Options to Methyl Bromide for the Control of Soil-Borne Diseases and Pests in California with Reference to the Netherlands

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 nursey stock. The fumigant is applied generally before planting in combination with chloropicrin. Mixtures of these two fumigants combine the greater soil penetration of methyl bromide and higher fungal toxicity of chloropicrin.

Methyl bromide was listed in 1993 by the Parties of the Montreal Protocol as an ozone-depleting compound. Because methyl bromide has an ozone depletion potential larger than 0.2, this fumigant was placed under the U.S. Clean Air Act of 1990. Under this Act, the domestic production in 1994 will be frozen at 1991 levels. In addition, the importation and production of methyl bromide will cease by the year 2001.

In California, methyl bromide is widely used to control soil-borne diseases and pests of economically important crops. The largest use of methyl bromide is for the treatment of fields before planting of strawberries, followed by soil treatment by the nursery industry. It is essential that environmentally sound and economically feasible alternatives are in place and available to California farmers and pest control advisors well before the year 2001 to meet the mandate specified in the U.S. Clean Air Act. Based on an extensive review of relevant scientific publications, proceedings of international conferences, and consultation of United States and Dutch scientific experts, the California Department of Pesticide Regulation evaluated chemical and non-chemical options to methyl bromide.

The largest use of methyl bromide in the Netherlands is for greenhouse production of strawberries, several vegetable crops, and cut flowers. Because of concern for public safety and

for air and groundwater quality, the Netherlands decided to gradually phase out methyl bromide soil fumigation from 1982 through 1992 by adopting new pesticide policies and farming systems.

No single synthetic chemical or non-chemical option to methyl bromide in the broad-spectrum of field applications for which it is currently used could be identified. There are partial synthetic chemical and non-chemical options and all can be used for the development of integrated pest management and integrated farming systems. Integrated pest management and integrated farming systems could be a viable strategy to replace the use of methyl bromide and concurrently reduce the use of and dependence on synthetic pesticides. However, due to the availability of effective synthetic pesticides, in specific the broad-spectrum soil fumigants like methyl bromide, there has been no need for the development of integrated pest management and integrated farming systems. This may change if all broad-spectrum synthetic pesticides are phased out. Government, university, and agricultural industry cooperation will be needed for the development of integrated pest management and integrated farming system approaches.

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DISCLAIMER

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INTRODUCTION

The introduction of the broad-spectrum soil fumigants after World War II led to the replacement of traditional diversified farming systems by large-scale monocultures. Soil fumigants provided reliable and excellent disease and pest control, increased yields, high quality produce, extended crop seasons and reliable 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 (163).

The increased use and dependency on pesticides in high-yielding crops have not only led to high and stable yields but also to increased risk to soil, water, and air pollution. A reduced crop rotation frequency can increase the epidemiological potential of soil-borne diseases and pests which can increase pesticide use. In addition, soil fumigation leaves a biological "vacuum" suitable for re-infestation by plant pathogens, requiring that the soil be treated each growing season.

Because of 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 chemical pesticides for disease and pest control. Sweden and Denmark, for example, reduced their pesticide use by 50 percent and 25 percent respectively in weight of active ingredient used (21, 72). The Multi-Year Crop Protection Plan of the Netherlands requires that pesticide use be reduced by 35 percent before 1995 and 50 percent before 2000 (7, 8, 10, 21). Soil fumigation with methyl bromide (MB) is not allowed in Switzerland for food crops due to concern of the build-up of high levels of bromine in these crops. MB soil fumigation is only allowed in the production of flowers and in tree nurseries in this country (25, 82). When MB is used to control potato nematodes, the production of vegetables on fumigated land is not permitted in Germany for the following three years (9). In 1991, Germany banned the use of 1,3-dichloropropene (1,3-D) (50) and priority is given to non-chemical plant protection measures (21). In California, many of the soil fumigants such as 1,2-dibromo-3-chloropropane (DBCP) and 1,2-dibromoethane (EDB) have been canceled due to environmental pollution and/or health concerns (22).

MB, one of the few remaining broad-spectrum soil fumigants left, has been listed in 1993 by the Parties of the Montreal Protocol as a stratospheric ozone-depleting compound. An international panel of atmospheric scientists recently estimated the ozone depletion potential (ODP) for MB at 0.7. The U.S. Clean Air Act of 1990 requires all compounds with an ODP of 0.2 or higher be listed as a Class I substance and their production and importation be phased out within seven years. In addition, all Class I compounds may be subject to a tax. This tax has been proposed for MB; implementation requires Congressional approval (11, 14). Furthermore, according to a U.S. Environmental Protection Agency (USEPA) final rule, MB domestic production in 1994 will be frozen at 1991 levels and production and importation of MB will cease by January 1, 2001. To meet the mandate specified in the U.S. Clean Air Act of 100 percent phase out of MB production and importation by the year 2001, it is essential that environmentally sound and economically feasible alternatives are in place and available to California farmers and pest control advisors well before the phase out date.

The purpose of this report is to identify and assess potential control methods other than MB for soil-borne diseases and pests. This report is based on an extensive review of scientific publications, proceedings of international conferences, information provided by scientists, and personal experience of the senior author while visiting nurseries and experimental stations in the Netherlands. Not all of the chemical pesticides mentioned in this report are registered in California, or if registered may not be labeled for the described use. The report will not assess whether each identified option or combination of options is a practical or economically feasible alternative, or identify what the possible regulatory limitations are for these options. Adverse biological impacts or environmental concerns may limit the practical use of an option, whether chemical or non-chemical. An economic assessment on the loss of MB was prepared by the National Agricultural Pesticide Assessment Program, U.S. Department of Agriculture (USDA) (14).

METHYL BROMIDE IN CALIFORNIA

To properly assess any potential option to MB preplant soil fumigation, it is essential to identify the attractive characteristics of MB, to understand how this fumigant is used and why it is so important to many California crops.

MB has quick and deep soil penetration (MB has a low boiling point of 3.6 °C and high vapor pressure), leaves the soil rapidly (short waiting period before replanting), and has low residual phytotoxicity (61, 85, 149). Its ability to penetrate extends to pathogens in protected locations. Stark and Lear demonstrated that MB could penetrate root-knot galls and kill the embedded nematodes (137).

MB is commonly used in combination with chloropicrin (CP) to fumigate soil. Various mixtures of MB and chloropicrin (MBC) combine the advantages of the greater soil penetration of MB and higher fungal toxicity of CP (161). It has been shown, for instance, that mixtures of MB and CP more effectively control Verticillium wilt and weeds than either compound alone (77, 136, 158, 163). Difficult to kill sclerotia of Botrytis cinerea (104), Sclerotinia sclerotiorum (109), and Sclerotium delphinii (104) are also more effectively controlled by these mixtures than with either compound alone.

The various mixtures of MB and CP effectively control soil-borne pathogens, nematodes, some bacteria, weeds, and replant problems in the production of fruit and nuts, ornamentals, and vegetables in California. Preplant application of these mixtures also generally permits the soil to be replanted within a short waiting period with the same crop on the same land year after year. Furthermore, the mixtures of these chemicals allow for the important consideration of tailoring a fumigant to meet the specific problem. For these reasons, preplant soil fumigation has become an integral part of the growing routine in the production of these crops.

The limiting factor in strawberry production is the replant problem, a complex disorder which is still not clearly understood. Verticillium spp., several other soil-borne fungi and possibly nematodes could be involved in this disease complex. The Verticillium wilt fungus (Verticillium dahliae) produces microsclerotia which are notably tolerant to environmental stress, such as desiccation and high temperatures, and difficult to kill. These microsclerotia have been shown to survive up to 20 years in soil (47), making crop rotation, depending on propagule density, ineffective for Verticillium wilt control (47, Norman C. Welch, personal communication). In addition, V. dahliae has an extensive host range (> 300 different plant species) which includes economically important crops, such as cotton, grapes, tomatoes, and stone fruits. Many weeds and rotational crops such as alfalfa, vetch, and several lupines, are also included in the host range of Verticillium wilt. V. dahliae is widespread in California soils (141). The extensive host range of Verticilium wilt and its widespread presence and long survivability in California soils limits the implementation of an effective crop rotation strategy.

The successful control of the Verticillium wilt disease complex in strawberries began in 1961 with the prophylactic use of MBC (159). By 1990 growers preplant applied slightly more than 4 million pounds of MB for the field production of strawberries, the highest reported use for a California commodity (15). MBC fumigant has provided effective and reliable control of this disease. The use of MBC fumigant has also resulted in significant increases in yield and fruit quality and made it possible to cultivate ever-bearing strawberries in California on a continuous basis on the same field (17, 162). MBC soil fumigation has been credited for saving the California strawberry industry from foreign competition (14, 159).

Because of the effectiveness of MBC, limited effort was made to elucidate the disease complex of strawberries or to find alternatives to MBC soil fumigation. The breeding program, for instance, was focused on the development of new cultivars with better fruit quality and production instead of resistant varieties (164, 163). Strawberry varieties which were 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 (163).

The use of MBC, applied before planting, is also crucial for the control of soil-borne diseases and pests of fruit trees. A problem with fruit trees occur when young fruit trees are grown on replanted orchard sites. They may exhibit retarded early growth and death of root tips often resulting in poor yield. Factors responsible for the retarded growth may 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 (147). The specific plant pathogenic soil microorganisms responsible are in many cases still unknown. MBC is the only available fumigant that effectively controls organisms associated with the replant problems in fruit trees. To control the oak root fungus (Armillaria mellea) of fruit and nut trees and grapes, the University of California recommends the use of MBC soil fumigation (3). This disease is, because of its nature, very difficult to control, and so far, MBC soil fumigation seems to be the only effective way to manage this disease.

The use of MBC preplant soil fumigation is 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 (3).

The use of MB is also crucial to the nursery industry. Nursery stock is a high cash value crop where even a small crop loss can have a significant economic impact. In general, infested or diseased nursery stock will not be accepted by buyers in California or in other states and countries. In addition, to prevent the spread of serious nematode pests and soil-borne diseases, California law required in the past that certain nursery stock be grown on soil treated in an approved manner, or required the County Agricultural Commissioner to sample nursery stock for commercial farm planting for nematodes using a procedure approved by the California Department of Food and Agriculture (California Code of Regulations, sections 3060.1(b) and 3060.2)(1, 64). This past mandatory program, may be part of the reason that, after strawberries, the California nursery industry is the second largest user of MB. About 2.3 million pounds of MB were used in the nursery industry in 1991 (Jack Wick, personal communication).

According to an announcement by the Department of Food and Agriculture, "a recent review and evaluation of California's nematode control program has resulted in a change from a mandatory program for all producers of nursery stock for farm planting to a voluntary participation 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 using MB. Nursery stock, voluntary 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. An approved treatment is soil fumigation because this control method is very effective in killing nematodes. Only three fumigants were approved for use in the nursery regulations: MB, 1,3-D, and 1,2-dichloropropane-1,3-dichloropropene (D-D®, a 1,3-D containing pesticide). Since the suspension of all permits for use of 1,3-D and the loss of D-D, the only available approved treatment for certification is soil fumigation with MB (1).

MB became more widely used for the control of soil-borne diseases and pests after DPR suspended permits for use of 1,3-D in 1990, following the detection of 1,3-D in ambient air at levels of concern. There was an increase of 1 to 1.5 million pounds of additional MB use following the suspension of permits for use of 1,3-D (14). Prior to the suspension of permits for use, 1,3-D was used on a wide variety of economically important crops to effectively control nematodes (11, 90) and, in combination with chloropicrin to control replant- and soil-borne diseases (106). Economic losses due to 1,3-D's unavailability totaled an estimated $106.8 million, according to an economic assessment study by Landels (91). Sugar beet, carrot (84, 91), tomato, and broccoli growers suffered the biggest losses (91).

Attempts to use metam-sodium (Vapam®) as a replacement were often unsuccessful because it did not always provided consistent results (11, 16, 56, 61, Norman C. Welch, R. Rodriguez-Kabana, Becky Westerdahl, A. Paulus, personal communications). Poor control of soil-borne pests created an emergency situation for crops such as carrots, sweet potatoes, and watermelons in California. Emergency uses of MB were approved by the Department of Pesticide Regulation (DPR) for these crops following the suspension of permits for use of 1,3-D.

METHYL BROMIDE IN THE NETHERLANDS

In contrast to California, the largest use of MB in the Netherlands before 1982 was soil fumigation in greenhouses. More than 3 million kg of MB were used each year to fumigate soil under greenhouses for the production of tomatoes, lettuce, strawberries, cucumbers, sweet peppers, and cut flowers. Intensive monocropping was usually the practice in greenhouses. MBC was also routinely used in the propagation of fruit trees (75).

To prevent the build-up of high levels of bromine due to MB soil fumigation, it is common practice to leach soils under greenhouses with large amounts of water (80-100 L/square meter) after treatment for the production of certain crops. Vegetables, such as lettuce, parsley, and spinach may take up bromine at levels exceeding national tolerance levels established for daily intake (66, 75). Furthermore, many plants such as carnations, onions, chrysanthemums, melons, spinach, garlic, and sugar beets are very sensitive to bromine which may adversely affect these crops (75).

In the Netherlands, high use of MB and the practice to leach soils with large amounts of water led to the contamination of ground, surface, and drinking water, and the detection of unacceptable levels of MB in ambient air (107). The use of MB soil fumigation became a great health concern. For this reason, the Dutch government decided in 1982 to gradually phase out the use of MB soil fumigation over a 10-year period (107).

The first step of the phase-out of MB was to reduce the quantity used to disinfest soil in greenhouses by using gas-tight plastic sheets with greater gas-retaining qualities when applying the fumigant and reducing the rate by more than half (12). However, after this first step of the phase out, experiments had shown that residual MB in the treated soil still resulted in unacceptable MB levels in the air after removal of the plastic sheets.

The need for MB soil fumigation was eventually eliminated over the 10-year period through the adoption of new pesticide policies. Chemical substitutes such as 1,3-D (cis-dichloropropene, see under "alternative control methods"), aldicarb, metam-sodium, dazomet, ethoprop, and oxamyl can only be used by prescription; that is, approval for the use of these pesticides will be granted, with certain exceptions, only when the need of the use of the compound has been demonstrated. An approved compound can only be used once in every four years. These requirements have accelerated the integration of the non-chemical options such as improved steam sterilization techniques, artificial and natural growth substrates, crop rotation and resistant varieties (10, 12, 13, 107). They have also stimulated the research and development of an innovative production system for strawberries (see under "Soilless culture systems for greenhouses") and new farming systems (see under "Integrated pest management and integrated farming systems").

ALTERNATIVE CONTROL METHODS

This section discusses options or strategies as potential replacement to MB soil fumigation:

I. **Chemical soil disinfestation.**

A. **Fumigants.**

1) Metam-sodium (Vapam®): This product, which is formulated as a water-soluble solution, is a broad-spectrum biocide and may be used to control soil fungi, nematodes, soil insects, and weeds (6, 16, 144). Metam-sodium applied to moist soil will decompose to methyl isothiocyanate (MIT), which is the biocidal ingredient.

For several crops, metam-sodium has not always provided control of soil-borne diseases and pests which is consistent and comparable to MB. When carrot fields in Kern County were treated with metam-sodium for nematode control after the suspension of 1,3-D permits, the results varied from excellent to disastrous, depending on the proper application and use of the product. In addition, metam-sodium does not have the penetration capacity as MB and is not controlling root-knot nematodes as well as MB. Diseases such as those caused by Fusarium and Verticillium spp. are also not controlled by this fumigant (14)..

Conventional methods of application of this fumigant do not provide a uniform distribution of pesticide in soil (61). It has been shown, for instance, that metam-sodium appears to move as a fumigant only 8 to 10 cm from the point of injection (130); i.e., the fumigant does not disperse well in the soil and requires water for good movement (14, 106). Its poor dispersion may limit the control of soil-borne diseases and pests of deep-rooted crops like stone fruits, almonds and grapes. Due to its poor dispersion in the soil, metam-sodium has a narrow margin for error in its application in comparison to MBC.

Improved control may require increased rates or application of large quantities of water as a carrier (105). However, these practices may result in higher costs and possible groundwater contamination (11, 82). 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 (132). Another limitation of metam-sodium is the long waiting period between application and planting to prevent damage due to phytotoxicity (11, 16, 56, 61).

2) Dazomet (Basamid®): This compound is like metam-sodium a precursor to the formation of the biocidal ingredient MIT. Upon contact with the moist soil, dazomet also converts to MIT (MIT releaser) (5). Dazomet is not registered for food crops in the U.S. In cool climates, dazomet needs a 60-day re-entry waiting period (17).

Dazomet effectively controls weeds, nematodes, and fungal pathogens, resulting in cost-effective yield increases (5, 62). This product is applied preplant to seed beds in nurseries, greenhouses, 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 (6, 16, 129).

However, good results with dazomet are dependent on proper application, which includes thorough mixing with soil to desired depth and efficient sealing (2). A drawback of the MIT releasers is the slow diffusion of MIT through soil compared to MBC (110). Groundwater contamination is also of concern for the same reasons cited for metam-sodium (11, 82).

3) 1,3-D (e.g.,Telone®): 1,3-D has two isomers: *cis*- and *trans* dichloropropene. The *cis* -isomer is more volatile and is considered more active biologically than the *trans*-isomer (98, 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. Telone is as efficacious as MB in controlling nematodes but does not control fungi or insects (16). At high rates, 1,3-D has some efficacy against a few weeds (11, 75).

1,3-D was used in California on a wide variety of economically important crops to effectively control nematodes (11, 90) and, in combination with chloropicrin (e.g., Telone-C17) or MIT (Vorlex®), to control replant and soil-borne diseases (14, 106). 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 more damaging to cotton than the infestation of either one alone. Infestations usually occur on light-textured sand-loam and sand soils which are very amenable to soil fumigation under California conditions (114, Philip A. Roberts, personal communication).

In April 1990, high levels of 1,3-D were detected in ambient air in selected sites in Merced County, California. Residues in the air detected exceeded several orders of magnitude over the level of health concern. DPR immediately suspended all permits for use of 1,3-D. As a consequence, Vorlex and Telone-C17 and other 1,3-D-containing formulations could not be used in California (14). Telone is now under special review by USEPA. The inability to use 1,3-D as a soil fumigant created emergencies for many economically important crops which were dependent for reasons stated above on the availability of this fumigant (see "Methyl bromide").

Under a research authorization granted by DPR to DowElanco Company, a project was initiated in the Salinas Valley in September 1993 to determine whether new technology and equipment, training and certification of personnel, can insure that concentrations of 1,3-D in ambient air do not exceed acceptable levels.

Accelerated biodegradation of 1,3-D by soil microorganisms after repeated soil application in the Netherlands was suggested by Smelt **et al.** (131, 133). Additionally, the presence of 1,3-D in shallow groundwater was reported by Loch and Verdam (95). The shallow water table in most areas of the Netherlands coupled with high rainfall after fumigation provide ideal conditions for movement of 1,3-D through the soil profile to groundwater. To reduce possible environmental pollution and the amount of pesticide applied, the *trans*-isomer of 1,3-D was removed from

Telone and only the *cis*-isomer is now allowed to be used as a soil fumigant in the Netherlands (Hugo E. van de Baan and Joop A. van Haasteren, personal communications). Cis-dichloropropene is currently sold in Europe under the trade name of Nematrap® by Shell Nederland Chemie B.V. in Rotterdam, the Netherlands.

4) Chloropicrin (e.g., Tear Gas®): 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 MB (19). It is formulated as either a liquefied gas or in combination with MB or 1,3-D (see MB and 1,3-D, respectively) to broaden its spectrum (6, 11, 16).

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 MB (14). 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 (63).

CP has several undesirable attributes. It has a pungent odor and thus can be unpleasant to handle (11). Use of CP in the Netherlands is not permitted due to phytotoxicity problems and many complaints by the public about its pungent odor (Joop A. van Haasteren, personal communication). After application, the dispersion of CP into soil and evaporation from the soil occurs much slower than MB (129). Therefore, a longer waiting period for CP is required before planting to prevent damage due to phytotoxicity than for MB.

5) Dichloroisopropyl ether (Nemamort®): This product is not registered in the U.S. and may only be used in Japan and Taiwan. Nemamort may be effective in the management of nematodes in fruit crops, citrus, vegetable crops and ornamentals (11). However, results are inconsistent.

6) Bromonitromethane: This product is still under development and will require several years of research before registration is possible (120).

7) Enzone®: Enzone is a new compound that may control nematodes, soil-borne diseases and insects, but may not be as effective as MB for weed control (Norman Welch, personal communication). The active ingredient of Enzone is sodium tetrathiocarbonate that releases the biocide carbon disulfide. Enzone has recently received a USEPA registration (18). A California registration is pending for grapes and citrus (Becky Westerdahl, personal communication).

Enzone can be pre- or postplant applied to vines that are at least one year old (142) and could become a replacement for DBCP (Becky Westerdahl, personal communication). It is short-lived and frequent applications may be needed (33).

Research is in progress at the University of California, Davis, to evaluate Enzone's efficacy to control soil-borne diseases and pests on many crops (Becky Westerdahl, Doug Gubler, and Joe Ogawa, personal communications).

B. Non-fumigants.

1) Systemic nemastat/insecticides.

The following systemic compounds can be used as a pre- and postplant nemastat/insecticide treatments. They may be used for shallow rooted crops or to treat the upper soil fraction in combination with soil fumigants. A wet, cold climate and soils with high organic content may limit the efficacy of soil fumigation (31, Becky Westerdahl, personal communication).

a) Ethoprop (Mocap®). Ethoprop may be incorporated into the soil at planting and is also used as a layby treatment. This compound has an emulsifiable concentrate (E.C.) and granular formulation (6, 145).

b) Aldicarb (Temik®). Aldicarb is applied as an in-furrow treatment at planting time. Broadcast and side-dress treatments may be utilized. Watering after application will improve the effectiveness. This compound has a granular formulation only, because of the high toxicity of the parent compound (6, 65, 145).

c) Carbofuran (Furadan®). Carbofuran may be band or furrow applied and has a granular and flowable formulation (11, 145).

d) Oxamyl (Vydate®). Oxamyl may be preplant applied and should be incorporated into the soil. This compound may also be used as an in-furrow application. It has an E.C. and granular formulation (11, 145).

e) Fenamiphos (Nemacur®). Fenamiphos may be broadcast, in-the-row, in band applied, or by drench before or at planting time. This product has an E.C. and granular formulation (11, 145).

A major drawback of these compounds is that their efficacy is not comparable to fumigants such as MB and 1,3-D for nematode control (65). Nemastats do not kill nematodes but typically work by delaying hatching, impeding migration of invasive larvae to host roots, impairing feeding behavior, or disorienting males toward females. They also do not effectively control weeds and soil-borne fungi. Control of diseases and pests located deeply in the soil cannot be adequately controlled by these compounds (11).

Rapid leaching and enhanced biodegradation of pesticides due to physiological adaptation of soil microorganisms after repeated application of the same pesticide may reduce their efficacy (11, 115). A loss in efficacy due to microbial degradation was reported for carbofuran (48, 53, 133), fenamiphos and oxamyl (140). Increased population of Pseudomonas spp. and Flavobacterium spp., for instance, were associated with less efficacy after repeated carbofuran soil applications (48).

The ability of the above mentioned compounds to leach through soil may also lead to a contamination of groundwater (11). In 1983, for instance, residues of the pesticide aldicarb were detected in groundwater in the Smith River Plains in Del Norte County, California. Aldicarb use was eliminated in Del Norte County by exclusion on the California label registered with USEPA and the DPR. Because of groundwater contamination, the Netherlands may prohibit the use of aldicarb as a soil disinfectant for flower bulbs before 1995. Oxamyl will then be a partial alternative to aldicarb for flower bulb production (10). Fenamiphos was never registered for use in the Netherlands because the compound leaches easily from the soil (M. Leistra and D. J. Bakker, personal communications).

2) Formaldehyde: Formaldehyde effectively controls soil-borne fungi, bacteria and weeds. This product is used as a seed, soil, and space disinfectant in some countries. Formalin is also used as an additive to enhance the efficacy of hot water treatments to kill nematodes in plant tissues (Phil Roberts, personal communication). Phycomycetes, also known as "water mold fungi," are most susceptible to formaldehyde (129). A 6 percent dust, adsorbed on inert carrier (charcoal, ground oat hulls, sawdust), is used for soil treatment. Sewell and White showed in an experiment that soil treatments with formalin (38 percent formaldehyde solution) for the control of the replant disease of apple resulted in growth increases of more than 100 percent and did not differ significantly from treatments with chloropicrin (3,000 L/ha), propylene oxide (1 ml/L soil) and steam (3 cm deep soil layers free-steamed for 15 min.) (128).

Formaldehyde is used as a space disinfectant in the edible mushroom culture in the Netherlands (10). The availability and use of formaldehyde in the United States depends on the generation of the necessary data for the re-registration process by potential registrants.

3) **Furfuraldehyde:** The chemical properties of 2-furfuraldehyde, also known as furfural, resemble those of formaldehyde and benzaldehyde, which suggests the possibility of its use as a fungicide (54). It may control nematodes and soil-borne fungi (Rodriguez-Kabana, personal communication, 26), and may be integrated with biological control measures (11).

However, this compound may not control soil insects and weeds. Furfuraldehyde is still an experimental compound and it may take many years of research before registration of this product can be considered (120, Rodriguez-Kabana, personal communication).

4) **Inorganic azides** (Na or K - azides): Azides are enzyme inhibitors, which affect the activity of peroxidases, oxidases, and other metal-containing enzymes (97). Thus, azides may be expected to affect a broad-spectrum of microbiological activities. Hydrozoic acid is considered the biocidal ingredient and is formed after azide hydrolysis (122).

Inorganic azides can be applied as a pre- or postplant treatment. They may control soil-borne fungi, bacteria, weeds, and insects, but do not control nematodes (11, 55, 146). However, Kelley and Rodriguez-Kabana have shown in field studies, that the level and spectrum of soil-borne diseases and pests controlled with sodium azide resembled that of methyl bromide when the concentration of sodium azide was increased, and when it was applied under plastic seal to minimize loss (81).

Azides are acutely toxic (11), explosive, and thus dangerous to handle (123). Their use is limited since they are not yet tested on a wide range of crops (3). Furthermore, hydrozoic acid is formed only in acid soils and decomposes with the liberation of nitrogen (30). Parochetti and Warren reported that in soil, depending on soil type and pH levels, potassium azide was weakly adsorbed and thus, could be prone to leaching (111).

5) Systemic fungicides.

The following compounds are systemic fungicides and can be used as a pre- and postplant treatment to control plant pathogenic fungi.

a) Benomyl (Benlate®). Benomyl provides control of a broad-range of plant pathogenic fungi. This compound may be applied through a sprinkler system or as a soil drench on some crops. This fungicide is formulated as a dry flowable, oil dispersible, and wettable powder (6, 143).

b) Metalaxyl (Ridomil®): Metalaxyl can be used to control specific soil-borne pathogenic fungi belonging to the Phycomycetes. This fungicide is used as seed bed treatment. Metalaxyl is formulated as emulsifiable concentrate, dust, flowable, and wettable powder (6, 143).

Benomyl controls diseases caused by species of Verticillium, Fusarium, Rhizoctonia, and many other pathogens on a wide variety of crops. When benomyl was applied as a soil drench, it reduced Verticillium wilt in potatoes and strawberries (27, 79).

Metalaxyl effectively controls species of Pythium, Phytophthora, and Peronospora. For instance, crown rot of tomato caused by Phytophthora capsici resulted in considerable losses in the San Joaquin and Sacramento Valley during 1955-1965. Ioannou and Grogan have shown that seed treatments with metalaxyl were as effective against this pathogen as metalaxyl applied to soil, without being phytotoxic (73).

The development of resistant or tolerant strains after frequent application of these compounds is a major limitation in their use; their use should thus be restricted to integrated programs (11, 75, 96).

II. **Non-chemical soil disinfestation.**

1) Steam. 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 could be used in nurseries as an alternative to soil fumigation.

New and more effective steam application methods, such as negative pressure steaming, were developed and described by Runia for greenhouse soil disinfestation (124). 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 (50, 75, 124,). 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 (13, 50).

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 (50). Steaming with the Fink method resulted in a better control of soil-borne diseases of roses than MB fumigation (13). The Hood system is a semi-automatic system using insulated steel or aluminum hoods (50). Detailed information on the different methods and their costs are reported by Ellis (50).

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 to control soil-borne diseases and pests under field conditions (Mike McKenry and Rick Abbott, personal communications).

Steam is very expensive and is generally considered only practical and economical under greenhouse conditions (61). A steaming method for field application has recently been developed by a German company and will be evaluated by Yoder Brothers, Inc. in Florida (Andrew Bishop, personal communication).

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, as do most soil fumigants, a biological "vacuum" suitable for re-infestation by plant pathogens. 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 (80). Certain crops such as lettuce, beans, and roses, are very susceptible to manganese toxicity. Watering before planting should reduce soil toxicity after steaming.

2) Soilless culture systems for greenhouses. Soilless culture of crops can be accomplished by using artificial substrates such as rockwool, rock, clay granules, and flexible polyurethane foam-blocks to allow plant roots to absorb nutrients and water. Soilless culture of tomatoes, strawberries, cucumbers, peppers, eggplants, and some flowers are grown in greenhouses using artificial substrates as a replacement to MB soil fumigation.

An economically and environmentally sound greenhouse strawberry production system was developed in the Netherlands using artificial substrates on hanging shelves or on raised shelves outdoors. Runners and their roots are thus prevented from coming in contact with the soil and infection by soil-borne pathogens or pests is avoided. A regulated trickle irrigation system pumps a nutrient solution to the plants. The nutrient solution may be recycled to reduce waste and to prevent environmental contamination after sterilization by heating to about 90 °C (13). Runners are harvested and placed into a substrate for root development.

To stimulate bud formation, runners are then exposed to short-day light. Plants may be stored at -2 °C up to eight months in a dormant condition or may be placed in substrates in the greenhouse or outdoors. Under warm weather conditions, plants may produce strawberries within 60 days without the use of methyl bromide or any other soil fumigant (13). Because of the short cropping period, growers can take advantage of market conditions by either quickly increasing production or by selecting another cash crop. Production can be significantly increased to more than 40,000 Kg/ha/4-month growth and harvest cycle. Growers also have the option to produce 2 to 3 crops/year (12, 13).

Establishing a computerized substrate system that controls water and fertilizer needs and heating system for strawberry production in the Netherlands may cost approximately $1,950,000/ha. This high price is coupled with a possible high risk: Failure of water and/or heating systems may result in a substantial loss if not fixed within 12 hours (13). Furthermore, the use of artificial substrates may result in substantial waste streams, such as substrates and plastics (155).

Although soilless media are usually pathogen-free, infestations of these media by plant pathogenic microorganisms may occur in the greenhouse if proper sanitation procedures are not followed (138). Steam could be used to sterilize these artificial substrates for reuse. Sneh et al. reported that formaldehyde and metam-sodium could effectively control F. oxysporum f. sp. lycopersici, Rhizoctonia solani, and Pythium myriotilum in Tuff medium for strawberry production (135). Composted hardwood bark may also be used since it is considered naturally suppressive because of microorganisms that are hyper-parasites of plant pathogens (36, 49, 86, 108) or that produce microbial inhibitors (67, 108). The USDA is developing soilless media in combination with EPA-registered biological control agents to selectively control damping-off diseases (8).

3) Soil solarization. Many pathogenic fungi, bacteria, weeds, and nematodes have been controlled by the use of soil solarization, and it is considered an attractive alternative to soil fumigation. Soil solarization is compatible with other physical (see under microwaves), chemical, and biological methods. It may be combined with soil fumigants, crop rotation, biocontrol agents, and soil amendments to improve its efficacy and reduce the use of soil fumigants (41, 50, 60, 80). For example, soil solarization is more effective in controlling soil-borne diseases and pests when combined with chloropicrin or a biological control agent (17). Species of Phytophthora, Pythium, Pyrenochaeta, Fusarium, Verticillium, Sclerotinia, Sclerotium and other genera have been successfully controlled by soil solarization. Soil solarization has been used to successfully control Verticillium wilt diseases in California.

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. Methyl bromide was not as effective in controlling the disease, while broadcast tarping the orchard floor for two months during the hot season was more effective in the control of Verticillium wilt (V. dahliae). The fungus could not be detected to a depth of 120 cm. 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 (80). Re-infestation of solarized soils by this pathogen was delayed in contrast to soil treated with MB (80).

Some plant pathogenic bacteria are controlled by soil solarization. Agrobacterium tumefaciens is very sensitive to soil solarization in contrast to Pseudomonas solanacearum (41).

Soil solarization has also been shown to be effective in the control and reduction of weeds in California. Elmore et al. have shown that bermudagrass and johnsongrass in the Central Valley and near-coastal sites of California can be controlled by soil solarization (51). 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 (80). Several summer annual weeds (Echinochloa crus-galli, Malva parviflora, and Solanum nigrum) were also found to be controlled by soil solarization (28). Soil solarization also kills weed seeds. There was no need for the use of pre-or post-emergent herbicide treatments (80).

Nematodes, such as Ditylenchus species and Pratylenchus thornei, have also been effectively controlled by soil solarization (80).

In the warmer areas of Italy, soil solarization could replace some uses of MB (13). In the Liguria region of northern Italy for example, soil solarization has been practically implemented in plastic houses to control soil-borne diseases such as Verticillium wilt (V. dahliae) and corky root (Pyrenochaeta lycopersici) of tomatoes (61).

Solarization of nursery potting mixes could be an alternative to steam or fumigation with methyl bromide (46). A solar collector, consisting of aluminum gutters or galvanized iron tubes covered with transparent plastic, effectively controlled soil-borne pathogens (57).

Soil solarization has limitations. Growers consider soil solarization too labor-intensive and prefer soil fumigation for crop insurance. Field workers have to cover the land with plastic material, leaving it unproductive for 6-8 weeks or delaying planting dates. Its efficacy may depend on weather, soil type, and pest or disease to be controlled. Soil solarization is less effective or not effective at all in cooler climates in the control of pest and diseases under field conditions. However, the application of soil solarization in closed plastic houses may make it an effective method in cooler climates. Soil solarization appears to be less effective in soil with low water-holding capacity (41). Soil solarization does not effectively control certain weeds (e.g., nutsedge) and deeply located fungal pathogens in the soil such as Armillaria species (17).

Disposal of the plastic material may be an environmental pollution problem. Recycling is technically possible and economically warranted when a large volume of plastic film is involved. Recycling is successfully done in Jordan (80).

4) Microwaves. The use of microwaves for soil disinfestation is at the present time not considered practical under most conditions (61). Conventional microwaves have limited application for soil disinfestation in nurseries. More research is needed to assess their potential to control soil-borne pests and diseases. A study is proposed by the University of California, Davis, on the "Control of Pests and Pathogens in Agricultural Soils with Radio Frequency Power." Radio frequency heating operates on the same principal as microwave heating with the exception of different frequency and target size. One of the proposed studies will combine radio frequency power, using non-selective heating modes, with soil solarization in order to improve efficacy and reduce cost by using less electricity to kill pests and plant pathogens in nursery soil. Efficacy and cost will be compared with those of methyl bromide and steam treatments for soil. If successful, this technology will have wider applicability such as for structural and commodity treatments. This five-year study will be a cooperative project with Titan Beta (Dublin, California), CPC International, Sandia National Laboratory, Lawrence Livermore National Laboratory, and several companies in agricultural and energy industries (151). A method using radio frequency power to disinfect mushroom compost has been patented and is already on the market (50).

5) Crop Rotation. 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 (47).

However, crop rotation needs time to be effective and the crop is often rotated with non-cash crops, contributing little to farm income (101). Rotating carrots with small grains, for instance, to reduce nematode populations was not considered an economical and viable option in Kern County (83).

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 (70, 71). Ben-Yephet et al. and Davis have demonstrated that crop rotation alone is not effective for control of V. dahliae (23, 40). Davis estimated the minimum period required to effectively reduce inoculum in moderately infested land to be 5 to10 years when a grain crop is used as a rotational crop (40).

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" (38). 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 (4, 43, 59). The National Research Council reported that, "a number of government policies and programs have strongly encouraged farmers to specialize and deterred them from adopting diversified farming practices (4)."

Label restrictions may also discourage or restrict the choice of rotational crops for reasons such as lack of residue or tolerance data and phytotoxicity. Fenamiphos, for instance, has a 120-day waiting period for planting any crop not on the label (B. Westerdahl, personal communication). A 120-day waiting period is not considered an effective and economical use of the farmer's land in today's intensive agricultural system.

Furthermore, land and water costs are considered too high in California to adopt crop rotation for many crops (17).

6) Biological control methods. Antagonistic microorganisms established in the infection site in advance of the pathogen may be used to prevent infection or as colonists of the infected tissues to arrest disease development. They may have the potential to increase crop yield without adverse effects to the environment (32).

Releasing these antagonistic microorganisms with the seed at time of planting is considered an effective way of using these microorganisms (38). The antagonistic Trichoderma and Gliocladium spp., used as seed treatments, have shown potential to control soil-borne plant pathogens. These antagonistic agents are generally highly specific for the control of a certain disease or pest. This characteristic could be an advantage in some instances but a disadvantage in others such as in a replant problem where many pathogenic organisms are involved.

The integration of biological and fungicidal seed treatments has been found to improve disease control. Trichoderma and Gliocladium spp. have been found to be compatible with many of the chemicals used for seed treatments. They are not affected by compounds such as carboxin, metalaxyl, captan, copper oxychloride, quintozene, oxadixyl, and copper sulfate. This allows the possibility of integrating the use of these fungicides at lower rates with biological seed treatment by Trichoderma and Gliocladium spp. (102, 103).

Soil microorganisms also may be used to turn on (induce) plant defense genes in the plant. Inoculative release of beneficial bacteria at the beginning of the disease cycle may function as the equivalent of host-plant "resistance" to the target root disease. Agrobacterium radiobacter (K-84) has the ability to protect plants against crown gall and is currently sold worldwide for biological control of crown gall.

The population of antagonistic microorganisms tends to build up in response to, rather than in advance of, disease and thus may be too late or too early to control disease (38). For instance, research with crown gall, caused by Agrobacterium tumefaciens, has shown that beneficial root-associated bacteria increase in numbers in response to the disease, but usually too late for control.

When introduced into the soil, microbial agents are less successful than MB in the control of soil-borne diseases and pests. Often, these agents do not persist in high numbers for a sufficient length of time to protect plants adequately, and multiple applications are needed (37). Yield increases associated with the use of these products are quite sporadic (32). Other limitations in the use of these products may include difficulties in mass production, formulations, delivery systems, their high degree of pathogen or pest specificity, limited shelf life (76), and their inconsistent, less rapid field performance in comparison to chemical pesticides (76, 113).

The use of biological control options to manage soil-borne diseases and pests require a thorough knowledge of microbe ecology and mode of action of biological agents. However, there is lack of fundamental understanding of the ecological relationships of the diverse microbial population, including plant pathogens and biological control agents in the soil (69). Much research, education and training in the proper use of these products are therefore a prerequisite for the development of a successful biological control strategy (16, 74).

The commercialization of biological disease control products is still in its infancy (76). Some commercial formulations of biological control agents are sold in several countries. Streptomyces griseoviridis was isolated from a suppressive Finnish sphagnum peat and developed into a commercial biocontrol product Mycostop® (88). Trichoderma-based mycofungicidal preparations have been registered in at least six countries (117, 118). Recent registration of Gliocladium virens by the USEPA as a biocontrol agent suggests that many other biocontrol agents may follow for commercial use (119, 134). Biological control is likely to be an integral part of the disease management strategy for many crops in the near future.

7) **Resistant varieties.** Host plant resistance may contribute to the solution of many soil-borne diseases and pests. Furthermore, resistant varieties may be incorporated into an effective rotational scheme. However, because of the availability of broad-spectrum and effective soil fumigants, such as MBC, for the control of soil-borne diseases and pests, the need for host-plant resistance diminished and plant breeders spent more time and effort into the improvement of yield and quality (155). This is particularly true for strawberries in California and potatoes in the Netherlands (154, 167).

One of the principal drawbacks of resistance breeding is that most genes are only effective against a single pathogen and sometimes one race of a pathogen. The frequent use of resistant varieties may enhance the development of new pathotypes. Resistance by pathogens and insects may be prevented by reducing the selection pressure on the microorganisms by crop rotation, the use of tolerant varieties and/or integrating other control options.

Mogen International, a biotechnology company in the Netherlands, has "found a key to giving plants resistance to multiple fungal species that has not been obtained with conventional methods" (151). Mogen's research efforts are focused on exploiting the natural phenomenon of broad-spectrum, inducible resistance. Broad-spectrum, inducible resistance evolved from the discovery that all plants produce an array of novel proteins as a result of infection or stress. Some of these proteins, especially the ones that belong to the chitinase and glucanase families, have demonstrated a broad-spectrum fungicidal effect (Peter J. M. van den Elzen, personal communication).

Resistance to a disease or pest may not always be available. For instance, host plant resistance to Meloidogyne arenaria and some races of Heterodera glycines are not available (166). To overcome the lack of resistance genes, Schots et al. have designed an approach to engineer possible long lasting resistance against nematodes using "plantibodies" that are genes that encode monoclonal antibodies against plant- pathogen specific proteins (127). Nematode-active Bacillus thuringiensis (Bt) strains have been recently discovered (38). Mycogen plans to isolate the Bt genes and, through genetic engineering, incorporate the genes for the Bt toxin into plants. This could reduce the use of and dependency on chemical soil fumigation for nematode control.

Genetic resistance to root-knot nematodes has been developed only in a few crops, such as tomatoes and sweet potatoes (Philip A. Roberts, personal communication). More research may be needed in the development of resistant and agronomically desirable varieties through conventional breeding or genetic engineering techniques.

8) Cover crops, multicrop interplantings, organic amendments, and compost. Many successes (121), but also failures (42, 150), 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. 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 (100).

Soil-borne diseases can be positively, but are often negatively, affected by organic amendments to soil (75, 94). 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 experimental field conditions. In California, field and greenhouse grown lettuce seedlings in soil amended with green crop residues have been shown to be negatively affected due to root damage (112).

Combining soil amendments with green crop residues with a steam-air mixture at 60 °C for 50 minutes damaged lettuce roots (112). 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 (148). It was shown that organic residues from previous crops can be used as nutrient substrates by plant pathogenic microorganisms, such as Sclerotium rolfsii, and their 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 (94)." This may explain the reported successes and failures to control soil-borne diseases and pests in the literature.

At the South Coast Research and Extension Center of the University of California, Irvine, field and greenhouse experiments were performed to assess the value of sewage sludge as a soil amendment or soil conditioner for horticultural crops. 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 USEPA (52). Concerns, 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 (26). Preliminary results have shown a significant increase in yields. No further results of this study were available at this time . According to Mayberry, composted sludge products mixed with lawn clipping, leaves, and tree branches are sold in California. The products are used as soil amendments (99). 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 (93).

The addition of chitin into soil suppressed Rhizoctonia solani (134) and additionally may reduce nematodes due to a stimulation of chitinolytic microorganisms (119). Chitin amendments to soil are also known to increase soil populations of actinomycetes (156). They are important for the decomposition of crop residues, making mineral nutrients available to crops. 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.

The recent registration by USEPA of Clandosan for both pre- and postplant use against nematodes prompted the need to obtain efficacy data for this material on crops grown in California. 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 (157). To be effective, high rates of Clandosan must be used: 1-3 tons/acre on a broadcast basis (8). This product is not registered for use in California.

Compost appears to improve soil water holding capacity, infiltration, aeration, permeability, soil aggregation and micro nutrient levels and supports soil microbial activity (24, 34). 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 (35, 86, 139). 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 Phytophthora fragariae for up to two years (68). Little is understood about the mode of action of compost.

INTEGRATED PEST MANAGEMENT (IPM) AND INTEGRATED FARMING SYSTEMS (IFS)

The synthetic chemical and non-chemical options presented under "alternative control methods" are potential components of IPM. IPM involves the use of all these options and "suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury (92)." Since none of the synthetic chemical and non-chemical options taken separately can replace MB, IPM could be a viable strategy to replace MB as well as for the reduction of and dependency on synthetic chemical pesticides. IPM can also be considered as a first step to improve the economic, social and environmental sustainability of crop production. However, IPM has 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. Van Lenteren et al. state that "an IPM program is far more complicated to develop and implement than to rely on chemical control (92)." IPM requires extensive research and grower education (20, 98). It needs active political support by governments for its implementation (20, 92).

Characteristics of conventional farming, as reported by Doering, are: "Specialized crop and livestock farming; high crop prices or low input costs, encouraging particular crop choices and/or production intensification; extensive use of off-farm inputs; little necessity for concern with off-farm impacts of the production process; and increasing size and concentration of production (157)." According to Vereijken, there is no need for a conventional agricultural system in industrialized countries since they are already struggling with increasing surpluses of agricultural products, decreasing income and employment in most rural areas and the growing concern of the consumers about the quality of their food, air, soil, and drinking water. For the short term, Vereijken recommends direct research and policy on IFS as a necessary compromise between socio-economical and socio-ecological interests (155). IFS are defined as "farming systems which 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 (152)." 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 (155).

Industrialized countries appear to be considering the adoption of IFS (58). 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 (165)." For example, in 1987 the Dutch government prepared a long-term policy to have the use of pesticides reduced in halve by the year 2,000 (10, 21, 58). Recently, the U.S. government has pushed for the implementation of IPM on 75 percent of U.S. farms by the year 2,000. These current trends in the reduction of, and dependency on, synthetic pesticides will stimulate the search for alternatives and the integration of chemical and non-chemical options. These options should fit into the total crop-production system for the development of successful IFS. The farming systems are based on a sound crop rotation, the use of resistant varieties and other non-chemical control strategies.

The Dutch government has stimulated the research and development of IFS to reduce the use of pesticides and fertilizers without a decline in yield and product quality (10). For the development of IPM and IFS, more knowledge is needed on the ecology and epidemiology of important diseases and on the population dynamics of key pests and major diseases for the development of IFS. To accurately monitor pests and diseases and to determine threshold levels for the development of computer-based models for pest and disease control, rapid and cost effective detection methods, such as the enzyme linked immunosorbent assay (ELISA), DNA probes, and isozyme analysis techniques have to be developed. Early detection of plant pathogens and pests with these methods or others coupled with accurate field sampling strategies is a necessity for development of IFS (125). Various ELISA's using polyclonal and monoclonal antibodies, DNA probes, and isozyme analysis techniques for rapid detection and identification of plant pathogens are already developed and many assays are commercially available (29, 39, 78, 83, 126).

Research is in progress in the above mentioned areas and in the development of IFS for various agricultural field crops (153) and nursery stock production (45). In the Netherlands, the first studies on IFS were performed some fifteen years ago (20, 58). Experimental IFS are currently developed at three regional experimental farms, with region-specific cropping systems. Results reveal that most pesticide inputs may be replaced by non-chemical options, with economic returns comparable to conventional farming systems. A network of study groups have been established to transfer the developed IFS in the farming community to evaluate them under different soil, farm and management practices. An IFS for potato production in the Netherlands has been developed (154).

In California, various Commodity Advisory Boards in coorporation with the University of California and DPR are pursuing research into chemical and non-chemical alternatives to MB soil fumigation. For example, the Strawberry Advisory Board has a total annual expenditure of $749,800 to be spent on research projects such as the evaluation of experimental compounds, application strategies, resistance to soil-borne diseases and other non-chemical options (Frank Westerlund, personal communication).

CONCLUSIONS AND DISCUSSION

Of all the methods evaluated, MBC soil fumigation is the most effective immediate solution to the control of many soil-borne diseases and pests. Broad-spectrum soil fumigants provide growers reliable and excellent disease and pest control, increased yields, better product quality, extended crop seasons and more reliable economic returns. Mixtures of CP and MB are more fungicidal, more nematicidal and more herbicidal than either of the individual compounds alone. The mixture of chemicals also allows for the use of fumigants to manage a specific problem. For instance, if a particularly difficult weed or nematode problem exists, the proportion of MB in the mixture may be adjusted accordingly. Preplant application of these mixtures generally permits the soil to be replanted within a short waiting period with the same crop on the same land year after year. Their use also makes it possible to reduce crop rotation frequency and to limit the number of crops grown on the farm.

Due to the availability of these effective and reliable broad-spectrum soil fumigants, they have become very important pest management tools for the field production of many economically important crops in California. There are few incentives to search for replacements for these fumigants or to elucidate the etiology of complex soil-borne diseases as long as effective and inexpensive synthetic chemical pesticides are available. Breeding for disease and pest resistance, for instance, have received low priority in strawberry breeding programs. Strawberry varieties, bred with agronomically desirable characteristics but susceptible to one or more soil-borne disease(s), planted in MBC preplant fumigated soil produce the highest yields in the nation.

The availability of MB became also crucial for the production of certain nursery stock after the suspension of 1,3-D because a California law required these crops to be grown on soil treated with MB or to be sampled for the presence of nematodes. Soil sampling for pests is considered uneconomical.

No single synthetic chemical or non-chemical alternative could be found for MB in the broad-spectrum of field applications for which it is currently used. There are partial options, but none of the synthetic chemicals or non-chemical options are fully comparable to this fumigant.

Non-chemical options, such as crop rotation, biological control, soil amendments, steam, and others, are usually considered too risky and/or uneconomical. Negative pressure steaming may be a useful alternative to soil fumigation for low-volume soil disinfestation and greenhouse use. A German company has developed a method for field application. Its cost effectiveness is now been evaluated by Yoder Brothers, Inc. in Alva, Florida. If effective and economical, steam treatment may be preferred over soil fumigation, since it usually permits the soil to be replanted more promptly (12, 136).

Synthetic chemical and non-chemical options all have potential for the development of IPM and IFS, but this concept has sofar received little attention due to the availability of broad-spectrum soil fumigants. If MB and other broad-spectrum soil fumigants are to be replaced by IPM and IFS approaches, then government, university and agricultural industry cooperation will be needed.

Since January 1992, the use of MB for soil fumigation is prohibited in the Netherlands. Through the adoption of new pesticide policies and farming systems the use of MB was gradually phased out. Since the largest use of MB in the Netherlands was soil fumigation in greenhouses, it is difficult to assess whether their alternatives to MB are applicable to California field conditions.

Developing IPM programs and evaluating different farming systems in California may also provide a solution to the replacement of MB soil fumigation and the reduction of the use of and dependence on synthetic pesticides. The University of California, Davis and Riverside, are already looking at long-term alternative farming systems to see whether there are viable low pesticide input or organic agricultural options to current agricultural practices. The USEPA, USDA, and the University of California, along with farmers, are also developing research programs to investigate environmentally sound and economically feasible alternatives to MB. The California Department of Pesticide Regulation and the California Department of Food and Agriculture are heading up a Methyl Bromide Task Force which is exploring the research needs for alternative technologies and procedures in California.

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