nematodes would not be controlled unless CHT_{30} values were in excess of 120°C h. Therefore, as a first-order approximation, active solarization resulted in CHT_{30} values that were sufficiently large to control citrus nematodes within a 30-cm radius of the drip line. For passive solarization, control would be limited to a 10- to 20-cm radius. For the bare soil plot, nematode populations would be unaffected.

From Fig. 6, it is clear that irrigation management would be an important consideration in developing a uniformly heated soil treatment zone. For agronomic applications, more than one drip line per meter width of soil would probably be used for irrigation purposes. For example, in strawberry (*Fragaria* × *ananassa* Duchesne ex Rozier) production, 75-cm beds (130 cm center to center) are commonly used (Hartz et al., 1993). The beds frequently have two drip lines that are placed on top of the bed and separated by 20 to 30 cm. Such a configuration would lead to a more uniform temperature pattern across the treatment zone than the results shown in Fig. 6.

CONCLUSIONS

Using solar energy to heat irrigation water increased soil temperatures compared with bare-soil and passive solarization conditions. The experiment was conducted during a period of reduced solar radiation and cooling air temperatures (i.e., the fall season). Active solarization resulted in soil temperatures and cumulative heat stress index values that were similar to levels found in experiments conducted during midsummer.

Active solarization during the summer would probably increase heating and improve pest control compared with active solarization conducted in the fall (i.e., October). These preliminary results indicate that active solarization may be a useful nonchemical alternative to soil fumigation for controlling plant pest organisms.

A significant advantage of this approach, if shown to work in large-scale production systems, is the reduced dependence on soil fumigants and associated reduction in public and environmental health risks from the use of toxic organic chemicals. This new method to heat the soil may provide another approach for controlling plant pests in an environmentally benign manner.

ACKNOWLEDGMENTS

The research was funded by USDA-ARS Project 5310-12130-008-00D. We gratefully acknowledge Qiaoping Zhang and Dr. Fred Ernst for assistance setting up the field site and conducting the experiments.

REFERENCES

Air Resources Board. 1978. Air pollution emissions associated with pesticide applications in Fresno County. Rep. ARB A7-047-30. Air Resour. Board, Sacramento, CA.

Air Resources Board. 1997a. Draft emission inventory report—1995. Air Resour. Board, Sacramento, CA.

Air Resources Board. 1997b. Draft emission inventory tables—1995. Air Resour. Board, Sacramento, CA.

Ajwa, H., S. Klose, S. Nelson, A. Minuto, M.L. Gullino, F. Lamberti, and J.M. Lopez-Aranda. 2003. Alternatives to methyl bromide in strawberry production in the United States of America and the Mediterranean region. Phytopathol. Mediterr. 42:220–244.

Awuah, R.T., and J.W. Lorbeer. 1991. Methyl-bromide and steam treatment of an organic soil for control of fusarium yellows of celery. Plant Dis. 75:123–125.

California Department of Food and Agriculture. 1990. Use of pesticide suspended by CDFA. News Release 90-45. 13 April. CDFA, Sacramento.

Chase, C.A., T.R. Sinclair, D.O. Chellemi, S.M. Olson, J.P. Gilreath, and S.J. Locascio. 1999. Heat-retentive films for increasing soil temperatures during solarization in a humid, cloudy environment. HortScience 34:1085–1089.

Coelho, L., D.O. Chellemi, and D.J. Mitchell. 1999. Efficacy of solarization and cabbage amendment for the control of *Phytophthora* spp. in North Florida. Plant Dis. 83:293–299.

Dahlquist, R.M., T.S. Prather, and J.J. Stapleton. 2007. Time and temperature requirements for weed seed thermal death. Weed Sci. 55:619–625.

Espí, E., A. Salmerón, Y. Fontecha, Y. García-Alonso, and A.I. Real. 2006. New ultrathermic films for greenhouse covers. J. Plast. Film Sheeting 22:59–67.

Federal Register. 2000. Protection of stratospheric ozone: Incorporation of Clean Air Act amendments for restrictions in Class I, Group VI controlled substances. 65:70795–70804.

Fields, P.G.J. 1992. The control of stored-product insects and mites with extreme temperatures. J. Stored Prod. Res. 28:89–118.

Freeman, S., and J. Katan. 1988. Weakening effect on propagules of fusarium by sublethal heating. Phytopathology 78:1656–1661.

Gallo, L., F. Siverio, and A. Rodrıguez-Perez. 2007. Thermal sensitivity of *Phytophthora cinnamomi* and long-term effectiveness of soil solarisation to control avocado root rot. Ann. Appl. Biol. 150:65–73.

Hartz, T.K., J.E. DeVay, and C.L. Elmore. 1993. Solarization is an effective soil disinfestation technique for strawberry production. HortScience 28:104–106.

Heald, C.M., and A.F. Robinson. 1987. Effects of soil solarization on *Rotylenchulus reniformis* in the lower Rio Grande Valley of Texas. J. Nematol. 19:93–103.

Iapichino, G., C. Prinzivalli, and F. D'Anna. 2008. Soil solarization as an alternative to methyl bromide fumigation for annual strawberry production in a Mediterranean area. J. Sustain. Agric. 32:365–375.

Jayaraj, J., and N.V. Radhakrishnan. 2008. Enhanced activity of introduced biocontrol agents in solarized soils and its implications on the integrated control of tomato damping-off caused by *Pythium* spp. Plant Soil 304:189–197.

Katan, J. 1981. Solar heating (solarization) control of soilborne pests. Annu. Rev. Phytopathol. 19:211–236.

Luvisi, A, A. Materazzi, and E. Triolo. 2006. Steam and exothermic reactions as alternative techniques to control soil-borne diseases in basil. Agron. Sustain. Dev. 26:201–207.

Mahrer, Y. 1979. Prediction of soil temperatures of a soil mulched with transparent polyethylene. J. Appl. Meteorol. 18:1263–1267.

Matthiessen, J.N., and J.A. Kirkegaard. 2006. Biofumigation and enhanced biodegradation: Opportunity and challenge in soilborne pest and disease management. Crit. Rev. Plant Sci. 25:235–265.

Noling, J.W. 2002. The practical realities of alternatives to methyl bromide: Concluding remarks. Phytopathology 92:1373–1375.

Noling, J.W., and J.O. Becker. 1994. The challenge of research and Extension to define and implement alternatives to methyl bromide. J. Nematol. 26:573–586.

Porter, I.J., and P.R. Merriman. 1985. Evaluation of soil solarization for control of root diseases of row crops in Victoria. Plant Pathol. 34:108–118.

Ryan, P.J., and K.D. Stolzenbach. 1972. Engineering aspects of heat disposal from power generation. Dep. of Civ. Eng., Mass. Inst. of Technol., Cambridge.

Tamietti, G., and D. Vallentino. 2006. Soil solarization as an ecological method for the control of fusarium wilt of melon in Italy. Crop Prot. 25:389–397.

United Nations Environment Programme. 1992. Methyl bromide: Its atmospheric science, technology, and economics. U.N. Headquarters, Nairobi, Kenya.

United Nations Environment Programme. 1995. UNEP 1994 report of the Methyl Bromide Technical Options Committee. U.N. Headquarters, Nairobi, Kenya.

Wang, K.H., and R. McSorely. 2008. Exposure time to lethal temperatures for *Meloidogyne incognita* suppression and its implication for soil solarization. J. Nematol. 40:7–12.

Wang, S., J.N. Ikediala, J. Tang, and J.D. Hansen. 2002. Thermal death kinetics and heating rate effects for fifth-instar *Cydia pomonella* (L.) (Lepidoptera: *Tortricidae*). J. Stored Prod. Res. 38:441–453.

Xue, S.K., J. Gan, S.R. Yates, and J.O. Becker. 2000. Nematode response to methyl bromide and 1,3-dichloropropene soil fumigation at different temperatures. Pest Manage. Sci. 56:737–742.

Yates, S.R., J. Gan, and S.K. Papiernik. 2003. Environmental fate of methyl bromide as a soil fumigant. Rev. Environ. Contam. Toxicol. 177:45–122.