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ARTICLES

SOIL SOLARIZATION: AN ALTERNATIVE SOIL DISINFESTATION STRATEGY COMES OF AGE,

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Solarization is a natural, hydrothermal soil disinfestation process which is accomplished through passive capture of solar radiation in moist soil. Soil solarization occurs through a combined physical, chemical, and biological mode of action, and is compatible with other disinfestation materials, such as organic amendments, biological control organisms, or pesticides. It is currently used on a relatively small scale worldwide as a substitute for synthetic chemical toxicants. The use of solarization is expected to increase as methyl bromide is phased out. Solarization, as any other soil disinfestation method, has both benefits and limitations. It is simple, safe, effective within its use limitations, and can be readily combined with biological and chemical control measures. On the other hand, solarization is dependent upon local meteorological conditions, is most effective near the soil surface, does not consistently control certain heat-tolerant pathogens such as *Macrophomina phaseolina* and *Meloidogyne* spp., should be done during the hottest part of the year, and requires disposal of plastic film.

The practical value of soil solarization, as of any pest management strategy, must be assessed by several factors, including pesticidal efficacy, effect on crop growth and yield, economic cost/benefit, and user acceptance (Stapleton, 1995; Stapleton & DeVay, 1995). Its routine use as a viable alternative to chemical fumigants in several areas of the world indicates that solarization has already achieved limited user acceptance. There is now a substantial body of literature describing

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organisms which are controlled or partially controlled by solarization, including in excess of 40 fungal plant pathogens, more than 25 species of nematodes, numerous weeds, and a few bacterial pathogens (Katan, 1987; Stapleton and DeVay, 1995; Stapleton, 1996; Elmore *et al*., 1997). In addition to the major pathogens that are reduced by solarization, a number of minor pathogens also are reduced. This is one of the reasons that an "increased growth response" (IGR) is often observed after solarization, similar to that commonly found after chemical fumigation. Solarization has been frequently documented to stimulate IGR in plants even when no major pathogens can be isolated, and reductions in the overall number of soil microorganisms have been significantly correlated with increased plant growth following treatment (Katan, 1987; Chen *et al*., 1991; Stapleton and DeVay, 1995).

Current Use

The principal use of solarization, on a total acreage basis, is probably in conjunction with greenhouse grown crops. For example, routine commercial solarization of soil in more than 4,500 ha of greenhouses was reported in Japan as of 1991 (Horiuchi, 1991). Greenhouse production is an ideal system for using solarization because greenhouses are not used during the summer in many parts of the world due to excessive heat. Therefore, during the summer off-season, greenhouses can be closed to maximize heating and soil can be effectively solarized. Apart from Japan, greenhouse solarization is being used in several Mediterranean and Near-Eastern locations.

Another application for which solarization has come into common use, particularly in developing countries, is for disinfestation of seedbeds, containerized planting media, and cold-frames (Stapleton and Ferguson, 1996). As with use in greenhouses, these are natural niches for solarization, since individual areas to be treated are small, soil temperature can be greatly increased, the cost of application is low, the value of the plants produced is high, and the production of disease-free planting stock is critical for producing healthy crops. Solarization of containerized soil can be accomplished in less than a 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 69^{o}C, and in sleeves covered by a double plastic layer temperatures reached 72^{o}C in the San Joaquin Valley of California (Stapleton and Ferguson, 1996). These temperatures are lethal to most soilborne pests within hours, and approach the heat levels produced during soil disinfestation using aerated steam.

On a global scale, solarization for disinfesting soil in open fields is being implemented at a relatively slow but increasing rate. It has been used commercially in areas such as the central and southern desert valleys of California and Israel where air temperatures are very high during the summer and much of the cropland is out of production at this time due to excessive heat (Bell & Laemmlen, 1991; Becker & Wrona, 1995) (Grinstein & Ausher, 1991). This system is also a natural window of advantage for using solarization, since the summer fallow provides a time period of several weeks for rotating into solarization. Most growers in California who are now using solarization in production fields are those that have some aversion to the use of methyl bromide or other chemical soil disinfestants, either because of their close proximity to urban or residential areas, personal preference, or because they are growing for organic markets. Nevertheless, a number of large, conventional farms in California's interior valleys field test solarization in order to have a basis of knowledge so that, if they want to implement it on a large scale, they will have sufficient technical knowledge to convert to solarization without losing production. Implementation of production field solarization in more humid areas with suitable temperatures appears to be progressing at a similar rate (Chellemi *et al*., 1994).

In addition to commercial use, the importance of solarization in home garden and subsistence production should not be overlooked. Although most of these users do not use chemical soil disinfestants under any circumstances, solarization has been widely embraced and mainstreamed by gardeners, and should be credited for at least modest increases in plant health and production in these settings. An updated extension publication on solarization was recently released by DANR (Elmore, et al., 1997).

Most transparent polyethylene films are suitable for conducting solarization. However, use of lower quality films may be problematic since the plastic may break down prematurely, leaving a myriad of fragments which are difficult to dispose of. Higher quality film more resistant to degradation by ultraviolet light is worth the extra price. The thickness (gauge) of the film is relatively unimportant, except for cost; film strength does not directly correlate with thickness. Plastic is priced based on the cost of petroleum, so thicker plastic weighs more and costs more than thinner film. Certain plastics

manufacturers produce films specially designed for solarization. Most farm supply outlets and many nurseries stock or can order suitable films.

The cost-benefit ratio of solarization compared to other soil disinfestation practices must be calculated on a case-by-case basis. Few economic analyses have been done to compare solarization with conventional disinfestation practices (Elmore, 1991; Yaron *et al*., 1991). As a rough estimate, the cost of solarization, including film, application, and removal, is one-third to one-half that of tarped, methyl bromide fumigation ($400-600 per treated acre vs. $1,100). The yield, quality, and value of the following crops will determine the relative benefit of the soil disinfestation treatments. In organic production without the use of chemical disinfestants, crop yield and quality are often lower than in conventional production, but the unit value of produce is often higher. In this case, only small increases in yield following solarization are needed to pay for the treatment, and large increases in yield often occur (Elmore, 1991).

How Solarization Works

Physical factors. The principal mode of action of solarization is usually direct thermal inactivation of soilborne pathogens and pests (Katan, 1987; Stapleton and DeVay, 1995). The "heat dosage" of solarization, which is a relationship of soil temperature x time, is affected by numerous factors. Some of the more important physical components affecting soil temperature during solarization include diurnal air temperature (the hotter the better, day and night), radiation intensity (the higher the better), wind speed and duration (less wind allows greater heat retention), precipitation events (cloudy sky and water on the film surface lower soil temperature), soil texture (soils with high clay content tend to retain more heat), color (darker soils absorb more heat), and moisture content (moist soils allow better heat transfer), and characteristics of the mulch film (color, transparency, permeability). Models for predicting treatment duration and efficacy (i.e. when a solarization treatment is "done") by soil temperature alone have not been successful to date because of the passive and complex mode of action of the process over a broad range of target organisms.

Another critical treatment component is the thermal sensitivity of the target pest(s), which varies widely among species. Soil that is moist rather than dry prior to solarization will stimulate microorganisms to break dormancy from their survival structures and commence active metabolism thus becoming more susceptible to the biocidal effects of treatment. In many cases, it is not necessary to kill pest organisms - they may be weakened by "sub-lethal" heat (in general, soil temperatures below 38-40 C) to the extent that they are unable to cause damage to plants and/or are more susceptible to chemical toxicants or to attack by antagonists (Chellemi, *et al*., 1994; Stapleton and DeVay, 1995; Tjamos and Fravel, 1995).

Biological factors. Complex biological changes occur when soils are solarized. These have been shown to play important roles in the overall mode of action. The effects of solarization are more pronounced on soilborne plant pathogens (Stapleton and DeVay, 1995), which are often more stringently dependent upon their host(s) for survival, than other more competitive soil microflora, many of which are antagonists of plant pathogens. The antagonists tend to tolerate solarization or rapidly recolonize the soil once the treatment has ended. For example, there have been several reports of the rapid proliferation of fluorescent pseudomonads in the soil and plant rhizosphere following solarization. Also, *Bacillus* spp., many of which are antibiotic-producing antagonists, tend to survive solarization due to the heat tolerant characteristics of their endospores, and more extensively colonize the rhizosphere of subsequently planted crops (Chen *et al*., 1991; Gamliel and Stapleton, 1993b; Stapleton and DeVay, 1995).

Chemical factors. Important chemical changes occur in solarized soils which often result in increases in soluble mineral nutrients following treatment. These chemical changes can be another important factor in the IGR phenomenon observed following treatment. The augmentation of available mineral nutrient concentrations, particularly of nitrogen, in solarized soil is often equivalent to that of recommended preplant fertilization for crops, and in some cases, care must be taken after solarization to avoid adding excessive levels of exogenous fertilizer (Katan, 1987; Chen *et al*., 1991; Stapleton and DeVay, 1995).

How Can Solarization be Improved?

With both benefits and limitations considered, solarization is an effective soil disinfestant in numerous geographic areas for certain agricultural and horticultural applications. Nevertheless, there are many situations where it may be desirable to increase the efficacy and/or predictability of solarization through combination with other methods of soil disinfestation. Since solarization is

a passive process with biocidal activity dependent to a great extent upon local climate and weather, there are occasions when even during optimal periods of the year, local atmospheric conditions (i.e. cool air temperatures, extensive cloud cover, frequent or persistent precipitation events) may not permit effective solarization. This uncertainty must be overcome if widespread implementation of solarization is to occur, since commercial users cannot tolerate soil disinfestation treatments which are not consistently effective. Integration of solarization with other disinfestation methods may be essential in order to increase treatment predictability, and thus, commercial acceptability (Stapleton, 1995).

Previous studies have shown that solarization may be productively combined with other chemical and biological control methods (Katan, 1987; Chellemi *et al*., 1994; Stapleton and DeVay, 1995; Tjamos and Fravel, 1995). Recently, considerable interest has been generated regarding the use of organic amendments in combination with solarization to achieve biofumigation (Gamliel and Stapleton, 1993a; b). A wide range of organic amendments, including plant residues, by themselves have some degree of soil disinfestation activity. Addition of biocidal soil amendments or crop residues as part of a crop rotation scheme may in certain cases be useful for managing population levels of soilborne pests. However, for routine use in high value, intensively-farmed horticultural crops, it is unlikely that periodic rotations into bioactive plants alone will provide sufficient efficacy, predictability, or economic return to be of consistent value. Combining a variety of soil amendments with solarization to accomplish biofumigation is an improved option.

One promising combination of organic amendments with solarization involves residues of cruciferous plants, which release a number of biotoxic volatile compounds into soil during the decomposition process (Ramirez-Villapudua and Munnecke, 1987). Production and release of these compounds was demonstrated to be greatly increased, both qualitatively and quantitatively, when cabbage (*Brassica campestris* var. *capitata*) amendment was combined with soil heating. The aldehydes and isothiocyanates produced by the decomposing cabbage were positively correlated with fungicidal activity in treated soil (Gamliel and Stapleton, 1993a). Release of these compounds was a function of the decomposition process. Various products and intermediaries were produced and dissipated in a chemical cascade. In conjunction with soil heating, the formation and release of these biotoxic volatile compounds occurred mainly during the first three weeks of solarization. After that time, concentrations of most compounds dropped to low or undetectable levels.

Perhaps the solarization combination most likely to be widely implemented is that employing chemical pesticides. As methyl bromide is phased out, many current users will turn to other, less effective, pesticides (e.g. metham sodium and 1,3-D) for soil disinfestation. Combining these pesticides (perhaps at lower dosages) with solarization (perhaps for a shorter treatment period) may prove to be the best option for users who wish to continue chemically fumigating soil.

Feasible alternatives to chemical soil fumigants must provide effective, predictable, economical, and relatively rapid reductions of pest and disease organisms. Solarization has limitations which prevent it from universally replacing fumigants. However, in suitable climates and for compatible applications, solarization alone, or in combination with other agents, is ready for implementation.

Note: This article was adapted from Stapleton, 1997 (See Literature cited)

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ABSTRACTS

ORGANIZATION OF TROPICAL NEMATOLOGISTS, Cancun, Mexico, July, 1997

Nematode Control 90 Days After Various Eradication Attempts, *M. V. McKenry, T. Buzo, and S. Kaku, U.C. Kearney Ag Center*

A sandy loam soil infested with *Pratylenchus vulnus* and *Paratylenchus hamatus*, but having no remnant tree or vine roots larger than pencil-sized, was treated with 16 soil treatments (four replicates each) and then sampled for nematodes 90 days later at 30 cm increments down to 1.5 m depth. Six treatments provided 99.4% nematode control or better and they include: 1) Shanked treatments of methyl bromide at 270 kg/ha or methyl iodide at 360 kg/ha; 2) Incorporation of 360 kg/ha Basamid granules followed by intermittent sprinkling with 15 ha·cm water; 3) Drenches of 360 kg/ha MIT (Vapam) or 360 kg/ha 1,3-dichloropropene EC with 17% chloropicrin or 360 kg/ha 1,3-dichloropropene EC plus Vapam in a stacked injection with all treatments receiving 15 ha·cm water. Two treatments that performed slightly poorer than those above included a drench of 1,3-dichloropropene EC at

360 kg/ha or a shanked injection of 360 kg/ha 1,3-dichloropropene followed in two weeks with 100 kg/ha drench of MIT in 5 cm water. Several treatments performed poorly or were inadequate to meet nursery certification requirements. These were all drenches in 15 ha·cm water and included: 1) A 654 kg/ha drench of urea; 2) A drench of 1142 kg/ha sodium tetrathio carbonate; 3) A drench of 20 kg/ha phenamiphos; 4) Drenches of peroxyacetic acid mixed 1:1 with a stabilizing agent at 21 kg/ha each whether applied as a uniform injection or wave injection; 5) A drench of picric acid solution over the surface of incorporated calcium hypochlorite granules at 1:15 ratio. All the drenchings were conducted with a portable device that provides one drip emitter for each 900 cm^2 of field surface. Studies at this site will continue for two years as the rate of nematode return is further quantified in the presence of *Prunus* spp. rootings.

SOCIETY OF NEMATOLOGISTS, Tucson, AZ, July, 1997

Impact Of Systemic Herbicides On Nematodes Within Woody Roots *M. V. McKenry, T. Buzo, S. Kaku, and R. Ashcroft, U. C . Kearney Ag Center*

In July 1996 the roots in a 20-year-old Lovell Peach, *Prunus persica*, orchard were observed to be heavily galled by root knot nematode and supporting 10 to 100 juveniles of *Meloidogyne incognita*/g root. For the purpose of killing the old root system before replanting, various systemic herbicides were painted onto cut tree trunks on August 1. Sixty days later, portions of the root systems were excavated and assayed for root death and changes in nematode population level. None of our treatments provided visible root death, however populations of *M. incognita* juveniles were significantly reduced by each of three treatments across four replicates in the heavily infected portion of the orchard. The nontreated trees provided 19 J_2 / g root whereas roots from trees painted with 1) 50 ml Garlon 3A® (DowElanco) and 25 ml diesel, 2) 50 ml Roundup® (Monsanto) and 25 ml diesel or 3) 25 ml Roundup and 8 ml fosthiazate and 25 ml diesel produced only 0.05, 0.05, and 1.0 J_2 / g root, respectively. Population levels of *Meloidogyne* spp. in woody roots may provide a more sensitive bioassay for root death than vital stains or visual assessments.

ENTOMOLOGICAL SOCIETY OF AMERICA, PACIFIC BRANCH, San Jose, CA, June, 1997

Integrating Chemical, Biological, and Cultural Management of Grape Mealybug *Pseudococcus maritimus* Infesting Table Grapes, *Walter J. Bentley, Jason Kosareff, and Peggy Schrader, U. C. Kearney Ag Center and UCCE, Kern County*

The grape mealybug has become the key pest infesting table grapes in the San Joaquin Valley. This has occurred despite a reduction of disruptive insecticides used to control other key pests such as grape leafhopper, omnivorous leafroller, and western grape leaf skeletonizer. Field studies have demonstrated the success of delayed dormant applications of chlorpyrifos in managing grape mealybug. These trials have also shown this timing to be non disruptive to another key pest, Pacific mite. Marking infested field locations during harvest allows grape growers to selectively treat problem areas while leaving untreated locations in the vineyard for key mealybug parasitoids such as *Acerophagus notativentris* and *Pseudaphycus angelicus* to reside. In untreated areas, grape bunches can be selectively thinned to reduce the severity of infestation while still allowing for a reservoir of mealybug, without unacceptable levels of infestation.

California Red Scale as a Practical Example of a Pesticide Resistance Monitoring Program, *Beth Grafton-Cardwell, U.C. Kearney Ag Center*

Developing a pesticide resistance monitoring program for agricultural arthropod pests frequently has many practical limitations. Factors such as insect stage, numbers available, and distribution on the host plant strongly influence choice of bioassay methods and analysis. For California red scale, only 2 of 4 generations occur on new fruit, limiting the time period for testing using a fruit dip bioassay method. Poor availability of scale-infested fruit has restricted most of the pesticide testing to discriminating concentrations and has biased sampling towards resistant populations. To combat some of the logistical problems, we have developed a biochemical method of testing for resistance. This has allowed us to test many more populations and from twigs and leaves as well as fruit, but may not always be a good indicator of the severity of the resistance problem.

Aphids, Citrus Tristeza Virus (CTV), and California Citrus: Understanding CTV Spread in the San Joaquin Valley, *Greg Montez, Sandy Kelly, Marv G. Kinsey, Elizabeth E. Grafton-Cardwell, Diane E. Ullman, and Marylou Polek, U. C. Kearney Ag Center, U.C. Riverside, and Central California Tristeza Eradication Agency*

Citrus tristeza virus (CTV) is transmitted semipersistently by several species of aphids. Little is known about which aphid species colonize citrus in the San Joaquin Valley, seasonal variations in their abundance, or their efficiency as vectors of CTV. This information is important for designing management strategies to limit CTV spread. In a multidisciplinary effort, we have shown that at least 5 species of aphids colonize citrus. All five aphid species were present during the spring flush of growth, however, *Aphis gossypii* was the most abundant species. During the autumn flush, *A. gossypii* was the only species found. Numerous species that do not colonize citrus were collected from horizontal pan traps and identified. Aphid colonizer or vector species represented 19-30% of the total number of aphids trapped, depending on the site. Seasonal abundance of all species varied significantly with the greatest numbers occurring during the spring and autumn flushes of citrus growth. Titer of CTV (measured by enzyme-linked immunosorbent assay) also varied significantly over time and peaks in aphid numbers coincided with highest virus titer. Tests of the ability of *A. gossypii* collected from CTV infected field trees to transmit CTV to Mexican lime seedlings are underway.

Mechanisms of Resistance to Organophosophate and Carbamate Insecticides in California Red Scale, *Aonideilla aurantii* (Maskell) (Homoptera: Diaspididae), *Yuling Ouyang and Elizabeth E. Grafton-Cardwell, U. C. Kearney Ag Center*

Potential mechanisms of resistance to organophosphate and carbamate insecticides were examined in three populations of California red scale, *Aonideilla aurantii* (Maskell) in the San Joaquin Valley. An assay for total nonspecific esterase activity showed significantly higher levels in resistant scale populations compared to susceptible population. Thus, esterase enzymes are involved in resistance of California red scale. The inhibition of acetylcholinesterase by paraoxon, chlopyrifos oxon, methidathion oxon, propoxur, and carbaryl were tested in vitro using a microtiterplate assay. The Vmax in the resistant populations was higher than the susceptible population without inhibitors. But the percentage remaining activity of AChE with the inhibitors was similar between susceptible and resistant populations. Therefore, the resistance to organophosphate and carbamate insecticides in California red scale is not due to the modification of the target site.