plants corn in cold soils and then places a rowcover over the rows, poor germination and emergence still can result. Under cloudy conditions, the soil does not warm fast enough, and the corn seed imbibes cold water, which will slow germination. While the herbicides do not cause the problem, they can accentuate it. If soil temperature is adequate and rowcovers are ventilated, the likelihood of crop injury is greatly reduced. Another example involves high temperatures. Although solid clear tunnels are excellent for rapid soil warming, excessive air temperatures under the cover can kill the crop. This can result regardless of whether or not a herbicide was used. It is important to monitor air temperatures under rowcovers and ventilate or remove rowcovers if air temperature becomes extreme [e.g., 100 °F (38 °C)].

In conclusion, weed management in plasticulture requires a higher level of management than bare-ground culture. Observing all of the guidelines above will go a long way to ensure effective weed control with minimal adverse crop effects.

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Fumigation and Solarization Practice in Plasticulture Systems

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Summary. Soil disinfestation strategies for intensive vegetable crop production, which have relied heavily on chemical fumigants for the past 40 years, are now undergoing rapid change. The principal driving force of change has been governmental regulatory action to phase out chemicals with properties deemed to be hazardous to the environment and/or public health. Softer methods of soil disinfestation, which rely more on physical, cultural, biological, or integrated modes of action, likely will predominate in future vegetable-cropping systems. In conducive (i.e., warm) climates, solarization can be adopted economically in plasticulture systems. Solarization can be combined with other chemical, physical, and biological methods for enhanced management of soil and root pests and diseases.

Agricultural production systems using plasticulture are necessarily those of intensively managed, high-value crops. Sophisticated microirrigation systems, including surface or subsurface drip, often are used in this type of production. The input costs are high, and production quantity and quality must be maximized to recoup the risk capital involved. In

many cases, land used for this type of agriculture is in use almost constantly, with one or several crops planted and harvested each year. The land may not be rested periodically, and production costs may be too high to allow for soil-building rotations or cover crops to fit into the schedule. Under these conditions, inoculum of soil-borne diseases (caused by fungi, bacteria, viruses, and nematodes) and pests (including insects and weed propagules) may build up in sufficient numbers to threaten the high-value crops with economically catastrophic damage.

Recent history of soil disinfestation

Under intensive crop cultivation, soil disinfestation may provide the difference between reasonable profit and total crop loss. For the past 50 years, the chemical soil disinfestants have allowed such intensive cropping schemes to exist. Coming into widespread use after World War II, and using many compounds generated as by-products of the war effort, farmers reaped the benefits of highly effective, relatively inexpensive soil disinfestants such as 1,2-dichloropropane/1,3-dichloro-propene (D-D mixture), methyl bromide, chloropicrin, ethylene dibromide (EDB), and others (Newhall, 1955). Interest and practice in older, nonchemical strategies for managing soil-borne pest problems waned as the new fumigant compounds provided what seemed to be the long-sought-after magic bullet treatment. Hand in hand with new fertilizer formulations, which provided plants with optimal fertility levels, the readily available soil fumigant chemicals allowed a tremendous upward leap in crop productivity (Johnson and Feldmesser, 1987).

After 30 years of continual use, however, problems began to arise in the mid-1970s from overdependence on chemical fumigants, particularly in the irrigated valleys of the arid western United States. Due to the sheer volume of fumigant chemicals that had been poured into the sandy desert soils, accumulations of these products entered into the groundwater reserves and began to show up in drinking-water supplies in several metropolitan areas. In addition, public sentiment was stirred by reports of worker illnesses and deaths in United States facilities manufacturing fumigants such as DBCP and EDB. Governmental regulatory actions began to take effect and several fumigant chemicals were forced off the market. Intensive agriculture soon found itself in a situation in which only a few chemical soil disinfestants remained available, and efforts are underway to limit or phase out those that do remain on the market (Grossman and Liebman, 1995; Stapleton and DeVay, 1995).

Soil fumigation

Methyl bromide is widely considered to be the best chemical soil fumigant, providing excel-

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lent control of many nematode, fungal, and weed pests. It is also among the most expensive, with custom, tarped applications costing \$1000 to \$1200 per acre. Another fumigant, 1,3-dichloropropene, approaches the efficacy of methyl bromide as a nematicide but has lower efficacy on other targeted pest organisms. In addition to the true fumigants, quasi-fumigants such as metam sodium often are used, along with other nonfumigant fungicides, nematicides, and herbicides, and generally are not as effective. All of the fumigants and some of the quasi-fumigants are highly phytotoxic and must be used as preplant treatments only, while other quasi- and nonfumigant soil pesticides can be applied while crops are growing.

One of the drawbacks of highly biocidal fumigant treatments is the creation of biological vacuums in which the pest organisms and those that are beneficial are destroyed. Many beneficial organisms are naturally antagonistic to soilborne pests, representing a naturally occurring mechanism of biological control in soil. After fumigation, pest organisms that are redeposited in treated soil (e.g., via contaminated seed or soil on farming equipment) may be able to freely proliferate in the absence of their natural enemies (Stapleton and DeVay, 1983; Stapleton and Heald, 1991).

Broadcast application is still the most common method of treating soil with disinfestants, although, with intensive vegetable production systems moving toward drip irrigation, more chemigation techniques have been used or tested to apply materials through irrigation systems. There are advantages and disadvantages of both methods. Broadcast application treats the greatest soil volume and allows efficient coverage with highly volatile fumigant materials. Application of soil disinfestants through irrigation systems is made most often with materials such as metam sodium, and pest control results have been inconsistent (Browne et al., 1994). Methyl bromide traditionally is applied in the United States by injecting the liquefied product through shanks into soil, where it vaporizes and diffuses through the soil atmosphere, knocking out a wide spectrum of soilborne organisms. However, in other parts of the world, a hot gas method is used to apply methyl bromide, using a generator to vaporize the liquid and pump it through perforated tubing on the soil surface while a plastic tarp covering the soil surface contains the material. The hot gas technique may be adapted to allow application of methyl bromide through drip irrigation systems.

Currently, the future of methyl bromide remains unclear. Complete phaseout of the chemical for soil fumigation is scheduled within 5 to 10 years. However, much political action, for and against methyl bromide use, is now underway. Given a perceived unfriendly horizon for registration of new fumigant chemicals, along with the high registration costs necessary for new synthetic pesticides (\$20 to \$30 million), it is likely

Table 1. Representative plant pathogens controlled by soil solarization.²

	Species controlled
Fungi	<i>Bipolaris sorokiniana</i>
	<i>Didymella lycopersici</i>
	<i>Fusarium oxysporum</i>
	f. sp. <i>conglutinans</i>
	f. sp. <i>fragariae</i>
	f. sp. <i>lycopersici</i>
	f. sp. <i>vasinfectum</i>
	<i>Phytophthora cinnamomi</i>
	<i>Plasmidiophora brassicae</i>
	<i>Pyrenochaeta lycopersici</i>
	<i>Pyrenochaeta terrestris</i>
	<i>Pythium ultimum</i>
	<i>Rhizoctonia solani</i>
	<i>Sclerotium cepivorum</i>
	<i>Sclerotinia minor</i>
	<i>Sclerotium oryzae</i>
	<i>Sclerotium rolfsii</i>
	<i>Thielaviopsis basicola</i>
	<i>Verticillium dahliae</i>
	<i>Verticillium albo-atrum</i>
Bacteria	<i>Agrobacterium tumefaciens</i>
	<i>Streptomyces scabies</i>
Nematodes	<i>Criconebella xenoplax</i>
	<i>Ditylenchus dipsaci</i>
	<i>Globodera rostochiensis</i>
	<i>Helicotylenchus digonicus</i>
	<i>Heterodera schachtii</i>
	<i>Meloidogyne hapla</i>
	<i>Meloidogyne javanica</i>
	<i>Paratrichodorus porosus</i>
	<i>Paratylenchus hamatus</i>
	<i>Paratylenchus penetrans</i>
	<i>Paratylenchus thornei</i>
	<i>Paratylenchus vulnus</i>
	<i>Tylenchulus semipenetrans</i>
	<i>Xiphinema</i> spp.
	Species partially or not controlled
	<i>Fusarium oxysporum</i> f. sp. <i>opini</i>
	<i>Macrophomina phaseolina</i>
	<i>Meloidogyne incognita</i>
	<i>Paratylenchus neaomlycecephalus</i>
	<i>Pythium aphanidermatum</i>

²Adapted from Stapleton and DeVay (1986).

that intensive agriculture will continue to operate with a dwindling arsenal of fumigants for the foreseeable future. Under this scenario, it will be desirable, perhaps necessary, for an historically fumigant-dependent industry to develop and adopt alternative soil disinfestation technologies. Agricultural scientists now are making concentrated research efforts worldwide to develop soil treatments that can replace methyl bromide effectively.

Solarization

In the present atmosphere of reduced pesticide usage in agriculture, solarization is becoming an increasingly important method of soil disinfestation for high-value crops (Stapleton and DeVay, 1995). Solarization is a passive hydrothermal process of disinfesting soil by using solar radiation trapped under plastic mulch to create a greenhouse effect, heating soil to temperatures that are deleterious or lethal to a broad spectrum of soil-borne pathogens and pests (DeVay and Katan, 1991; Elmore, 1991; Katan, 1987; Stapleton, 1991; Stapleton and DeVay, 1986). Clear plastic usually is used for solarization to transmit solar heat as deeply as possible into the soil. Periods of solarization in production fields generally range from 3 to 6 weeks. Techniques for predicting treatment duration and efficacy (e.g., the day when a solarization treatment is done) by soil temperature along have not been widely used commercially users because of the passive and complex mode of action of the process. Although a detailed discussion of soil heating dynamics is beyond the scope of this paper, it should be noted that the heat dosages of solarization, which is a relationship of soil temperature $\times$ time, is affected by many factors. Some of the more important physical components affecting soil temperature during solarization include diurnal air temperature maxima, minima, and duration; wind speed and duration; soil texture, color, and moisture content; and characteristics of the mulch film.

Another critical treatment component is the thermal sensitivity of the target pests, which varies widely among species. In many cases, it is not necessary to kill pest organisms—they may be weakened by sublethal heat (in general soil temperatures below 100 to 104 °F) to the extent that they are unable to damage plants. At the other extreme, solarization of containerized soil may be accomplished within 1 week during periods of hot weather. For example, moist soil in black polyethylene nursery sleeves covered by a single layer of clear plastic film reached 149 °F, and, in sleeves covered by a double plastic layer, temperatures reached nearly 160 °F in the San Joaquin Valley of California. These temperatures are lethal to most soil-borne pests within a few hours and approach the heat levels produced during soil infestation using aerated steam.

In addition to heat, other mechanisms of physical, chemical, and biological control have been shown to be involved in the solarization process (Chen et al., 1991; Katan, 1987; Stapleton and DeVay, 1986). There is now a long list of organisms that have been shown to be susceptible to the effects of solarization, including many fungi, bacteria, nematodes (Table 1), and weeds (Tables 2 and 3) (DeVay and Katan, 1991; Elmore, 1991; Katan, 1987; Stapleton, 1991; Stapleton and DeVay, 1986).

Because of its passive nature, solarization by

Table 2. Susceptibility of annual weeds to soil solarization.²

Winter, controlled	Summer, controlled	Summer, partially or not controlled
<i>Anagalis coerulea</i>	<i>Abutilon theophrasti</i>	<i>Anchusa aggregata</i>
<i>Arum italicum</i>	<i>Alhagi maurorum</i>	<i>Astragalus boeticus</i>
<i>Avena fatua</i>	<i>Amaranthus blitoides</i>	<i>Conyza canadensis</i>
<i>Brassica niger</i>	<i>Amaranthus retroflexus</i>	<i>Crozophora tinctoria</i>
<i>Capsella bursa-pastoris</i>	<i>Anoda cristata</i>	<i>Malva niceaensis</i>
<i>Capsella rubella</i>	<i>Carthamus syriacus</i>	<i>Melilotus sulcatus</i>
<i>Centaurea iberica</i>	<i>Chenopodium album</i>	<i>Portulaca oleracea</i>
<i>Chrysanthemum coronarium</i>	<i>Chenopodium murale</i>	<i>Scorpiurus muricatus</i>
<i>Daucus aureus</i>	<i>Chenopodium pumila</i>	<i>Solanum luteum</i>
<i>Emex spinosa</i>	<i>Commelina communis</i>	<i>Xanthium strumarium</i>
<i>Erodium spp.</i>	<i>Conyza bonarinsis</i>	
<i>Heliotropium suaveolus</i>	<i>Coronilla scorpiodes</i>	
<i>Hordeum leporinum</i>	<i>Hypericum crispus</i>	
<i>Lactuca scariola</i>	<i>Ipomoea lacunosa</i>	
<i>Lamium amplexicaule</i>	<i>Lavatera cretica</i>	
<i>Medicago polymorpha</i>	<i>Malva parviflora</i>	
<i>Mercurialis annua</i>	<i>Malva sylvestris</i>	
<i>Montia perfoliata</i>	<i>Orobancha aegyptica</i>	
<i>Notobasis syrica</i>	<i>Orobancha crenata</i>	
<i>Papaver dubium</i>	<i>Orobancha ramosa</i>	
<i>Phalaris brachystachys</i>	<i>Polygonum persicaria</i>	
<i>Phalaris paradoxa</i>	<i>Polygonum polyspermum</i>	
<i>Poa annua</i>	<i>Proscopis furcata</i>	
<i>Polygonum equisetiforme</i>	<i>Setaria glauca</i>	
<i>Raphanus raphanistrum</i>	<i>Cyperus spp.</i>	
<i>Senecio vernalis</i>	<i>Sida spinos</i>	
<i>Senecio vulgaris</i>	<i>Datura stromonium</i>	
<i>Sinapis arvensis</i>	<i>Solanum nigrum</i>	
<i>Sisymbrium spp.</i>	<i>Digitaria sanguinalis</i>	
<i>Sonchus oleraceus</i>	<i>Striga hermonthica</i>	
<i>Stellaria media</i>	<i>Echinochloa crus-galli</i>	
<i>Urtica urens</i>	<i>Trianthema portulacastrum</i>	
	<i>Eleusine indica</i>	
	<i>Tribulus terrestris</i>	
	<i>Ergrostris magastachys</i>	
	<i>Xanthium pensylvanicum</i>	
	<i>Xanthium spinosum</i>	

itself is limited to growing areas with hot summers. It was developed primarily in hot, arid climates, such as the desert valleys of Israel and California (Bell and Laemmle, 1991; Katan, 1987; Stapleton and DeVay, 1986), but also has shown considerable promise for vegetable production in more humid areas, such as the southeastern United States where average soil temperature at 5 cm depth was 50 °C in solarized plots and 36 °C in bare ground (Chellemi et al., 1994; Ristaino et al., 1991; Stevens et al., 1990). Perhaps the widest adoption to date has been in the greenhouse vegetable industry in Japan, where more than 3300 ha (8154 acres) were being solarized routinely as early as 1988 (Horiuchi, 1991). There, growers discovered that greenhouses could be closed up and solarized effectively during the hot summer off-season, then planted to begin the normal cropping cycle in the fall.

Variations of the principle have been used in other locations. In the Rio Grande Valley of Texas and in northern Florida, transparent film used to solarize field soil during the hot summer off-season was then painted white and left in place to serve as a mulch for the fall melon or tomato crops (Chellemi et al., 1994; Hartz et al., 1985); and in the Jordan Valley of Jordan, black plastic was used to solarize soil during the extremely hot summer months, and then was left in place to aid the fall vegetable crops as a mulch in conjunction with plastic tunnels (Abu-Gharbieh et al., 1991). These are excellent adaptations of the technique for maximizing the value of investments in plastic.

Even in the hottest climates, many growers wish to augment solarization by integrating it with other, more active methods of soil-borne pest management. For example, many types of fertilizers, particularly those containing ammonium ni-

trogen, can increase the pesticidal effects of solarization when incorporated in soil before heating (Gamliel and Stapleton, 1993a; Horiuchi, 1991; Stapleton et al., 1991). Other organic amendments, e.g., residues of cruciferous crops, have been shown to release biotoxic volatile compounds when heated (Gamliel and Stapleton, 1993b) to increase the effect of solarization through a process of biofumigation (Ramirez-Villapudua and Munneke, 1988; Stapleton et al., 1995). Other studies showed that combining solarization with either soil pesticides (Chellemi et al., 1994; Stapleton and DeVay, 1983; Stevens et al., 1990) or biological control agents (Ristaino et al., 1991; Tjamos and Fravel, 1995) also can increase the pesticidal toxicity of the treatment effectively. A pamphlet describing solarization is available from University of California Publications and is currently being revised and updated (Pullman et al., 1982).

Table 3. Susceptibility of perennial weed species to soil solarization.²

Weed species controlled	
<i>Chloris gayana</i>	
<i>Convolvulus althaeoides</i>	
<i>Convolvulus arvensis</i> (seed)	
<i>Convolvulus arvensis</i> (plant)	
<i>Cynodon dactylon</i> (seed)	
<i>Equisetum arvense</i>	
<i>Equisetum ramosissimum</i>	
<i>Oxalis corniculata</i>	
<i>Plantago</i> spp.	
<i>Sorghum halepense</i> (seed)	
Weed species partially or not controlled	
<i>Cynodon dactylon</i> (plant)	
<i>Cyperus esculentus</i>	
<i>Cyperus rotundus</i>	
<i>Sorghum halepense</i> (plant)	

²Adapted from Elmore (1990).

Where are we going?

Historically, soil disinfestants have been judged by their effects on yield, rather than on numbers of pest organisms killed; the term increased growth response or IGR has long been associated with these soil treatments and has been the subject of a comprehensive review (Chen et al, 1991). Although agriculture appears to be moving away from highly eradicated fumigants and toward softer soil disinfestation treatments, there is no reason to believe that this evaluation standard will change. Nevertheless, agricultural pest management also seems to be evolving from a philosophy of "the only good soil microorganism is a dead microorganism" to a more integrated cropping systems approach. Many growers are recognizing advantages of soil-building programs to improve the long-term profitability of their operations.

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