Alternatives to Methyl Bromide for the Control of Soil-Borne Diseases and Pests in California

by

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ABSTRACT

Methyl bromide is a broad-spectrum soil fumigant. It is widely used in California and other parts of the world to control soil-borne diseases and pests of economically important crops such as strawberries and nursery stock. The fumigant is applied generally before planting in combination with chloropicrin as one component of a pest management system. Mixtures of these two fumigants work synergistically in controlling soil-borne pests and pathogens. In addition, the increased root health provides increased plant vigor thus reducing water, fertilizer, and pest control input requirements.

Methyl bromide was listed in 1993 by the Parties of the Montreal Protocol as an ozone-depleting compound and was regulated by the U.S. Clean Air Act of 1990. Under this Act, the domestic production in 1994 was frozen at 1991 levels. The U.S. Congress changed the Act in 1998 to harmonize U.S. phase-out of methyl bromide with the Montreal Protocol schedule. The importation and production of methyl bromide will be reduced by 50%in 2001, by 70% in 2003 and by 100% by 1st January 2005 (Anonymous, 1998c). In order to meet the mandate specified in the U.S. Clean Air Act, it is essential that environmentally sound and economically feasible alternatives are integrated in a pest management system and implemented by California farmers and pest control advisors by the year 2005.

In California, methyl bromide is widely used to control soil-borne diseases and pests of economically important crops. The largest production agriculture use of methyl

bromide is for the treatment of fields before planting of strawberries, followed by soil treatment by the nursery industry.

Based on an extensive review of relevant scientific publications, proceedings of international conferences, and consultation of scientific experts, the California Department of Pesticide Regulation evaluated chemical and non-chemical alternatives to methyl bromide.

There is no single registered alternative for all of the uses of methyl bromide. Many workers in the field believe that integrated strategies combining chemical and nonchemical pest management methods are the best alternative to methyl bromide soil fumigation. The 50% reduction in the availability of methyl bromide in 2001 will result in a higher price for this product. Consequently, growers will have to rely more on the currently registered chemical fumigants 1,3-Dichloropropene (1,3-D), chloropicrin, and metam sodium. While1,3-D and chloropicrin have been shown to be the best partial replacements for methyl bromide at this time; regulatory concerns and use restrictions limit their usefulness in the field. Chloropicrin, 1,3-D, and metam sodium, are most efficacious against plant pathogenic fungi, plant pathogenic nematodes, and weeds, respectively. Field studies with the non-registered methyl iodide and propargyl bromide have shown that these compounds can potentially be used as a single replacement for methyl bromide.

A great deal of research has found several technically feasible non-chemical alternatives to methyl bromide. These include soil solarization for nursery plants and tree crops, crop rotation with broccoli for strawberry production, plug plants for strawberry nursery plants and compost for containerized nursery plants. The non-chemical alternatives generally control disease, nematodes or weeds, but not all three. Partial alternatives can be used to develop integrated pest management (IPM) systems and integrated farming systems (IFS). In the past, there was no need for the development of IPM and IFS due to the availability of effective synthetic pesticides, such as the broad-spectrum soil fumigants like methyl bromide. This is changing, as fewer unrestricted broad-spectrum synthetic pesticides are available. The emerging approaches of IPM and IFS are aimed at replacing the use of methyl bromide, and reducing grower dependence on broad-spectrum chemical pesticides. These approaches are not yet established as a replacement for methyl bromide for all cropping systems. Government, university and the agricultural industry are developing environmentally sound, economically feasible alternatives that can be adopted once the phase-out of methyl bromide is complete.

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DISCLAIMER

INTRODUCTION

Broad-spectrum soil fumigants were introduced into California after World War II and ultimately contributed to the replacement of traditional, diversified farming systems with large-scale monocultures. Soil fumigants provide excellent, reliable disease and pest control, increased yields, high quality produce, extended crop seasons and dependable economic returns. Consequently, present-day California agriculture can be characterized by increased use and dependency on synthetic pesticides, a reduction in crop rotation frequency, and a limitation in the number of crops grown (Wilhelm et al., 1972).

The environmental and human health consequences of these agricultural changes were not well understood when the broad-spectrum soil fumigants were introduced. The increased use and dependency on pesticides has not only led to increased yields but also to increased contamination of soil, water, and air (World Resources Institute, 1993). Less frequent crop rotation can increase the epidemiological potential of soil-borne diseases and pests, which in turn can increase pesticide use (Katan and DeVay, 1991). In addition, soil fumigation leaves a biological "vacuum" suitable for re-infestation by plant pathogens, requiring that the soil be treated each growing season (Katan and DeVay, 1991). Due to concerns about the quality of the environment and food, there is growing pressure on agriculture in the United States and Western Europe from the public and the government to rely less on synthetic broad-spectrum pesticides for disease and pest control.

Methyl bromide (MeBr), one of the few remaining broad-spectrum soil fumigants still registered, was listed in 1993 by the Parties of the Montreal Protocol as a stratospheric ozone-depleting compound. Recent research has shown that even thought MeBr is damaging to atmospheric ozone, it is difficult to quantify the damage because the behavior of MeBr in the atmosphere is influenced by complex processes and is still not well understood (Anonymous, 1998d). The U.S. Clean Air Act of 1990 required that all compounds with high ozone-depleting potential be classified as Class I substances and their production and importation phased out within seven years. This requirement changed when the Clean Air Act was amended in 1998. MeBr domestic production in 1994 was frozen at 1991 levels. Production and importation of MeBr must be reduced from a 1991 baseline by 25% in 1999, 50% by 2001, 70% by 2003 and 100% by January 1, 2005. Preshipment and quarantine uses will be exempt. Critical and emergency uses will be allocated after 2005. More detail on this subject can be found at the US-EPA website: http://www.epa.gov/ozone/mbr/harmoniz.html. To meet the mandate specified in the U.S. Clean Air Act without adverse economic consequences to California agriculture, it is essential that environmentally sound and economically feasible alternatives are in place and available to California farmers and pest control advisors during this phase-out process.

This report identifies and describes alternatives to MeBr, including chemical and non-chemical methods, for the control of soil-borne diseases and pests in California production agriculture. This does not include post-harvest commodity or structural fumigation. It is based on an extensive review of scientific publications, proceedings of international conferences and information provided by scientists (Braun and Supkoff, 1994). Not all of the synthetic pesticides mentioned in this report are registered in California, or if registered, may not be labeled for the described use. This report will not assess whether each identified alternative or combination of alternatives is practical or economically feasible. An economic assessment on the loss of MeBr was prepared in February of 2000 by the National Center for Food and Agricultural Policy (Carpenter et al., 2000). The authors indicate that the phase-out of MeBr could cause yield loss of up to $500 million in the United States. The practical use of an alternative method may also be limited by adverse biological impacts or environmental concerns. It is the intent of this report to summarize the recent advances in methyl bromide alternatives in California production agriculture.

METHYL BROMIDE IN CALIFORNIA

Methyl Bromide Characteristics and Uses

To properly assess potential alternatives to MeBr as a pre-plant soil fumigant, it is essential to identify the attractive characteristics of MeBr, to understand how this fumigant is used and why it is so important to many California crops, in particular strawberries. MeBr has quick and deep soil penetration due to its low boiling point and high vapor pressure. It leaves the soil rapidly, thus has a short waiting period before replanting, and low residual phytotoxicity (Gullino and Lodovica, 1992; Kuter et al., 1983; Van Assche et al., 1968). Its ability to penetrate extends to pathogens in protected locations. Stark and Lear demonstrated that MeBr could penetrate root-knot galls and kill the embedded nematodes (Stark and Lear, 1947).

MeBr is commonly used in combination with chloropicrin (CP) to fumigate soil. Various mixtures of MeBr and chloropicrin (MeBrC) combine the advantages of the greater soil penetration of MeBr and higher fungal toxicity of CP (Wilhelm, 1966). The various mixtures of MeBr and CP effectively control soil-borne pathogens, nematodes, some bacteria, weeds, and the "replant problem" (see below) in the production of fruit and nuts, ornamentals, and vegetables in California. This mixture more effectively controls Verticillium wilt and weeds than either compound alone (Johnson et al., 1962; Stark et al., 1944; Wilhelm and Koch, 1956; Wilhelm et al., 1974). Sclerotia of *Botrytis cinerea* (Munnecke and Melban, 1964), *Sclerotinia sclerotiorum* (O'Brien and van Bruggen, 1990), and *Sclerotium delphinii* (Munnecke and Melban, 1964) are typically difficult to kill and are also more effectively controlled by these mixtures than with either compound alone. Pre-plant application of these mixtures also permits the soil to be replanted after a short waiting period with the same crop on the same land year after year. For these reasons, pre-plant soil fumigation has become an integral part of pest management for many high-value crops.

The use of MeBr in production agriculture in California has fluctuated between 12.5 million and 16.2 million pounds in the last 9 years (Fig. 1). Strawberry growers at pre-plant used 35% of the total MeBr used in production agriculture in California in 1999 while non-strawberry nursery growers used 14% of the total and unspecified soil application accounted for 15% of the total (Fig. 1). There is no indication that use is decreasing as the phase-out date approaches. Use of MeBr on strawberries in California increased from 4.2 million lbs in 1998 to 5.2 million lbs in 1999. Use of MeBr in soil applications increased from 1.5 million lbs in 1998 to 2.2 million lbs in 1999, but non-strawberry nursery use decreased slightly. Much of the increase has occurred in the coastal regions from Ventura to Monterey counties and in the strawberry nursery area in the northeastern part of the state (Fig. 2) and may be due to increased acreage. However, growers in some counties, e.g. Santa Cruz County, have decreased their use of MeBr in both strawberry fields and soil applications (Figs. 2 & 3), although the reasons for this decrease are unclear. These numbers are based on the preliminary 1999 Pesticide Use Report data, DPR and are subject to revision.

Strawberry Production

The limiting factor in strawberry production and several other crops is the replant problem, a complex disorder that is still not clearly understood (Anonymous, 1998a). *Verticillium* spp., several other soil-borne fungi and possibly nematodes are involved in this disease complex. The Verticillium wilt fungus (*Verticillium dahliae*) produces microsclerotia, resting structures that are notably tolerant to environmental stress, such as desiccation and high temperatures. These microsclerotia are difficult to kill and can survive up to 20 years in soil (Easton et al., 1992). Crop rotation in heavily infested fields is therefore ineffective for Verticillium wilt control (Easton et al., 1992; Norman C. Welch, personal communication). In addition, *V.dahliae* has an extensive host range (>300 different plant species), including economically important crops such as cotton, grapes, tomatoes, and stone fruits. Many weeds and rotational crops such as alfalfa, vetch, and several lupines are host plants. *V.dahliae* is widespread in California soils (Storkan and Ivancovich, 1992). The extensive host range of Verticillium wilt and its widespread presence and long survivability in California soils limits the implementation of an effective crop rotation strategy. Successful control of the Verticillium wilt disease complex in strawberries began in 1961 with the prophylactic use of MeBrC (Wilhelm et al., 1961).

The use of MeBrC fumigant has resulted in effective, reliable disease control, significant increases in yield and fruit quality and have made it possible to cultivate ever-bearing strawberries in California on a continuous basis in the same field (Anonymous, 1993a; Wilhelm et al., 1972). MeBrC soil fumigation has been credited for saving the California strawberry industry from foreign competition (Anonymous, 1993c; Wilhelm et al., 1961). Limited efforts were made to elucidate the disease complex of strawberries or to find alternatives to MeBrC soil fumigation because of the effectiveness of these soil fumigants. The breeding program, for example, was focused on the development of new cultivars with better fruit quality and production instead of resistant varieties (Wilhelm and

Paulus, 1980; Wilhelm et al., 1974). Strawberry varieties bred with these agronomically desirable characteristics, but susceptible to one or more soil-borne diseases, resulted in the highest per acre yield in the nation (Wilhelm et al., 1974).

Strawberry Nurseries

California nurseries provide almost 100% of the strawberry rootstock used within California and a significant portion used in other states and countries. Nursery rootstock is a high cash value crop and even a small crop loss can have significant economic effects. Soil fumigation with MeBrC is used in all California nursery stock, including those for organic production. This treatment reduces plant mortality due to control of lethal pathogens and increases plant vigor by controlling sub-lethal and/or competitive microorganisms (Shaw and Larson, 1999). All nursery stock must be free of nematodes to meet the strict certification requirement mandated by the California Department of Food and Agriculture. Nursery stock must also be disease-free in order to ensure high yield in production. Currently no single registered alternative exists for the standard methyl bromide/chloropicrin treatments used by California strawberry nurseries. This important California industry faces potentially serious economic damage, considering the current critical need for methyl bromide in strawberry nurseries and the phase out schedule for methyl bromide. The California Strawberry Commission has recently included the nursery industry in their MeBr alternatives research program.

Orchards and Vineyards

The use of MeBrC, applied before planting, is also crucial for the control of soil-borne diseases and pests of pome, stone fruit and nut trees, as well as grapevines. MeBr fumigation of orchards and vineyards is the fourth largest use of MeBr in production agriculture in CA. MeBr use for fruit and nut orchards and grape vineyards increased from 1.7 million lbs in 1998 to 2.1 million lbs in 1999 in order to control soil-borne diseases and pests (Fig.1).

Fruit trees as well are susceptible to replant problems when young fruit trees are grown on replanted orchard sites. The trees may exhibit retarded early growth and death of root tips, which often results in poor yield. Factors responsible for the retarded growth can include: soil compaction; poor aeration; drought stress; extremes of soil acidity; inorganic and organic chemical toxicity; nutrient deficiency or imbalance; and presence of plant pathogenic organisms (Traquir, 1984). The specific plant pathogenic soil microorganisms responsible are in many cases still unknown. Fumigation with MeBrC effectively controls the replant problems in fruit trees without knowledge of the problem's cause. Oak root fungus (*Armillaria mellea*), a serious soil-borne disease of fruit and nut trees and grapes, is very difficult to control, and so far, MeBrC soil fumigation seems to be the only effective way to manage this disease. The University of California recommends the use of MeBrC soil fumigation (Anonymous, 1986) as the only way to effectively control this disease when planting in Armillaria-infested soil. The use of MeBrC pre-plant soil fumigation is also recommended by the University of California for the control of branched broomrape in tomatoes and diseases caused by *Verticillium spp., Fusarium spp., Rhizoctonia spp*., and *Phytophthora spp*. in ornamental plants (Anonymous, 1986).

Nursery Production (Non-strawberry)

MeBr is also extensively used by the nursery industry. Nursery stock is a high cash value crop that must be free of disease and pests. In general, nematode-infested or diseased nursery stock is not acceptable to buyers in California or in other states and countries. Producers of nursery stock for farm planting in California can participate in a voluntary nematode-free certification program administered by the Department of Food and Agriculture and funded by fees paid by the participants. Applicants who choose to participate in this voluntary program grow nursery stock on soil treated in a manner approved by the California Department of Food and Agriculture, such as methyl bromide fumigation. Nursery stock voluntarily entered into the nematode control program that have not received such soil fumigation must be sampled for nematodes using a method approved by the California Department of Food and Agriculture (Donald R. Dilley, personal communication). Fruit and nut trees, grapevines, berries, vegetables, kiwis, and "any other nursery stock for commercial farm planting" are covered by this program. Soil fumigation is an approved treatment because this control method is very effective in killing nematodes. Only two fumigants are currently approved for use in the nursery regulations: MeBr and 1,3-D. An alternative to chemical fumigation, soil solarization, was found to be effective in control of nematodes and the California Department of Food and Agriculture approved this practice for disinfestation of containerized nursery stock in 1999 (Stapleton et al., 1999).

ALTERNATIVE CONTROL METHODS

This section discusses options or strategies as potential replacement to MeBr soil fumigation. Many of the registered fumigants are commonly applied in combinations since they do not have the broad-spectrum efficacy of MeBr. The major users of MeBr in CA are strawberries, containerized and field nursery plants, and fruit and nut trees. Much of the MeBr alternatives research has been conducted on strawberries. Potential alternatives to MeBr in these crops are summarized in Table 2.

Registered Chemical Alternatives

Metam sodium:

This active ingredient is a broad-spectrum biocide and may be used to control soil fungi, nematodes, soil insects, and weeds (Anonymous, 1990a, Anonymous, 1993b, Thomson, 1992), although it is best used as an herbicide. Metam sodium applied to moist soil will decompose to methyl isothiocyanate (MITC), the biocidal ingredient. For several crops, metam sodium has not always provided consistent control of soil-borne diseases and pests comparable to MeBr. When carrot fields in Kern County were treated with metam sodium for nematode control, the results varied from excellent to disastrous, depending on the proper application and use of the product. Metam sodium does not control root-knot nematodes as well as MeBr and diseases such as those caused by *Fusarium* and

Verticillium spp. are not controlled by this fumigant (Anonymous, 1993c). In addition, metam sodium does not have the penetration capacity of MeBr and conventional application methods of this fumigant do not provide a uniform distribution of pesticide in soil (Gullino and Lodovica, 1992). It does not disperse well in the soil and requires water for good movement (Anonymous, 1993c; Mus and Huygen, 1992). Its poor dispersion may limit the control of soil-borne diseases and pests of deep-rooted crops like stone fruits, almonds and grapes. Metam sodium has a narrow margin for error in its application in comparison to MeBrC. Improved control may require increased rates or application of large quantities of water as a carrier (Munnecke and Van Gundy, 1979). However, these practices may result in higher costs and possible groundwater contamination (Anonymous, 1992b; Kim, 1988). Improved control of soil-borne diseases and pests may be better achieved by redesigning application equipment to improve diffusion into the soil. Control failures were also attributed to a build-up of microorganisms that may result in increased degradation of the fumigant (Smelt et al., 1989). Another limitation of metam sodium is the long waiting period between application and planting to prevent damage due to phytotoxicity (Anonymous, 1992b; Anonymous, 1993b; Gerstl et al., 1977; Gullino and Lodovica, 1992). Metam sodium is listed in California as a carcinogen and as a developmental toxin (Office of Environmental Health Hazard Assessment, Cal/EPA). There are also concerns about air contamination (Kelley and Reed, 1996).

Dazomet:

Dazomet, like metam sodium, is a precursor to the formation of the biocidal ingredient MITC. Upon contact with moist soil, dazomet also converts to MITC (Anonymous, 1989b). Dazomet is currently in the registration process for California. In cool climates, dazomet needs a 60-day re-entry period (Anonymous, 1993a). Dazomet effectively controls weeds, nematodes, and fungal pathogens, resulting in cost-effective yield increases (Anonymous, 1989b; Harris, 1990). This product is applied pre-plant to seedbeds in nurseries, greenhouses, and substrates for potted plants, turf, and ornamentals. Its granular formulation can be easily applied, allowing adaptations to practical needs from small- to large-scale uses (Anonymous, 1990a; Anonymous, 1993b). However, good results with dazomet are dependent on proper application, which includes thorough mixing with soil to desired depth and efficient sealing (Anonymous, 1992a). A drawback of the MITC releasers is the reduced disease control caused by the slow diffusion of MITC through soil compared to MeBrC (Parochetti and Warren, 1970). Groundwater contamination is also of concern for the same reasons cited for metam sodium (Anonymous, 1992b; Kim, 1988).

1,3-Dichloropropene:

1,3-Dichloropropene (1,3-D) is a nematicidal fumigant. It is as efficacious as MeBr in controlling nematodes but does not control fungi or insects (Anonymous, 1989b). At high rates, 1,3-D has some efficacy against a few weeds (Anonymous, 1992b; Jarvis, 1992). It has two isomers: cis- and trans dichloropropene. The cis -isomer is more volatile and is considered more active biologically than the trans-isomer (Mayberry, 1993, Hugo van de Baan and Joop van Haasteren, personal communications). This fumigant has no potential to deplete the ozone layer and has a short half-life of 7 to 12 hours in air. Cis-1,3-D is another non-U.S.-registered alternative to MeBr. It was registered in the Netherlands when the Dutch regulators phased out the use of MeBr in 1990. Dutch scientists consider the cis-isomer more active than the trans-isomer and feel that the trans-isomer is more an environmental burden (M. Leistra, personal communication). 1,3-D has been used in California on a wide variety of economically important crops, such as strawberries, fruit and nut trees to effectively control nematodes (Anonymous, 1992b; Carpenter et al., 2000; Landels, 1992) and in combination with chloropicrin or MITC, to control replant and soil-borne diseases (Anonymous, 1993c; Mus and Huygen, 1992). Root-knot nematodes (*Meloidogyne spp.*) are the major nematode pest problems in field (e.g., cotton) and vegetable crops (e.g., lettuce) in California. The combined infestation of root-knot nematode (*Meloidogyne incognita*) with the Fusarium wilt pathogen (*Fusarium* oxysporum) can be extremely damaging to cotton. Infestations usually occur on light-textured sand-loam and sand soils which are very amenable to soil fumigation under California conditions (Radewald et al., 1987; Philip A. Roberts, personal communication). Duniway et al. reported that in five years of experimentation with California strawberries, shank applications of 1,3-D and chloropicrin "gave strawberry yields nearly equivalent to methyl bromide and chloropicrin" by controlling Verticillium wilt and Phytophthora root rot (Duniway et al. 1999). Treatment with 1,3-D to an orchard before planting can reduce nematode populations for up to six years after fumigation (Carpenter et al., 2000).

In April 1990, high levels of 1,3-D were detected in ambient air in Merced County, California. Residues in air exceeded several orders of magnitude over the level of health concern. DPR immediately suspended all permits for use of 1,3-D. Consequently, formulations containing 1,3-D could not be used in California (Anonymous, 1993c). DPR approved limited use of 1,3-D in 1994. Current restrictions in California include a limit on total amount used within 36-mile square townships and use of a 300-foot buffer zone (Anonymous, 1994, Carpenter and Lynch, 1999). This fumigant is also listed in California as a carcinogen and a known groundwater contaminant (Office of Environmental Health Hazard Assessment, Cal/EPA). Recently, a new product containing 1,3-D and chloropicrin received registration from US-EPA in 1998. It is currently in the California registration process.

Chloropicrin:

CP may be used for the control of nematodes, bacteria, fungi, insects, and weeds. The product is also used as a warning agent for odorless fumigants such as MeBr (Awuah and Lorbeer, 1991). It is formulated either as a liquefied gas or in combination with MeBr or 1,3-D (see MeBr and 1,3-D, respectively) to broaden its spectrum (Anonymous, 1990a; Anonymous, 1992b; Anonymous, 1993b). CP was shown to be a very effective fungicide for the control of soil-borne fungi, but not for weed and nematode control compared to MeBr (Anonymous, 1993c). CP alone at a rate of 150 L/ha reduced the amount of *V.dahliae* in strawberries to undetectable levels, but was not effective against weeds (Harris, 1991). A five-year study to develop alternative chemical fumigants in strawberry nurseries found that chloropicrin in combination with 1,3-D is an alternative but was not always as effective as the standard methyl bromide/chloropicrin treatment (Gordon et al., 1999). Strawberry production trials conducted over five years with CP and 1,3-D yielded comparable results to the standard MeBrC treatment (Sances and Ingham, 1999), particularly when VIF (virtually impermeable plastic film) mulch was used (Duniway et al. 1999). CP has several undesirable attributes. It has a pungent odor and thus can be unpleasant to handle (Anonymous, 1992b). After application, the dispersion of CP into soil and evaporation from the soil occurs much slower than MeBr (Smelt and Leistra, 1974). Therefore, a longer waiting period for CP is required before planting to prevent damage due to phytotoxicity than for MeBr. Chloropicrin does not have significant ozone depletion potential (Wilhelm and Westurland) but it is a potential groundwater contaminant.

Non-Registered Chemical Alternatives

Several non-registered chemical fumigants may be partial replacements for methyl bromide. Researchers have looked at the use of sodium tetrathiocarbamate and propiconizole for control of *Armillaria mellea* in almonds (Adaskaveg et al. 1999), propargyl bromide for tomato pre-plant fumigation (Noling and Gilreath, 2000; Norton, 2000) and InLine for strawberry pre-plant fumigation (Norton, 2000). InLine (an emulsified concentrate formulation of 1,3-D and chloropicrin) is a drip applied, non-registered product that has shown promising results. Application of InLine through drip-irrigation has been well received by strawberry growers. This application method can reduce emission to the air (Carpenter et al., 2000), providing less applicator exposure. It received a federal Experimental Use Permit, which allowed California strawberry growers to treat up to 800 acres this year. InLine soil applications covered with clear plastic, however, have not provided adequate weed control for growers. Strawberry growers in southern California prefer clear plastic because it helps plants develop quicker and eventually leads to earlier harvest. With the limited labor force available for weeding, the grower may not achieve adequate weed control.

Sodium tetrathiocarbamate is a registered soil fumigant that effectively controls soil nematodes and insects in grapevine, fruit and nut trees. It is not classified as a Restricted Use Pesticide hence it can be used on established crops (Phillips et al., 1999).

A Research Authorization has been issued for field trials of propargyl bromide applied through drip systems for strawberries. Preliminary results have shown that this compound has the potential to be a single replacement for MeBr.

Methyl Iodide

Methyl iodide (MI) has received a great deal of attention as a potential complete MeBr replacement. It appears superior to MeBr for several reasons. It is rapidly destroyed by UV light; therefore, its ozone depletion potential is likely to be low (Ohr et al., 1996). It is liquid at ambient temperature, increasing applicator safety. MeI fumigation does not require new fumigation equipment or different cropping practices (Ohr et al., 1996), although it is more expensive than MeBr. In a number of laboratory and field trials, it was shown to be as efficacious as MeBr as a soil fumigant for control of many soil-borne diseases, weeds (Eayre et al., 2000; Ohr et al., 1996), and nematodes (Eayre et al., 2000; Hutchison et al., 1999). In a peach trial, the MeI treatments were equivalent to the MeBr in the control of replant disorder (Eayre et al., 2000). MeI persists longer in the soil than MeBr, thus it requires a longer pre-plant interval but delivers a higher dose to the infested area (Hutchison et al., 1999). A Research Authorization was issued to conduct strawberry field trials of MeI applied through drip systems (DPR). Methyl Iodide is not currently registered and it is listed in California as a known carcinogen (Office of Environmental Health Hazard Assessment, Cal/EPA).

Ozone

Ozone is an extremely reactive gas naturally produced in the upper atmosphere. This reactivity makes it a very effective biocide and it is approved for use as a post-harvest fumigant. It decomposes very rapidly, leaving no residue, but must be produced on-site (Pryor, 1999). The use of ozone as a soil fumigant was investigated in tomato and carrot fields in Southern California and strawberry fields in Northern California. The studies demonstrated that reduction in Verticillium wilt was comparable to the MeBr treatment. Ozone has potential to be an effective general soil fumigant (Pryor, 1999).

Non-Chemical Alternatives

Steam

Soil treatment with steam at 80-100°C effectively controls most soil-borne pathogens and weeds. Aerated steam (air-steam mixture) selectively kills plant pathogens at 50-60°C in 30 minutes and is used in some nurseries as an alternative to soil fumigation (King and Greene, 2000). New and more effective steam application methods, such as negative pressure steaming, were developed and described by Runia for greenhouse soil disinfestation (Runia, 1983). Steam is introduced under a sheet and forced into the deeper soil layers by negative pressure created in the soil by a fan, which sucks air out of the soil through buried perforated polypropene pipes (Ellis, 1991; Jarvis, 1992; Runia, 1983). This method is more energy efficient, economical, and more reliable for the cultivation of chrysanthemums than the conventional steaming method used for soil disinfestation in glasshouses in the Netherlands (Anonymous, 1992a; Ellis, 1991). Soil-borne diseases, such as *Fusarium spp*. can be controlled with this method. Other steaming systems such as the Fink and Hood systems may be used for disinfecting greenhouse soil. The Fink method is a modification of the negative pressure method. Vertical suction pipes are inserted into the soil, instead of horizontal ones, and connected to a central suction pipe (Ellis, 1991). Steaming with the Fink method resulted in a better control of soil-borne diseases of roses than MeBr fumigation (Anonymous, 1992a). The Hood system is a semi-automatic system using insulated steel or aluminum hoods (Ellis, 1991). Detailed information on the different methods and their costs are reported by Ellis (Ellis, 1991). Supercritical steam is steam and water heated above 374°C at pressures of at least 3208 psi. (Rick Abbott, personal communication). This method has not yet been evaluated for control of soil-borne diseases and pests under field conditions (Mike McKenry and Rick Abbott, personal communications) although it considered an option for control of soil-borne diseases and nematodes in containerized plants and greenhouses (Carpenter et al., 2000).

Both steam and aerated steam are very expensive and only practical and economical under greenhouse conditions (Gullino and Lodovica, 1992). Another drawback of steam, as compared with aerated steam, is that it has a severe impact on the microbial balance in the soil. Soil steaming leaves a biological "vacuum" suitable for re-infestation by plant pathogens, a common characteristic of many soil fumigants. In some cases, plant growth can be suppressed, possibly due to the release of toxic compounds (high levels of ammonia, manganese, and soluble salts) and/or the killing of beneficial fungi, such as the mycorrhizal fungi (Mus and Huygen, 1992). Watering before planting should reduce soil toxicity after steaming.

Soil solarization

Many pathogenic fungi, bacteria, weeds, and nematodes can be controlled by the use of soil solarization, and it is considered an attractive alternative to soil fumigation. Soil solarization is compatible with other physical, chemical, and biological methods. It has been combined with soil fumigants, crop rotation, biocontrol agents, and soil amendments to improve its efficacy and reduce the use of soil fumigants (DeVay et al., 1990; Ellis, 1991; Greco et al., 1992; Katan and DeVay, 1991; Kokalis-Burelle et al., 1999; Pinkerton et al., 2000). For example, soil solarization is more effective in controlling soil-borne diseases and pests when combined with chloropicrin or a biological control agent (Anonymous, 1993a; Kokalis-Burelle et al., 1999). Pre-plant treatment with solarization and plant-growth-promoting rhizobacteria of tomato and pepper plants produced yields comparable to MeBr (Kokalis-Burelle et al., 1999). Species of *Phytophthora*, *Pythium*, *Pyrenochaeta*, *Fusarium*, *Verticillium*, *Sclerotinia*, *Sclerotium* and other pathogenic fungi were successfully controlled by soil solarization (Ghini, 1993). Soil solarization has been used to successfully control Verticillium wilt (*V.dahliae*) diseases in California since solarization works well with the hot, arid climate of much of the state. Ashworth and co-workers performed an experiment in the San Joaquin Valley to compare methyl bromide fumigation with soil solarization to control Verticillium wilt in a young pistachio orchard (Cook and Baker, 1989; Huisman and Ashworth, 1976). Methyl bromide was not as effective in controlling the disease, while broadcast tarping the orchard floor for two months during the hot season was. The fungus could not be detected to a depth of 120 cm and no damage was observed to the pistachio trees. Soil solarization has also successfully controlled Verticillium wilt in cotton. In some fields, the control lasted for 1 or 2 additional years (Katan and DeVay, 1991). Re-infestation of solarized soils by this pathogen was delayed in contrast to soil treated with MeBr (Katan and DeVay, 1991).

Soil solarization can also control some plant pathogenic bacteria. *Agrobacterium tumefaciens*, the bacterium that causes crown gall, is very sensitive to soil solarization in contrast to *Pseudomonas solanacearum*, another plant pathogenic bacterium (Cook and Baker, 1989).

Soil solarization has also been shown to be effective in the control and reduction of weeds in some parts of California. Elmore et al. have shown that Bermuda grass and Johnson grass in the Central Valley and near-coastal sites of California can be controlled by soil solarization (Elmore et al., 1993). Winter annual weeds (*Avena fatua, Capsella bursa-pastoris, Lamium amplexicaule, Poa annua, Raphamus raphanistrum, Senecio vulgaris*, and *Montia perfoliata*) were all effectively controlled by soil solarization (Katan and DeVay, 1991). Several summer annual weeds (*Echinochloa crus-galli, Malva parviflora*, and *Solanum nigrum*) were also controlled by soil solarization (Bill, 1993). There was no need for the use of pre-or post-emergent herbicide treatments (Katan and DeVay, 1991).

Plant pathogenic nematodes, such as *Ditylenchus spp.* and *Pratylenchus thornei*, have also been effectively controlled by soil solarization (Katan and DeVay, 1991). Recent studies in Oregon and Florida have shown soil solarization to be an effective tool in control of plant pathogens and nematodes, in some cases as effective as methyl bromide fumigation (Coelho et al., 1999; Pinkerton et al., 2000;Wilhelm and Westurland). Soil solarization could be practical in hot, sunny locations, like California's San Joaquin Valley, but not in the cool, foggy Central Coast region (Carpenter et al., 2000).

Solarization of nursery potting mixes is an alternative to steam or fumigation with methyl bromide (Duff and Barnaart, 1992) and was recently approved by CDFA for certification of nematode-free nursery plants (Stapleton et al., 1999). Solarization controls soil-borne diseases, weeds and nematodes when used with small amounts of potting mixes (Duff and Barnaart, 1992).

Soil solarization does have limitations. Some growers consider soil solarization too labor-intensive and prefer soil fumigation for reliability. The ground must be covered with plastic material, leaving it unproductive for 6-8 weeks. Its efficacy may depend on weather, soil type, and pest or disease to be controlled. Past studies had indicated that the application of soil solarization in cooler climates inside closed plastic houses would be needed to make it effective and soil solarization appears to be less effective in soil with low water-holding capacity. There are certain weeds (e.g. nut sedge) and deeply located fungal pathogens in the soil (*Armillaria spp.*) that are not killed by soil solarization (Anonymous, 1993a). Disposal of the plastic material can be an environmental pollution problem, although recycling is technically possible and economically warranted when a large volume of plastic film is involved. Recycling is successfully done in Jordan (Katan and DeVay, 1991), where soil solarization is used extensively.

Crop Rotation

Rotation of a susceptible crop with a resistant crop can decrease the pathogen inoculum in an infested field (Cook and Baker, 1989). Crop rotation can be an effective method for suppressing damage to annual crops caused by plant pathogens and other pests with limited host range. Crop rotation generally improves soil structure, maintains soil fertility and minimizes the need for pesticides (Easton et al., 1992). However, crop rotation needs time to be effective and the crop is often rotated with non-cash crops, contributing little to farm income (Mukhopadhyay, 1990). Rotating carrots with small grains, for instance, to reduce nematode populations was not considered an economical and viable option in Kern County (Klassen, 1992). The presence of long-lasting viable stages of microorganisms, such as microsclerotia, or the ability of the microorganisms to subsist as a saprophyte in competition with the soil flora and fauna, may also limit the use of crop rotation as a control strategy. Huisman and Ashworth reported that microsclerotia of *V.dahliae* can survive for periods of 10 to 20 years and could become the cause of failures of effective rotation schemes (Huisman and Ashworth, 1976a; Huisman and Ashworth, 1976b). Ben-Yephet et al. and Davis demonstrated that crop rotation alone is not effective for control of *V.dahliae* in potato (Ben-Yephet et al., 1980; Davis, 1985). Davis estimated the minimum period required to effectively reduce inoculum in moderately infested land to be five to ten years when a grain crop is used as a rotational crop (Davis, 1985). A great deal of work on crop rotation has been done recently to determine the most efficacious and economically viable rotation crops. Control of plant pathogenic nematodes was achieved in Florida with a summer-winter rotation scheme of beans and grains (McSorley, 1996). Rotations of rye or mustard in strawberry nursery plots were not effective in control of Verticillium wilt (Gordon et al., 1999), although wilt in strawberry production fields rotated with broccoli was comparable to fields fumigated with methyl bromide and chloropicrin (McSorley, 1996; Shetty et al., 1999). Based on the success of this work, a number of growers immediately began using this method (K. Subbarao, personal communication). Strawberry production plants in California that were grown in rotation with broccoli or Brussels sprouts had a lower disease incidence that was comparable to MeBr in some sites (Shetty et al., 1999). Broccoli rotation under moderate disease pressure has the potential to be part of a disease management system in strawberries.

Crop rotation is part of a national debate in the United States between advocates of so-called conventional agriculture and those who practice "alternative agriculture" (Cook, 1991). Practical rotation crops are limited by the Federal Commodity Program Support, as well as by environmental or economic factors. Growers who desire to grow a non-federally-supported commodity must waive their income from the commodity program. This was cited as a constraint for the implementation of long-term, diverse rotations (Anonymous, 1989a; Dobbs et al.,1988; Goldstein and Young, 1987). The National Research Council reported in 1989 that, "a number of government policies and programs have strongly encouraged farmers to specialize and deterred them from adopting diversified farming practices" (Anonymous, 1989a). Land and water costs can be too high in California to adopt crop rotation for some crops (Anonymous, 1993a). Growers that currently depend on methyl bromide, however, will have to contend with less efficacious chemicals and use these in concert with cultural methods like crop rotation to achieve the disease control and yield enhancements seen with MeBr fumigation (K. Subbarao, personal communication).

Biological Control

Effective biological control of soil-borne pests has been a challenge to agricultural researchers for many years. Soil is a complex ecosystem and many factors, such as soil pH and moisture can limit the success of introduced biological control agents. The broad definition of biological control is “the use by man of any organism for pathogen control”, although in soil ecosystems, biological control agents can be one or many different organisms (as is the case in suppressive soils) (Cook and Baker, 1989). Research has been conducted to simulate this general suppressiveness by adding suppressive soil to disease-conducive soil (Cook and Baker, 1989). The majority of this section discusses application of an antagonistic microorganism to soil to control plant pathogens.

A great deal of study has been done in the past decade using biological control agents, also known as antagonists, for control of soil-borne diseases (Anonymous, 1997a; Anonymous, 1998b; Bull and Ajwa, 1998; Eayre, 1996; Martin and Bull, 2000; Zehnder et al., 1997). They are not a complete replacement for methyl bromide fumigation, but function in an integrated pest management strategy (Gianessi, 1998). According to USDA-ARS researchers, successful biocontrol “most likely will require the development of an integrated systems approach that incorporates diverse aspects of the crop production system.” In the past decade, many biological control agents have been registered with US-EPA for use on crops to control disease (Anonymous, 1997b; Lumsden et al, 1996; Maliekal et al., 1998; Warrior, 1996). These microbial products are categorized as “biopesticides” by pesticide registration agencies. Currently in California, there are twenty-one biopesticides registered for use (CA Department of Pesticide Regulation, Sept 2000). These range from the well-known biocontrol agent *Agrobacterium radiobacter*, a bacterium used in biocontrol of crown gall to *Trichoderma harzianum*, a fungus used to control soil-borne diseases of strawberries and other crops. *Trichoderma spp*. are well-studied, efficient mycoparasites that perform best in moist, somewhat acidic soil (Cook and Baker, 1989). In a strawberry trial, addition of Trichoderma sp. to soil treated with ozone gas decreased Verticillium wilt in the first year, but this was not repeated the following year (Pryor, 1999). Another commonly used biocontrol agent is *Pseudomonas fluorescens*. This bacterium is a soil-dwelling antagonist that has several modes of action against pathogenic microorganisms. It favors moist soil with high organic matter and is compatible with mulching (Cook and Baker, 1989). No effect on fruit yield could be contributed to *P.fluorescens* when applied to strawberry plants (Bull and Ajwa, 1998). Many of these biological control agents can be effective but require specific environmental conditions to flourish (Cook and Baker, 1989). Only eight microbial-based biological control agents are registered for soil applications and are potential partial alternatives to methyl bromide (Table 3). None have the broad biocidal spectrum of MeBr but could be useful as part of an integrated pest management system.

Resistant varieties

Resistant plant varieties frequently contribute to the control of many soil-borne diseases and pests and can function in an effective rotational scheme. The availability of broad-spectrum and effective soil fumigants, such as MeBrC, diminished the need for host-plant resistance and plant breeders spent more time and effort on the improvement of yield and quality (Vereijken, 1992). This is particularly true for strawberries in California (Yuen et al., 1991). There are some nematode-tolerant rootstocks for fruit and nut trees, although these are used in conjunction with MeBr since they are not resistant to all nematode pest species (Carpenter et al., 2000).

One of the principal drawbacks of resistance breeding is that many genes for resistance are only effective against a single pathogen and sometimes one race of a pathogen. Plant resistance to a disease or pest may not always be available. Plants modified genetically to express pesticidal traits or “genetically modified pest-protected plants” have been created through genetic engineering. For example, genetically modified, insect-resistant tomatoes are in commercial production (National Research Council, 2000) and strawberry varieties that are genetically engineered to be resistant to the herbicide glyphosate are in development (Morgan and Baker, 1999). Use of these transgenic plants could reduce the use of and dependency on chemical soil fumigation although there is controversy as to possible human health and environmental effects (National Research Council, 2000). More research is needed in the development of resistant and agronomically desirable varieties through conventional breeding or genetic engineering techniques.

Another type of resistance in plants is a whole-plant defense response known as “systemic acquired resistance” (SAR). SAR is a non-specific reaction that enables the plant to produce defense compounds against multiple pests (National Research Council, 2000). It can be induced by a number of compounds, including salicylic acid and the harpin protein (active ingredient of Messenger™ biopesticide)(Anonymous, 2000b). External application of these chemicals may provide disease and pest control.

Cover crops, organic amendments, and compost

<u>*Cover crops*</u>: Many successes (Rothrock and Kendig, 1991; Subbarao et al., 1999), but also failures (Dillard and Grogan, 1985; Van Bruggen, 1990), have been published in the literature in the use of cover crops and multicrop inter-plantings to control soil-borne diseases and pests. Cover crops can suppress many weeds through competition for light and nutrients or allelopathy. Disease and pests may also be controlled since non-susceptible plants inter-planted with susceptible species may intercept pathogen inoculum or insect pests (Cook and Baker, 1989). The choice of cover crop is important; some nematode species may be affected by a cover crop, but others are not. It has been reported that cover crops such as rye and timothy release nematicidal substances during decomposition. Cover crops can also reduce nitrate leaching and runoff water from fields (Meisinger et al., 1972; Mukhopadhyay, 1990). Growing soybeans in California as a green-manure crop in the fall after potato harvest and incorporating the green crop in the soil before preparing the soil for spring planting effectively controlled potato scab caused by *Streptomyces scabies* under field conditions (Vruggink, 1970).

<u>*Organic Amendments*</u>: Soil-borne diseases can be reduced by organic amendments to soil and should be considered as a MeBr partial alternative (Jarvis, 1992; Linderman, 1989). Soil amendments must be chosen and prepared carefully so that disease is not exacerbated. In California, roots of field and greenhouse grown lettuce seedlings in soil amended with green crop residues were damaged (Phillips et al., 1971). When peas and beans were grown and incorporated into root-rot-infested fields immediately following the pea harvest, disease severity increased in peas planted the following season, while corn, sudan grass, sorghum and oats significantly reduced root rot severity (Tu, 1988). It was shown that organic residues from previous crops can be used as nutrient substrates by plant pathogenic microorganisms, such as *Sclerotium rolfsii*, and pathogen growth promoted. Linderman has shown that "the kind of organic matter and its state of decomposition

and/or microbial colonization determines the effects on root diseases (Linderman, 1989)." This may explain the reported successes and failures to control soil-borne diseases and pests in the literature. For instance, incorporation of broccoli residues into cauliflower fields in the Salinas Valley increased yield sometimes as much as chemical fumigation, but (Duniway et al. 1999; Sances and Ingham, 1999; Subbarao et al., 1999; Westerlund, 2000,) amendments were ineffective when applied to sterilized soil (Anonymous, 1997c). In strawberry fields, a single application of broccoli residues was not sufficient to control Verticillium wilt for the entire season (Sances and Ingham, 1999).

Compost: Compost improves soil water holding capacity, infiltration, aeration, permeability, soil aggregation and micro nutrient levels and supports soil microbial activity (Benedict et al., 1988, Chang et al., 1983, Hoitink, 1980). Research shows that soil amendments of composted sludge induce significant increases in crop yields (Anonymous, 1997c, Lewis et al., 1992, Mayberry, 1993,). For example, field and greenhouse experiments were performed at the South Coast Research and Extension Center of the University of California, Irvine to assess the value of composted sewage sludge as a soil amendment or soil conditioner for horticultural crops (Bevacqua and Mellano, 1993). The sludge was mixed with eucalyptus tree trimmings during composting. Potential human pathogens and weed seeds are killed by heat generated during composting. In addition, some organic chemicals are degraded, rendering the product odorless. The composting was performed according to regulations issued by US-EPA (Environmental Protection Agency, 1993). Lewis et al. have shown that *Rhizoctonia solani* and *Pythium ultimum* were significantly controlled using composted sewage sludge as a soil amendment in field plots (Lewis et al., 1992).

Some concerns about the proper preparation and usage of compost, such as the build-up in soil and crop tissue of heavy metals and build-up of soluble salts or changes in soil pH that may lead to depressed crop growth, have been addressed in this study (Bevacqua and Mellano, 1993). According to Mayberry, composted sludge products mixed with lawn clipping, leaves, and tree branches are sold in California (Mayberry, 1993). The products are used as soil amendments.

Composted bark can also be an effective soil amendment, particularly in containerized plants (Hoitink et al., 1977; Hoitink, 1980). Use of composted softwood and hardwood barks gave reproducible control of damping-off caused by *Pythium ultimum* in lettuce and cucumber and caused by *Rhizoctonia solani* in radish and bedding plants under greenhouse conditions (Chen et al., 1988; Hoitink et al., 1977; Lagunas-Solar et al., 1993; Stephens and Stebbins, 1985). Soil amended with ammoniated Douglas fir bark at rates of 90-225 tons/ha resulted in a significant control for strawberry red stele disease caused by *Phytophthor*a *fragariae* for up to two years (Hoitink, 1980). Compost has multiple modes of action for disease suppression, among them increased plant vigor caused by nutrient availability, presence of large populations of beneficial microorganisms and increased drainage.

Chitin Soil Amendments: Addition of chitin into soil suppressed *Rhizoctonia solani* (Sneh et al., 1971). It also may reduce nematodes due to a stimulation of chitinolytic microorganisms (Rodriguez-Kabana et al., 1987). Chitin amendments to soil are known to increase soil populations of actinomycetes (Vruggink, 1970). These microorganisms are important for the decomposition of crop residues, making mineral nutrients available to crops and frequently produce antifungal metabolites. Clandosan 618 is a commercial product with chitin (poly-N-acetyl-D-glucosamine)-protein as the active ingredient. The precise mode of action of chitin against nematodes and soil-borne diseases is still unknown. Studies by Westerdahl et al. have shown a significant reduction in nematode population after a chitin-urea soil amendment in potato and walnut field trials (Westerdahl et al., 1992). To be effective, high rates of chitin must be used: 1-3 tons/acre on a broadcast basis (Anonymous, 1990b). This product is registered by US-EPA for both pre- and post-plant use against nematodes. It is not currently registered in California, but it is in the registration process.

INTEGRATED PEST MANAGEMENT

The chemical and non-chemical options presented above are potential components of IPM. IPM involves the use of all these options and techniques that reduce pest populations and maintain them at levels below those causing economic injury (Linderman, 1989). Since none of the chemical and non-chemical options taken separately can replace MeBr, IPM is a viable strategy to replace MeBr as well as for reducing dependency on broad-spectrum pesticides. IPM can also be considered a first step to improve the economic, social and environmental sustainability of crop production (Jacobsen and Backman, 1993). In the past, IPM received little attention for the control of soil-borne diseases and pests of many crops, due to the availability of reliable broad-spectrum soil fumigants, and the constraints of IPM. IPM requires extensive research and grower education (Bal and van Lenteren, 1987) and active support by governments for its implementation (Bal and van Lenteren, 1987).

For the short term, Vereijken recommends direct research and policy on integrated farming systems (IFS) as a necessary compromise between socio-economical and socio-ecological interests (Vereijken, 1992). IFS are defined as "farming systems that aim for cost reduction and improvement of quality of products and production methods and at the same time maintain soil fertility and the quality of the environment"(Vereijken and Royle, 1989). For the long term Verijken recommends the development of an ecosystem-oriented farming system to solve the agricultural problems in a more comprehensive and sustainable manner (Vereijken, 1992). Industrialized countries appear to be considering the adoption of IFS (Girardin and Spiertz, 1993). A report by World Resources 1992-1993 states that " some government policies are beginning to change as awareness of environmental degradation grows, giving farmers new incentives to adopt resource-conserving alternative practices (World Resources Institute, 1993). For example, in 1987 the Dutch government prepared a long-term policy to reduce the use of pesticides by 50% by the year 2000 (Anonymous, 1991; Baerselman, 1992). They have stimulated the research and development of IFS to reduce the use of pesticides and fertilizers without a decline in yield and product quality (Anonymous, 1991).

The U.S. government has pushed for the implementation of IPM, rather than IFS, on 75 percent of U.S. farms by the year 2000 (USDA IPM initiative, 1994). According to the USDA, approximately 50% of all fruit and nut, vegetable, and major field crops in the U.S. are grown using IPM practices. This trend in the reduction of synthetic pesticides used stimulates the search for alternatives and the integration of chemical and non-chemical options. The IPM and IFS farming systems are based on a sound crop rotation, the use of resistant varieties and other non-chemical control strategies. Knowledge of the ecology and epidemiology of important diseases and on the population dynamics of key pests and major diseases is key for the development of IPM and IFS.

The California Legislature established the Biologically Integrated Farming Systems (BIFS) program in 1994 to enable the growth of integrated pest management techniques in California. The goals were expanded and the time frame extended in 1998. The University of California provides extension services, financial incentives and sets up demonstration programs for farmers wishing to reduce their use of agricultural chemicals. UC SAREP administers the methyl bromide alternatives grants program. Projects funded in 1999 include four strawberry projects, including one for strawberry nurseries using containerized transplants (Anonymous, 1999b).

One of these BIFS projects began in 1999 to test and demonstrate MeBr alternatives in strawberries. This SAREP-funded project, BASIS (Biological Agriculture Systems in Strawberries), includes eight farmers from the Monterey Bay region. Pest management techniques included the enhancement and release of beneficial species, such as soil inoculants and beneficial insects, non-chemical weed control and trap cropping (Anonymous, 1999b).

The California Strawberry Commission is conducting extensive field research under the Strawberry Pest Management Alliance. This alliance, funded by DPR's Pest Management Alliance Program, includes scientists from the University of California, UC Cooperative Extension, USDA-ARS, California Department of Food and Agriculture, CA Integrated Waste Management Board and members of the crop protection industry. The program is using a multi-faceted approach to develop a pest management program that balances cultural and biological control practices with synthetic chemicals. They showed that technically feasible alternatives to MeBr exist, and are currently working on an economically viable, practical pest management strategy for strawberry cultivation without MeBr.

A great deal of funding and research is being focused on integrated pest management approaches and in the future, elements of BIFS, the Strawberry PMA and projects like them are likely to become the standard in agriculture.

CONCLUSIONS AND DISCUSSION

Of all the alternatives to MeBr fumigation, soil fumigation with a broad-spectrum pesticide provides growers with the most reliable disease and pest control, increased yields, better product quality, extended crop seasons and therefore reliable economic return. Due to the prior availability of these effective and reliable broad-spectrum pesticides, they have become very important pest management tools for the field production of many economically important crops in California. In the short term, strawberry growers will likely continue to depend on chemical alternatives, such as combinations of chloropicrin, 1,3-D and metam sodium, since these alternatives are the most efficacious and reliable option. Vegetable growers will likely increase use of 1,3-D or metam sodium to control nematodes once MeBr is unavailable or too expensive. Growers of perennial tree and vine crops currently use 1,3-D as an alternative to MeBr. Unfortunately, many of these chemical alternatives have detrimental health and environmental effects and regulatory concerns which ultimately leads to use restrictions that limit their usefulness.

Sustainable and economical long-term alternatives, however, are beginning to emerge (Anonymous, 1998d). Currently these alternatives, when used in concert in an integrated systems approach, can achieve the same disease and weed control as MeBr. Non-chemical options, such as soil solarization, crop rotation, biological control, soil amendments, steam, and others, may be considered too risky and/or uneconomical when used alone, but are viable as part of an IPM program. In addition, non-chemical options may be preferred in certain situations. For example, effective and economical, steam treatment may be preferred over soil fumigation when the grower wants to replant more promptly than with chemical fumigants (Stark et al., 1944). Soil solarization of larger fields is another viable option for California, particularly in the Imperial Valley; although it does not treat soil deeply enough to control nematodes and Armillaria root rot. Greenhouse and containerized nurseries are extremely high value operations and could use the more expensive options of steam, artificial soils and solarization.

Utilizing all of these tools to develop IPM programs for the many different farming systems in California could provide the solution to the replacement of MeBr soil fumigation and the reduction in use of and dependence on synthetic pesticides. The California Strawberry Commission (CSC), University of California (UC), and the USDA-ARS continue to have an extensive research program underway in the search for chemical and non-chemical replacements for methyl bromide. The CSC has recently included the strawberry nurseries in their research program. USDA-ARS and UC research program include, besides strawberries, fruit and nut crops. In addition, there is limited research underway on alternatives to MeBr for vegetable production and cut flowers. DPR, CDFA, USDA-ARS, University of California, CSC, growers, and private industry continue to work together in the search for environmentally sound and economically feasible alternatives to MeBr.

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APPENDIX A: RESEARCH ON MeBr ALTERNATIVES

International MeBr Alternatives Conferences

Research on methyl bromide alternatives has been extensive in recent years (see Table 1). An international conference on MeBr alternatives and emissions reduction has been held each year since 1995. It is sponsored by Methyl Bromide Alternatives Outreach, in cooperation with US-EPA and USDA and aims, among other things, to enhance data exchange regarding alternatives to MeBr. Scientists come from all over the world to share the latest research on MeBr and the proceedings from these meetings are published.

Many of the California researchers are funded from multiple sources, including DPR's Reduced-Risk Pest Management Grants program, UC Sustainable Agriculture Research and Education Program (SAREP), USDA-ARS and UC Cooperative Extension (UCCE). The research and outreach efforts are extensive, requiring financial support from many sources in order to solve the complex problems involved with MeBr replacement.

DPR Pest Management Grants

The following organizations and alliances received funding from DPR to explore alternatives to MeBr soil fumigation (Table 1). These grants ultimately assist commodity groups to develop reduced-risk pest management practices.

California Strawberry Commission: The California Strawberry Commission (CSC) conducted a multi-year study into many MeBr alternatives for strawberry production. This program was an alliance of CSC, University of California, UCCE, USDA-ARS, CA Integrated Waste Board, CA Department of Food and Agriculture and members of the crop protection industry. The group explored alternate bed fumigation treatments and applications using 1,3-D+chloropicrin; ozone fumigation; mulching with VIF (virtually impermeable plastic film) mulch; crop rotations with rye or broccoli; and organic soil amendments of blood meal, feather meal and fishmeal. They found that these alternatives are technically feasible but the economic feasibility was not explored. The Commission currently has a Pest Management Alliance in place that is funded by DPR to explore the economic feasibility of several MeBr alternatives.

CA Assoc. of Nurserymen: DPR provided a grant for work in nursery fruit and nut trees to find alternative chemical fumigants. Preliminary results showed that soil fumigation with 1,3-D+Basamid provided nematode control equivalent to MeBr.

University of California: Amendments of garlic powder to the soil controlled white rot of onion and garlic, while in strawberries, soil incorporation of broccoli residues provided disease control similar to MeBr. Plastic mulches were studied at the UC Kearney Agricultural Station as an alternative to herbicides in vegetable production. Integrated pest management systems are being developed on grapes and lettuce by UCCE.

USDA-ARS: In support of USDA-ARS research efforts, DPR funded projects developing disease and pest resistant strawberry cultivars. These efforts are still underway.

Others: Two private companies performed research on MeBr alternatives for strawberries. SoilZone explored the use of ozone as a soil fumigant and Pacific Agricultural Research looked into an IPM approach using soil amendments, transplant of aseptically-grown plug plants, alternative chemicals and, inoculation of soil with mycorrhizal fungi. Plug plants are a promising alternative to MeBr fumigation, but may not be feasible economically or practically. This technology may be a useful alternative for the strawberry nursery industry on a small scale, such as for the organic growers, but it is not economical for the large-scale producers.

University of California/ UC SAREP

UC SAREP received $1million in funding for MeBr replacements. There is a strong integrated management emphasis to the work done at UC SAREP and they have developed the Biologically Integrated Farming System (BIFS) for multiple crops, including the Biological Agriculture Systems in Strawberries (BASIS).

In addition, a great deal of research into methyl iodide (MeI), a potential replacement fumigant for MeBr, has been conducted at University of California, Riverside

(Eayre et al., 2000, Hutchison et al., 1999, Norton, 2000, Ohr et al., 1996,). MeI has been shown to be highly efficacious on a number of crops, including vegetables (Hutchison et al., 1999, Norton, 2000) and peaches (Eayre et al., 2000), but is not currently registered.

Interregional Research Project #4 (IR-4)

IR-4 Chemical Alternatives: The IR-4 Methyl Bromide Alternatives Program for Minor Crops is researching several chemical and biological alternatives for disease control. Use of the chemical fumigants methyl iodide, InLine (emulsified concentrate of 1,3-D and chloropicrin), metam sodium, Basamid, Enzone and propargyl bromide, as well as DiTera, a microbial-based product, is being investigated in strawberries and tomatoes.

IR-4 Funded biopesticide projects: The IR-4 program, in addition to the IR-4 Methyl Bromide Alternatives Program for Minor Crops, funded 29 biopesticide research projects in 1999 (Anonymous, 1999a) and 37 in 2000 (Anonymous, 2000a). Two of the biopesticides funded by this program are of note to California strawberry growers. *Pseudomonas fluorescens,* a bacterium used for control of soil-borne strawberry diseases and *Trichoderma atroviride* used to control root rot on ornamentals and strawberries. Both of these biological control organisms are effective but require specific environmental conditions to flourish (Cook and Baker, 1989).

USDA-ARS

The research arm of the USDA has four California locations where MeBr alternatives are studied (Table 1). At the Fresno location, scientists are studying host plant resistance, biological control and alternative chemicals on strawberries, grapes, fruit and nut trees and vegetables. Researchers at UC Davis, in addition to studying host plant resistance in tree fruits and nuts, are investigating cultural methods of disease control. More work in biological control of strawberry and vegetable diseases, particularly in Plant-Growth-Promoting Rhizobacteria (Anonymous, 1998b), takes place at Salinas. Scientists there are also developing integrated pest management systems for strawberries and vegetables that include use of soil amendments and crop rotations. The USDA-ARS laboratory in Riverside is looking at soil fumigant emissions reduction in strawberries and vegetables, including MeBr.

US-EPA

The US-EPA published several Methyl Bromide Alternatives Case Studies in 1995, 1996 and 1997. Subjects covered include “Organic strawberry production,” “Compost,” “Soil Solarization in Orchards,” and “IPM in California Vineyards”(Anonymous, 1996). These reports are designed to highlight tools that are efficacious against the pests currently controlled by MeBr. It is stressed that none of these tools are complete replacements for MeBr.

Table 1: Overview of organizations currently involved in research on alternatives to methyl bromide soil fumigations

(Not meant to be inclusive)

	STRAWBERRIES	GRAPES	TREE FRUIT/NUTS	VEGETABLES
Biological Control	UC SAREP, USDA-ARS (Fresno, Salinas, IR-4) Pacific Ag Research, US EPA, CA Strawberry Commission (CSC)	UC SAREP, USDA-ARS (Fresno)	UC SAREP, USDA-ARS (Fresno)	UC SAREP, USDA-ARS (Fresno, IR-4)
Cultural Control	UC SAREP, USDA-ARS (Fresno, Salinas), UC Davis, CSC, Pacific Ag Research, US EPA	USDA-ARS (Fresno)	UC SAREP, USDA-ARS (Davis)	UC Kearney Ag Station, UC Davis
IPM	UC SAREP, USDA-ARS (Salinas, Fresno), CSC, UC Davis	USDA-ARS (Fresno)	UCCE, USDA-ARS (Fresno)	UCCE, UC Davis, USDA-ARS (Salinas)
Alternative Chemicals	CSC, Pacific Ag Research, Soil Zone, UC Riverside, UC Davis, USDA-ARS (Riverside, Fresno, IR-4)	USDA-ARS (Fresno)	CA Association of Nurserymen, USDA-ARS (Fresno)	USDA-ARS (IR-4, Fresno, Riverside)
Resistant /tolerant cultivars	USDA-ARS (Fresno), CSC; UC Davis	USDA-ARS (Fresno)	USDA-ARS (Davis)	USDA-ARS (Fresno)

Table 2: Potential methyl bromide alternatives for strawberries, non-strawberry nursery crops and pome fruit, stone fruit and nut trees.

POTENTIAL MEBR ALTERNATIVE[1,2]	PEST/DISEASE	CROP	EFFECTIVE?	PAGE(S) IN TEXT
Metam-sodium	Verticillium wilt	Strawberries	Not as effective as MeBr	14, 16
	Nematodes	Strawberries	Not as effective as MeBr	16
	Weeds	Strawberries	Yes	16
Dazomet	Nematodes	Nursery (non-strawberry)	Yes	16
	Weeds	Nursery (non-strawberry)	Yes	16
	Fungal pathogens	Nursery (non-strawberry)	Yes	16
1,3-D	Verticillium wilt	Strawberries	No	17
	Nematodes	Strawberries	Yes	12, 17
	Weeds	Strawberries	No	17, 19
	Nematodes	Fruit and Nut Trees	Yes	13, 17, 18
	Nematodes	Nursery (non-strawberry)	Yes	11, 17
Chloropicrin	Verticillium wilt	Strawberries	Yes	9, 12, 18
	Phytophthora root rot	Strawberries	Yes	18
	Nematodes	Strawberries	No	18
	Weeds	Strawberries	No	18
Propargyl Bromide	Verticillium wilt	Strawberries	Yes-preliminary	14, 19
	Nematodes	Strawberries	Yes-preliminary	14, 19
Methyl Iodide	Verticillium wilt	Strawberries	Yes-preliminary	12, 14, 19
	Nematodes	Strawberries	Yes-preliminary	12, 14, 19
	“replant” disorder	Fruit and nut trees	Yes	14, 19

POTENTIAL MEBR ALTERNATIVE[1,2]	PEST/DISEASE	CROP	EFFECTIVE?	PAGE(S) IN TEXT
Ozone	Verticillium wilt	Strawberries	Yes	12, 13, 20
Steam	Fusarium spp.	Nursery (non-strawberry)	Greenhouses only	20, 21
	Nematodes	Nursery (non-strawberry)	Greenhouses only	20, 21
Soil Solarization	Verticillium wilt	Strawberries	Yes: in some locations	22
	Verticillium wilt	Fruit and Nut Trees	Yes: in some locations	22
	Nematodes	Nursery (non-strawberry)	Yes	11, 22, 23
	Weeds	Nursery (non-strawberry)	Yes	22
Crop Rotation	Verticillium wilt	Strawberries	Partial	12, 14, 24
Biological Control	Verticillium wilt	Strawberries	Efficacy varies	14, 25
Host Resistance	Nematodes	Fruit and nut trees	Yes: preliminary	14, 26
	Verticillium wilt	Strawberries	No	9, 14, 26
Soil Amendments	Verticillium wilt	Strawberries	No	13, 28
	Phytophthora root rot	Strawberries	Yes	13, 28
	Nematodes	Fruit and Nut Trees	Yes: preliminary	29
	Pythium root rot	Nursery (non-strawberry)	Yes	27
	Rhizoctonia root rot	Nursery (non-strawberry)	Yes	27
	Weeds	Nursery (non-strawberry)	Yes	28

[1]The economic viability and practical feasibility has not been fully explored for many of these alternatives. Some of these alternatives are not registered for use.

[2]Many of these alternatives must be used as part of an integrated pest management program to be effective.

Table 3: Biopesticides currently registered in California for use in soil applications.

Biocontrol Product	Pesticide Type	Biocontrol Organism
GALLTROL-A	Bactericide	*Agrobacterium radiobacter*
ROOTSHIELD DRENCH	Fungicide	*Trichoderma harzianum rifai*
KODIAK CONCENTRATE BIOLOGICAL FUNGICIDE	Fungicide	*Bacillus subtilis*
MYCOSTOP BIOFUNGICIDE FOR VEGETABLE AND ORNAMENTAL CROPS	Fungicide	*Streptomyces griseoviridis*
GNATROL BIOLOGICAL LARVICIDE	Insecticide	*Bacilllus thurengiensis subsp. israelensis*
BOTANIGARD 22 WP	Insecticide	*Beauveria bassiana*
DITERA G BIOLOGICAL NEMATICIDE GRANULE	Nematicide	*Myrothecium verrucaria*
DITERA WDG BIOLOGICAL NEMATICIDE GRANULE	Nematicide	*Myrothecium verrucaria*

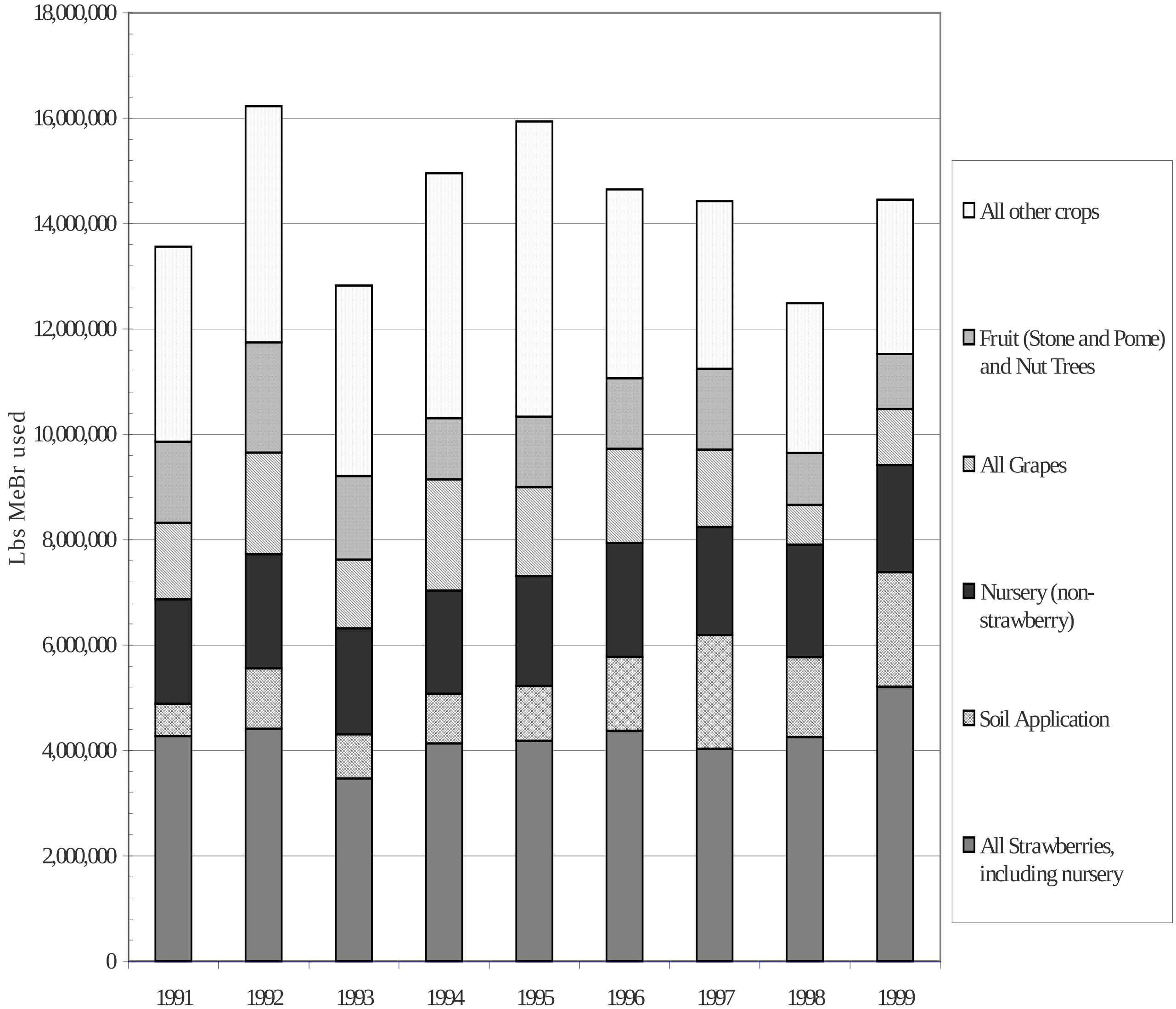
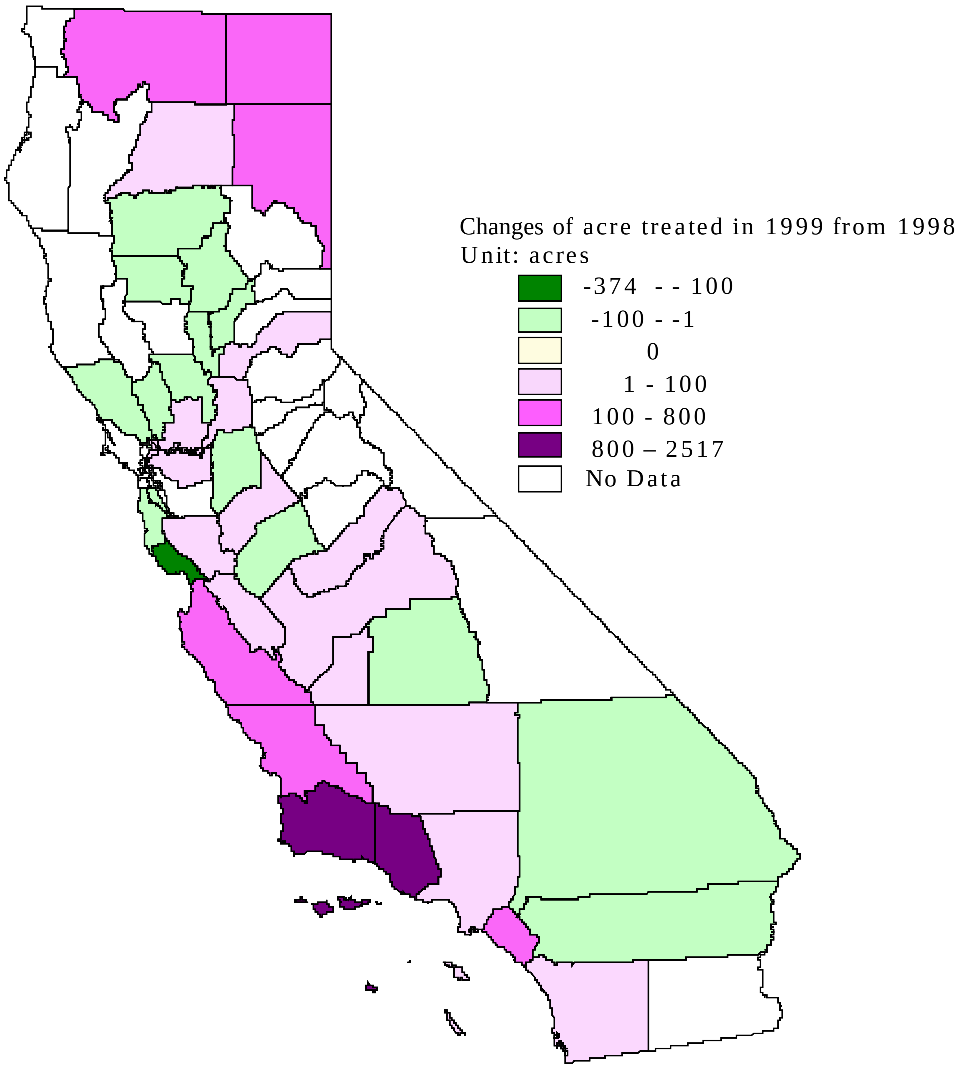
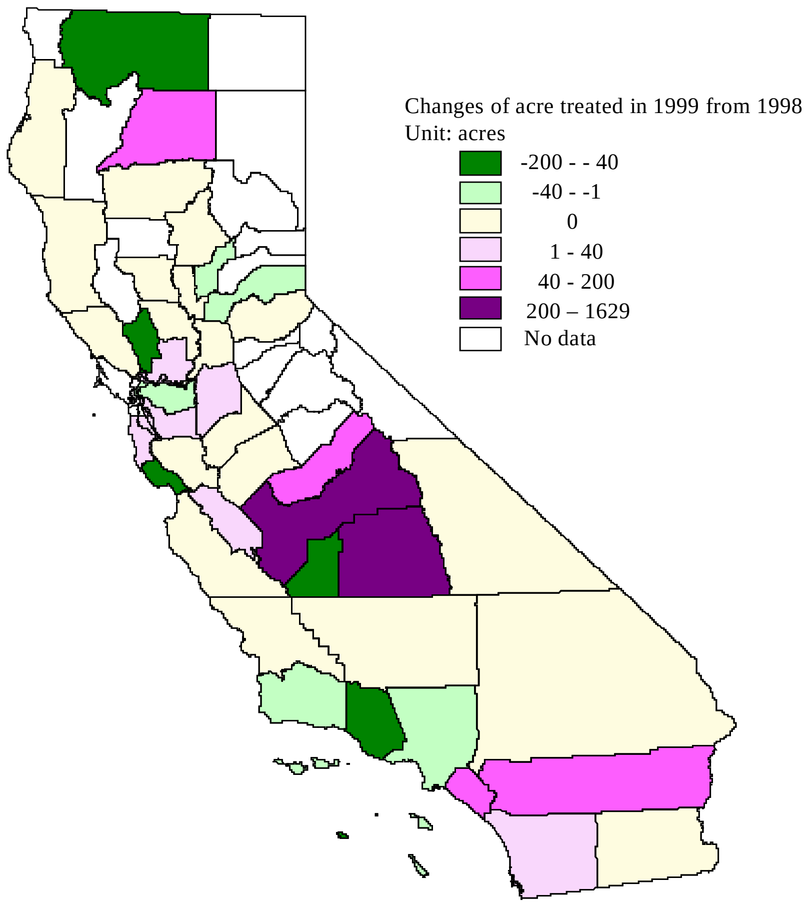


Figure 1: Methyl bromide use in production agriculture in California from 1991 to 1999 (all data from California PUR, 1999 data preliminary)



Data source: Pesticide Use Report 1998 and 1999
Larry Wilhoit, Belinda Messenger and Minghua Zhang

Figure 2: Differences in number of methyl bromide treated acres of strawberries between 1998 and 1999.



Data source: Pesticide Use Report 1998 and 1999
Larry Wilhoit, Belinda Messenger and Minghua Zhang

Figure 3: Differences in number of methyl bromide treated acres in soil applications between 1998 and 1999