

# DEVELOPMENT OF ALTERNATIVE STRATEGIES FOR MANAGEMENT OF SOILBORNE PATHOGENS CURRENTLY CONTROLLED WITH METHYL BROMIDE<sup>1</sup>

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■ **Abstract** The current standard treatment for management of soilborne pests in some high-value crop production systems is preplant fumigation with mixtures of methyl bromide and chloropicrin. With the impending phase-out of methyl bromide, the agricultural industries that rely on soil fumigation face the need for development of alternative pest management strategies. To maintain farm productivity, immediate term research has focused on evaluation of alternative fumigants, modification of current crop production practices to accommodate their use, and improvement of application technologies to reduce the environmental effects of fumigant applications. Longer-term research goals have focused on developing a more integrated approach for pest management that incorporates the use of cultural practices to reduce pathogen pressure, host resistance to disease, and biological approaches for stimulating plant growth and control of root diseases.

## INTRODUCTION

For the past four decades, methyl bromide (MB) has been the fumigant of choice for many preplant soil applications. The reasons primarily focus on the broad spectrum of activity of the fumigant, its high vapor pressure facilitating distribution through the soil profile, cost-effectiveness, and comparatively short plant-back intervals. For field crops it is generally applied by shank as a broadcast treatment with shank traces compacted or the top of soil that is covered with a polyethylene plastic tarp. More recently fumigation has been done by shank application into preformed beds and covering the beds with plastic tarps. Due to the synergistic

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activity that broadens the spectrum of pest control, applications are often combined with chloropicrin. Historically, MB was used primarily to control lethal soilborne pathogens such as *Verticillium dahliae* (86), but it also can provide excellent control of nematodes and a broad spectrum of weeds. This review focuses on the control of soilborne pathogens, but for the grower, this represents only part of the equation. The cost-effectiveness of preplant soil fumigation is measured by how it affects the total farming operation, ranging from post-fumigation plant-back intervals that may shorten the previous production cycle to allow enough time to fumigate and prepare the field for the next planting, management of weeds to reduce labor costs, to how treatments influence plant growth and the fruit production cycle in relationship to the grower's marketing window. Regulatory considerations can also play a part as buffer requirements may limit treatable area and, at least in California, the amount of certain products that can be applied in a given area. These problems, along with the fact that the production systems for some annual crops have evolved around the use of MB soil fumigation, complicate the search for economically viable alternatives for this fumigant.

The current phase-out of MB in the United States began in 1993, when it was classified as a class 1 stratospheric ozone-depleting substance. Under provisions of the U.S. Clean Air Act, MB production was capped at 1991 levels beginning in 1994 and was to be phased out by 2001. Federal legislation was subsequently passed in 1998 to alter the U.S. Clean Air Act and place the phase-out of MB on the same schedule as the rest of the developed nations that were signatories to the Montreal Protocol. This international treaty stipulates a gradual phase-out of production and importation of MB in developed countries beginning on January 1, 1999, with a 25% reduction in production relative to 1991 levels followed by 50%, 70%, and 100% reductions in 2001, 2003, and 2005, respectively. The production and importation are also restricted in developing nations, with levels in 2002 held at a baseline of the average use between 1995–1998 and a similar stepped phase-out progressing through to January 1, 2015 (80).

There are provisions in this treaty for the continued use of MB for specific purposes, e.g., for quarantine purposes such as commodity treatment, where the escape of fumigant into the atmosphere could be reduced by using recapture technology. Under the current definitions, nurseries also will be able to continue to use MB fumigation to meet mandated plant certification requirements. There also is a provision for a Critical Use Exemption (CUE), where affected industries could apply for an exemption to the phase-out if it could be demonstrated that there were no viable alternatives and the phase-out of MB would result in market disruption (79). Obtaining an exemption, however, is a multistep process, requiring review and approval at a national level, followed by a favorable review at several international levels of the United Nations Environmental Programme (Methyl Bromide Technical Options Committee and Technical and Economic Assessment Panel). A provision of this exemption is that the applicants reduce emissions by technologically and economically feasible steps as well as continue to aggressively search for MB replacements. Obtaining a CUE is not a guarantee of future availability of the fumigant, as reapplication for an exemption is required yearly.

In their 1996 article, Ristaino & Thomas (71) questioned if we could “fill the gaps” in providing alternatives for agriculture. Although some of the current results on development of alternatives are encouraging, to a certain degree this question is still largely unanswered, particularly for annual production systems. The currently registered alternative chemicals suggested as possible replacements have long been available for the growers to use and have not supplanted MB for most uses. It could be argued that the reason for this is that MB had been more fully integrated as the cornerstone of the production system for some annual crops and for a variety of reasons (such as plant-back intervals or spectrum of pest control), the available alternatives are not compatible. This highlights the need to search for alternatives from a production systems’ standpoint; changes in the systems may be needed for the alternative treatments to become economically viable. While immediate term research may need to focus on alternative fumigants to maintain farm productivity, it would be prudent for longer-term research to target development of integrated control approaches. With the widespread use and effectiveness of MB, there is a paucity of data for some cropping systems on which pathogens are responsible for constraining production, how cultural practices influence pathogen population dynamics and disease severity, and the selection of resistant germplasm and development of biological control agents have been under-explored options for disease management.

The subject matter is too broad to allow an exhaustive review in the allotted space; readers are therefore referred to existing reviews for additional details. In 1996, Ristaino & Thomas (71) reviewed the reasons for the phase-out and the state of the alternatives at the time. More recently, the proceedings of a symposium on methyl bromide alternatives held at the annual meeting of the American Phytopathological Society in 2000 was published in *Phytopathology* (3, 11, 20, 50, 51a, 59, 92).

## CURRENT STATUS OF PHASE-OUT

Under the terms of the Montreal Protocol, the production and importation of MB in the United States was frozen at a baseline level of 1991 production and importation (25,528 metric tons), with a 70% reduction in 2003. By 1999, this use had been reduced by 32% to 17,425 metric tons (80). According to 1997 statistics, 83% of the applied MB was for preplant soil fumigation (69% of this was used for small fruit and vegetables, 15% for orchards, and 15% for nurseries), 6% was for structural fumigation, 10% was used in postharvest applications, and 1% for quarantine use. Preplant use in California and Florida accounted for 42% and 36%, respectively, of the national preplant total.

In California there has been a 61.5% reduction in use of MB from 1995 (7,786,310 kg) to 2001 (3,000,881 kg), with 57% of the 2001 use devoted to strawberry nursery and fruit production (8). Some of this reduction is due to a drop in the treated acres in the state (from 43,680 ha in 1995 to 24,621 ha in 2001), although a switch to fumigation mixtures containing a greater amount of chloropicrin, or bed fumigation, whereby only the bed itself was treated rather than the

entire field, and to alternative fumigants has likely contributed as well. For example, during this same time, 1,3-dichloropropene (1, 3-D) use has increased nearly tenfold from 185,891 kg to 1,824,427 kg. The cost of the fumigant may be another factor altering its use pattern; according to EPA statistics, the average price of methyl bromide increased from \$2.71/kg in 1995 to \$9.92/kg in 2001 (80).

## CURRENT REGISTERED ALTERNATIVE FUMIGANTS

The fumigants currently registered for use as alternatives to MB were available to growers prior to the initiation of the phase-out process. Although some perennial production systems have shifted from MB to using these alternative fumigants (due in part to the increasing cost of MB), their use in many annual production systems has been more limited. Research efforts have recently focused on reevaluation of these products to address how application methods and rate studies can improve their efficacy as well as determine how production practices will need to be altered to accommodate their use. A recent review by Duniway (20) provides an historical background and more detailed information on their efficacy.

### Chloropicrin

Chloropicrin (trichloronitromethane) has been widely used as a preplant fumigant since initial studies of its efficacy against *V. dahliae* in strawberry production (85). Historically it has been shank-applied as a broadcast treatment and more recently by shank or drip applications to the planting bed. Although this product has strong fungicidal activity, it is generally less effective against nematodes and weed propagules than MB (20) and it is commonly applied in combination with other fumigants such as MB, 1,3-D, or MITC generators to broaden the efficacy of pest control. Recently, an emulsifiable formulation has been registered for applications through drip lines (TriColor, Shaddow Mountain Products). Its stability in soil is relatively short, with microbial degradation primarily responsible for inactivation of the fumigant (34). Microbial degradation is accelerated as the temperature increases and appears to be relatively independent of soil moisture. In field trials, Ajwa et al. (3) observed a half-life of 1 day.

In efficacy trials in strawberry production systems, broadcast applications as a stand-alone treatment with a rate of 336 kg/ha provided yields in California that were 94–96% of the standard MB + chloropicrin (Pic) fumigation treatment (20), whereas drip applications of Pic EC at 336 kg/ha resulted in strawberry yields similar to the standard MB + Pic fumigation (H. Ajwa, personal communication). However, weeds were not effectively controlled with this drip application rate, so follow-up drip applications 5 to 7 days later with metam sodium have been recommended (25, 40). In Florida, Noling (58) found that broadcast applications of chloropicrin (336 kg/ha) provided yields equal to the standard MB + Pic fumigation (393 kg/ha, 67:33). When used as a stand-alone product, the rates for chloropicrin may need to be as high as 336 kg/ha for effective control of pathogens

and weeds. In California, however, such high application rates may not be possible because of regulatory restrictions. Interestingly, Motis & Gilreath (57) reported that chloropicrin at 112–168 kg/ha sometimes stimulated nutsedge emergence in the field. A similar stimulation of weed seed germination following drip fumigation with chloropicrin may also be occurring in California trials and may contribute to the enhanced efficacy observed with follow-up applications of metam sodium (S. Fennimore, personal communication).

## 1,3-Dichloropropene

The fumigant 1,3-D (Telone<sup>®</sup>, Dow AgroSciences) is an effective nematicide that also has fungicidal properties. It is applied either alone or with mixtures of chloropicrin (C-17 for 17% chloropicrin and C-35) to improve efficacy against soilborne fungal pathogens. Registration of 1,3-D was suspended in California in 1990 because of air quality concerns in Merced County and was reinstated in late 1994. Traditionally, applications have been broadcast treatments by shank followed by compaction of the shank traces or application of polyethylene tarps. An emulsifiable formulation containing 33% chloropicrin was recently registered for applications through the drip lines (InLine<sup>®</sup>, Dow AgroSciences).

In 13 tomato trials in Florida, bed applications of Telone C-17 at 327 l/ha resulted in an average loss of 3.1% relative to the standard MB + Pic (393 kg/ha, 67:33) fumigation; broadcast applications at the same rate were not as effective (58). One contributing reason for this difference may be that the bed fumigations were tarped with plastic after application, whereas broadcast treatments in Florida were shank-applied at a depth of 30.5 cm but were not covered with plastic after fumigation. Increasing the concentration of chloropicrin in the mixture to 35% (Telone C-35) and applying the product to the beds resulted in yield that was equal to the MB + Pic broadcast treatments; this treatment also controlled nutsedge emergence in the bed. However, bed applications of 1,3-D-based products in Florida can be problematic, as it requires the use of personal protection equipment by the applicators at a time of the year when ambient temperatures would make this difficult. One approach to alleviate this reduced efficacy with broadcast treatments is to follow with a bed application of chloropicrin (112–168 kg/ha) (58). This additional application of chloropicrin improved control of soilborne diseases and nematodes and resulted in yields comparable to the standard MB + Pic fumigation (58). In large-scale field evaluations (98 ha) in Florida, Mirusso et al. (56) reported that untarped broadcast applications of Telone C-35 (187 l/ha) followed by bed applications of chloropicrin (134 kg/ha) and herbicide applications to control weeds provided pepper and tomato yields similar to those obtained with the standard MB + Pic fumigation. Some of these areas were in their second and third consecutive production cycle with this fumigation treatment without a breakdown of treatment efficacy. Application of 1,3-D has been reported to be effective in the strawberry production system in California as well (20). Although broadcast applications in combination with chloropicrin will likely be the treatment used by some growers

because of similarity in production practices to the current MB + Pic fumigation system, applications of the emulsifiable 1,3-D formulation through drip lines also is effective and likely to be utilized in many areas in the state. California statistics for 2002 indicate that 10% of the 1,3-D applied was by drip application (T. Trout, personal communication). The application costs for this year were approximately half of the standard MB and Pic broadcast fumigation.

Current regulatory restrictions will influence the use of 1,3-D as a methyl bromide alternative in California. For safety and air quality concerns, the state's Department of Pesticide Regulation (7) has instituted buffer zone requirements and placed limits on the amount of product that can be applied in a township. For drip applications, the suggested buffer zone is 30.5 m, whereas shank applications have a 30.5 m buffer zone if applications are made only once every 3 years, otherwise there is a 91.5 m buffer zone. In fields that are cropped to strawberry at least once every 3 years, this can influence the growers' ability to fumigate some portions of their fields, especially in agricultural areas faced with urban encroachment. Township caps limit the amount of product that can be applied in each township in the state (93.2 km<sup>2</sup> area). Depending on the time of the year and location in the state, the application rate is multiplied against an "application factor" (which ranges from 1.0 to 2.3 depending on the method of application) to determine the adjusted pounds that are applied and counted against the cap. There are townships where strawberry or perennial crops are grown whose need is estimated to exceed the amount of fumigant allowed by the cap (9; T. Trout, personal communication). Recent analysis indicates that approximately 33% of the acreage previously fumigated with methyl bromide could not be fumigated with 1,3-D without exceeding the township caps; doubling township caps would reduce the excluded acreage to 18% (T. Trout, personal communication). Although improvements in application technology, such as drip fumigation in the beds and use of VIF plastic tarps, will increase the amount of acres that can be treated, they are not likely to increase efficiency enough to treat all the acreage that currently rely on fumigation with MB for soilborne pest management.

## Methyl Isothiocyanate

There are several products that degrade when applied to soil to form the fumigant methyl isothiocyanate (MITC); metam sodium is a liquid formulation and dazomet is granular. Inconsistent control is the primary problem encountered with metam sodium. This may occur because the application method used is not delivering the fumigant to the desired location in the soil profile. For example, McGovern et al. (52) observed that application of metam sodium through the drip lines or shanked into the beds was ineffective in controlling *Fusarium* crown and root rot of tomato. Application to the soil surface of the bed provided inconsistent results, whereas rotoation into the bed provided control equivalent to the standard MB + Pic fumigation. Metam sodium does not move through soil like MB; in fact when it is applied by shank its movement is believed to be limited to 7.5 to 10 cm in

all directions from the point of application. A similar problem with distribution in the soil can be encountered with application of the granular product dazomet; a thorough mixing of the soil is needed to ensure even distribution and avoidance of "hot spots" where high concentrations of MITC do not fully dissipate and can result in phytotoxicity problems. In addition, uniform watering is needed to activate all product in the soil prior to planting or phytotoxicity problems may be encountered later when subsequent irrigations activate residual product. One potential use of dazomet in strawberry production is as an herbicide, using surface applications followed by sprinkler irrigation to activate the product and carry it through the top layers of the soil profile (83). Because of its strong herbicidal properties, MITC generators are commonly paired with other fumigants to broaden the spectrum of pest control (40). Interestingly, sublethal doses of MITC have been found to stimulate germination of some weed seeds (78).

## POTENTIAL ALTERNATIVE FUMIGANTS

### Methyl Iodide (Iodomethane)

The use of methyl iodide as a replacement for MB was recognized by researchers at the University of California, Riverside, and efficacy trials were initiated to evaluate its potential (62). Commercial development of this product has been pursued by Arvesta (Midas<sup>®</sup>). An application for registration was submitted to the U.S. EPA in early 2002 with the agency expecting a final decision on registration in the spring of 2003. For the product to be registered in California, mammalian chronic exposure studies currently in progress and anticipated to be finalized in 2005 need to be completed before a decision on registration can be made. However, the company is hopeful that an experimental use permit can be obtained in California after federal registration to allow for broader-scale field efficacy trials without the requirement of crop destruction (M. Allen, personal communication).

Of all the potential alternatives to MB, perhaps iodomethane (IM) comes the closest as a drop-in replacement. It has a higher vapor pressure than the other potential alternatives (although at 400 mm Hg it is still below MB at 1420 mm Hg) and functions effectively as a fumigant in the soil, has a broad spectrum of activity against a range of soilborne pests similar to MB, and can be applied with the same fumigation equipment as MB. It also has a longer persistence in the soil than MB, which may increase not only its efficacy in pest control but also potential problems relative to MB for groundwater contamination (36) and potential phytotoxicity to sensitive crops if plant-back intervals are not followed. It is not an ozone-depleting compound like MB and is a liquid rather than a gas at room temperature. It has been reported to be an effective fumigant in a carrot production system (41), for controlling peach replant disorder (21), and as a replacement for MB in strawberry production systems in California (2). Although it can be applied by shank in combination with chloropicrin using methods essentially the same as for MB + Pic, it also is as effective as MB + Pic in strawberry production

systems in California applied through the drip lines at 336 kg/ha of a 50:50 mix with chloropicrin (H. Ajwa, personal communication).

## Propargyl Bromide

Propargyl bromide was previously described as a soil fumigant but was not further developed because of stability problems. Albemarle Chemical Company recently reformulated the product to address these deficiencies. In strawberry production in California, Ajwa et al. (2) observed in one trial that application rates of 67 kg/ha (shank or drip) resulted in yields equal to the standard broadcast MB + Pic (67:33, 308 kg/ha) treatment and that increasing rates to 134 or 179 kg/ha increased yields 20–30% above the MB + Pic treatment. To ensure that adequate control of pathogens (in particular, *Verticillium* wilt) is obtained, the recommendation for strawberry field drip application is 134 kg/ha (H. Ajwa, personal communication). Although some residual phytotoxicity was observed in a field fumigated late in the fall season 2000 when temperatures were cool, this was believed to be due to the stabilizer used in the earlier formulation (20% toluene) and has not been observed in trials with the new stabilized product. Drip applications of 202 kg/ha in strawberry production also provided weed control equal to the standard broadcast MB + Pic (67:33, 308–420 kg/ha) and did a better job of controlling little mallow than the MB + Pic broadcast treatment (24). When applied as a shank or drip treatment (202 kg/ha) in vineyard replant trials, propargyl bromide effectively controlled nematode populations to a depth of 150 cm (76). At the end of the growing season these plants had pruning weights similar to the MB fumigated controls. Soil type has an influence on the stability of propargyl bromide after application, with Yates et al. (92) reporting a degradation half-life ranging from 1.2 to 5 days, whereas Ma et al. (48) observed a half-life of 7 h in a muck soil, compared to 67 h for a loamy sand soil. At the time of writing there were no registrants for this product.

## Additional Potential Alternative Fumigants

In an ironic twist, one MB alternative that is under evaluation for soil treatment is ozone. The gas is generated on site using portable ozone generators and applied into tree replant sites by shank or into tarped/untarped, preformed or flat beds through PVC pipes or subsurface drip irrigation lines buried at a depth of 7.5 to 15 cm. Application rates ranging from 28 to 448 kg/ha have been tested in California vegetable and strawberry production. Efficacy seems to be dependent on the pest problems present at the site, with nematodes more sensitive than fungal pathogens; rates as low as 28 kg/ha controlled root knot nematode in some carrot and tomato sites but 448 kg/ha did not manage disease at sites with heavy infestations of *V. dahliae* (A. Pryor, personal communication). An advantage of this treatment is that is an option for organic growers.

A number of other fumigants are in various stages of development as potential alternatives to methyl bromide, some of which are listed in Duniway (20). Additional information on potential alternatives may be found at the web sites of

the U.S. EPA ([www.epa.gov](http://www.epa.gov)), USDA ([www.ars.usda.gov/is/np/mba/mebrhp.htm](http://www.ars.usda.gov/is/np/mba/mebrhp.htm), [www.ars.usda.gov/is/bmebrweb.htm](http://www.ars.usda.gov/is/bmebrweb.htm)) or IR-4 program ([www.pestdata.ncsu.edu/ir-4/](http://www.pestdata.ncsu.edu/ir-4/)).

## POTENTIAL PESTICIDES WITH A REDUCED APPLICATION RISK

There are several pesticides that may provide a reduced risk of off-gassing from treated fields. Rather than fumigants they are biocides that must come into contact with pathogen propagules to kill them and, because of this, they are applied in the field through drip lines rather than by shank. One potential limitation for their use is that application methods must be refined to ensure even product distribution through the bed profile and may require alteration of production practices to include two rather than a single drip line for each bed [particularly in Florida with sandy soil (58)]. This is an active area of research in one of the labs evaluating these products (3; H. Ajwa, personal communication). However, an advantage of this approach is that there would be minimal impact of field treatments on surrounding areas, a consideration that is particularly important for production fields that are encountering urban encroachment.

Aqueous solutions of sodium azide are stable above pH 9 but convert to the biocide hydrazoic acid ( $\text{HN}_3$ ) below pH 8. For field applications, this product is mixed with a carrier/stabilizer that is above pH 9 and injected into the irrigation lines just before distribution to the drip tapes. With the formulations that are being examined, this delays conversion to hydrazoic acid until the product is in the soil profile; with a half-life in the soil measured in days, the prospect of groundwater contamination with this product is reduced or eliminated (H. Ajwa, personal communication). Applications of sodium azide have been reported to control soilborne pathogens, nematodes, and weeds in eggplant, tomato, pepper, and cotton trials (72–75). Field trials evaluating control of vineyard replant problems indicated that control of *Meloidogyne* spp. and *Tylenchulus semipenitrans* was not complete. However, since the product was applied through subsurface drip lines at a depth of 20–30.5 cm in this trial, incomplete distribution through the upper strata of the soil profile may have contributed to these observations (77). Field trials in California strawberry production systems point to some potential applications for use of this product, although incomplete control of Verticillium wilt was observed at the rates tested in 2002 (112 kg/ha) (H. Ajwa, personal communication). Additional trials to evaluate the efficacy of higher rates and applications done in combination with alternative fumigants are currently in progress.

Another contact biocide that is under development is an iodine-based product called Plant Pro<sup>®</sup> (Ajay North America). Two formulations have been tested in field trials (Plant Pro 45 and a more concentrated formulation Plant Pro 20EC) and have exhibited activity in controlling fungal pathogens and parasitic nematodes, with yields in tomato trials in Florida equivalent to standard MB fumigation (1). However, in strawberry field trials in California application rates of 655 l/ha

(168 kg AI) were not effective in controlling *Verticillium* wilt (H. Ajwa, personal communication). Additional strawberry trials to evaluate the efficacy of higher rates and applications done in combination with alternative fumigants are currently in progress.

## APPLICATION TECHNOLOGIES

One approach to increase the efficacy of fumigation treatments, reduce application rates, increase the potential number of acres that can be treated with a restricted amount of product (especially in California), and reduce potential problems of off-gassing and fumigant drift is to improve the technologies for fumigant application. This can be approached from several different directions, some of which may be implemented by the growers with minor modifications to their standard production practices. For example, many crops that utilize preplant soil fumigation with MB also use drip irrigation systems; with a few modifications, these systems also can be configured for application of fumigants (3). In some production systems where drip irrigation is not commonly used, it might be possible to fumigate plastic-mulched raised beds using a “shank” that comes in from the side of the bed (12). Likewise, some production systems do not tarp the ground after broadcast application of fumigants (such as 1,3-D applications in Florida); the use of tarps may improve efficacy as well as reduce potential off-gassing from the field.

### Drip Applications

The efficacy of drip application of fumigants has been evaluated in the strawberry production system of California with very favorable results (3). The advantage with this type of application is that the fumigants are applied to preformed beds already covered with polyethylene tarps, which not only improves the efficacy of fumigation by retaining the fumigants in the soil but also addresses the threat to air quality in surrounding areas and provides improved worker safety. Fumigant retention in the bed can be further enhanced by using virtually impermeable film (VIF) rather than polyethylene plastic tarps. The fumigants can be accurately metered into the irrigation lines to ensure an even distribution throughout the bed as well as the field. Furthermore, since it is a bed application, it reduces the area that is treated in a field by approximately 30% compared to a broadcast treatment. It requires a careful leak testing of the irrigation system prior to covering the beds with the plastic tarp and careful monitoring of the field during fumigation to ensure leaks do not occur. Adequate time to allow for dissipation of fumigants is also needed before the field can be planted. This approach for fumigation may not be compatible with currently used strawberry production practices in certain production areas of California since some growers in the central coastal production area do not normally cover beds with plastic until several months after transplanting to avoid increased bed temperatures that stimulate plant growth. However, this problem can be addressed by removing plastic from the beds 1–2 weeks after fumigation; this

also will speed up dissipation of the fumigants and reduce plant-back intervals. Drip-applied fumigants also show promise for management of vineyard (77) and orchard (79c) replant disease.

When using VIF plastic with drip applications, problems of anaerobic conditions in the bed can be encountered due to the lack of gas exchange through the plastic. This can lead to CO<sub>2</sub> concentrations as high as 2–5% (concentrations as high as 10% have been observed with chloropicrin applications), which in turn can influence the degradation of applied fumigants (H. Ajwa, personal communication). For example, degradation of MITC in soil is primarily by facultative anaerobes; under anaerobic conditions, degradation is delayed and there is a tendency for CS<sub>2</sub> to accumulate. Likewise, one of the degradation products of 1,3-D in soil is allyl alcohol, which accumulates at a higher level under anaerobic than aerobic conditions. In both examples, the degradation products are phytotoxic and can influence plant-back intervals. One approach for reducing the potential for anaerobic conditions is to cut planting holes through the plastic 10 days after fumigant application (H. Ajwa, personal communication).

The spacing of drip tapes on the bed as well as the flow rate of the tape are important when planning a drip fumigation (3). For example, Fennimore et al. (25) observed a reduced efficacy of weed control with drip applications of fumigants in strawberry beds if the water phase did not move to the edge of the bed. Likewise, a single drip tape is generally used in Florida tomato production and with the sandy soils in this area, it is not possible to get lateral movement of applied water to the bed shoulders (58). Flow rate of drip tape is also a consideration and must be adjusted to account for soil type at the treatment location.

An important prerequisite to utilizing this delivery system is understanding the characteristics of the chemicals that are applied to ensure their even distribution through the bed profile. Some products (such as 1,3-D and chloropicrin) are not very soluble in water (0.22 and 0.20% w/w, respectively) and need to be applied with an emulsifier (3). The use of stable emulsifiers will keep the product in suspension and allow the fumigant to move to the target site in the bed profile. In contrast, the use of unstable emulsifiers will cause the fumigant to separate from the water phase early and it will not move well through the bed. Likewise, some products (metam sodium) that are soluble in water move with the water phase but have limited transport through the soil pore spaces as a fumigant; they must be applied with enough water to ensure distribution through the bed profile. Fumigant compatibility must be evaluated before combinations can be applied simultaneously. For example, metam sodium cannot be applied at the same time as chloropicrin or 1,3-D-based products as it will inactivate those fumigants and result in poor control of soilborne pests (25; H. Ajwa, personal communication).

## Plastic Films

The standard tarp that is commonly used in broadcast fumigation is 1-mil (0.025 mm thick) high-density polyethylene (HDPE) plastic. Although the use of this

film reduces emission of MB into the atmosphere compared to untarped soil, it does not eliminate volatilization [reviewed in (92)]. For example, nearly all of the applied methyl bromide was lost into the atmosphere within a few days of application when no tarp was used compared to a 36% loss when the field was tarped (49). Yates et al. (90) also observed MB emissions through the plastic tarp; approximately 36% within the first 24 h of application and 64% for total emissions. The differences observed in these two experiments were attributed to the influence of higher temperatures increasing the permeability of the plastic to MB (45). In laboratory studies, Gamliel et al. (28) observed that low-density polyethylene (LDPE) and HDPE were permeable to MB, whereas high-barrier multilayer films [HBF or often referred to as virtually impermeable films (VIF)] that contain polyamide or ethylene vinyl alcohol (such as Bromotech, Hytibarr, and Barromide) were much less permeable. Field trials paralleled these findings, with soil MB concentrations significantly lower within 24 h of application in plots covered with LDPE or HDPE; increasing the thickness of the LDPE from 30 to 100  $\mu\text{m}$  had little effect on retaining the fumigant. The high-barrier films exhibited a slower decline in soil concentrations of MB, which corresponded to a higher concentration of the fumigant retained in the soil for a longer period of time. The enhanced control of several pathogens and the ability to obtain control with reduced application rates paralleled these findings (28, 29, 55). The use of VIF in Florida fruit and vegetable trials enabled fumigant application rates to be reduced by 50% without loss of efficacy (61). Wang et al. (81) observed that 64% of the applied MB volatilized into the atmosphere after 5 days under standard polyethylene tarp whereas this emission was reduced to 37.5% when the VIF Hytibar was used. This emission was reduced to 3.2% or less when the tarp remained in place for 10 days.

The use of VIF rather than the standard polyethylene plastic tarps also reduces atmospheric emissions of other fumigants and the effective rate of applications needed for pest control. From experiments with packed soil columns, Gan et al. (34) reported that HDPE film (0.035 mm) allowed only 20% volatilization of chloropicrin through the plastic film after 14 days; this was reduced to 4% when a VIF was used. With the same type of experimentation, Gan et al. (36) observed that there was a greater flux of IM than MB through 1.4 mil HDPE, but the use of a VIF was effective in reducing emissions of both fumigants. HDPE also was observed to be permeable to 1,3-D and propargyl bromide whereas VIF was impermeable (38, 82). The use of VIF rather than HDPE was found to enhance lateral distribution of 1,3-D in the sandy soils in Florida (12). Using VIF in broadcast applications of fumigants may result in a larger flux of fumigant into the atmosphere when the tarp is removed, although this may be moderated by leaving the plastic in place for a longer period of time to facilitate fumigant degradation.

Some early trials in California strawberry fields with VIF encountered problems with plastic performance, although these have been largely addressed through reformulation of the product. Due to the impervious nature of the plastic there have been problems with developing adhesives that will effectively glue strips of VIF together, although this is likely a technical problem that should be resolved.

Although VIF is more expensive than the standard HDPE, the cost savings associated with reduced rates of fumigant application and enhanced efficacy of pest control may make this a competitive option. Currently, the European Union requires that VIF (or another alternative procedure that provides an equal level of environmental protection) be used in all MB applications (70).

## FUMIGANT DEGRADATION IN THE SOIL

Fumigant that has not escaped into the atmosphere is degraded in soil by either a chemical or microbial process; understanding these processes may lead to modifications of application methods to enhance these effects to further reduce fumigant emissions. For alkyl halide fumigants such as MB, IM, or propargyl bromide, alkylation of soil organic matter by  $S_N2$  nucleophilic substitution is believed to be the primary means of chemical degradation; hydrolysis plays a less prominent role (65). Soil high in organic matter degraded these fumigants faster than soils with lower organic matter (36, 65). In trials conducted with packed soil columns, application of organic matter (composted manure) to the soil enhanced degradation of MB and MITC, with degradation of MB primarily chemical and MITC microbial (37). Similar results also were observed for 1,3-D, although both chemical and microbial processes contributed to degradation (33). In packed soil column studies, application of ammonium thiosulfate to the soil before fumigation was found to reduce volatilization of MB (32) and 1,3-D (35) due to enhanced chemical degradation. In field trials, applications of ammonium thiosulfate to the bed surface prior to covering the beds with HDPE tarps and application of an emulsifiable formulation of 1,3-D through the drip lines reduced emissions of 1,3-D but did not impact efficacy (39).

Temperature and moisture can also influence the rate of fumigant degradation in the soil (31). There was a positive relationship between increased temperature and chemical degradation, whereas for microbial degradation the results were fumigant dependent; microbial degradation of MITC was increased above 30°C and 1,3-D degradation decreased. The effect of soil moisture followed a similar pattern, with enhanced degradation of 1,3-D and reduced degradation of MITC as soil moisture increased. Microorganisms contribute to chloropicrin and MITC degradation to a greater degree than for MB or 1,3-D degradation (31, 34). Specific microflora associated with oxidation of methyl bromide in the soil have been described (54, 63, 64), and some are under evaluation for use in bioreactors for degrading MB used in contained fumigations (53).

## ADDITIONAL CONSIDERATIONS FOR ALTERNATIVE FUMIGANTS

When evaluating potential replacements for MB, it is important to keep in mind that in many cases the entire crop production system has evolved around the use of this fumigant and replacement with an alternative may require other alterations

in the current production system. An obvious example of this for annual production systems is weed control, for which some of the potential alternatives are not as effective as MB. The importance of weed control in these production systems should not be underestimated, for not only will they increase production costs due to herbicide applications and/or hand weeding (which in turn will influence the economic viability of alternative treatments), but they may also serve as hosts for the same soilborne pests that soil fumigation is trying to control. For example, Noling & Gilreath (60) observed that controlling weeds can be an important component of the effort to manage nematode populations as some weeds (*Amaranthus* spp.) can support high levels of reproduction of *Meloidogyne* spp. Application of alternative fumigants can also alter the phenology of plant growth and fruit production; strawberry plants were larger in plots where chloropicrin was bed applied by shank compared to the standard MB + Pic broadcast fumigation (F. Martin, unpublished), and strawberry plants in trials where chloropicrin was applied through the drip system initiated flowering sooner than the standard MB + Pic treatments (H. Ajwa, personal communication). Although earlier initiation of flowering is advantageous in the southern production districts of California where growers target early season production, it is not in the central coastal production areas. Thus, the integration of alternative fumigation strategies will likely require reevaluation of other production practices as well (such as application of other pesticides, plastic mulching, or management of fertility).

A wide range of methods and rates for application of fumigants exist in different parts of the country. Although there are valid reasons for some of these differences (different soil types and climatic conditions as well as spectrum of pests to control), some rates likely reflect an "insurance premium" to ensure pest control rather than rely on decisions based on specific data for what is needed to control the pests at hand. Given the increased regulatory oversight and environmental concerns associated with fumigant applications, it would be prudent to take a more active role in the stewardship of fumigant utilization to maximize efficacy and minimize the environmental effects of these applications. This would include clarification of pest control needs in a given area, determining fumigant rates necessary to control them, and optimizing application methods to increase efficacy of control and reduce off-gassing and other environmental impacts. A multidisciplinary team of researchers in California is currently addressing some of these concerns in the state's strawberry production system (26, 27). Different application technologies (shank and drip) and plastic tarps (polyethylene and VIF) are being compared to evaluate how they influence the concentration and distribution of fumigants in the soil profile following field applications. Fumigant fate and flux studies then will evaluate potential off-gassing and release of the fumigant into the environment. The survival of soilborne pests (several pathogens, nematodes, and weeds) is being assessed at different locations and depths in the bed and compared with fumigant concentrations to essentially conduct a field-based dose-response study. Finally, strawberry yield is monitored in these plots to determine how different fumigants and, just as important, application strategies, influence crop production cycles.

An agricultural economist also is investigating relative cost-effectiveness of treatments. Many members of this team also are conducting laboratory dose-response studies to compare with field-based results in an effort to develop laboratory-based fumigant evaluations that accurately reflect field performance (H. Ajwa, personal communication). These results should be available in the next few years and will, it is hoped, contribute to a more economically viable, efficient fumigation strategy for the strawberry industry in California.

## NONCHEMICAL APPROACHES FOR DISEASE MANAGEMENT

The broad spectrum of activity of MB has made it the primary means for control of soilborne pests of some cropping systems for some decades, allowing research and development activities to focus more on horticultural and agronomic aspects of crop production. This has led to a dearth of data on the specific pathogens responsible for constraining production in nonfumigated soils and the development of integrated control strategies for management of soilborne pests. Given the urban encroachment on farming operations in some areas of the country and the increased regulatory oversight that often follows, it would be prudent to approach the search for alternatives from a long-term perspective to develop more integrated approaches for pest control and not rely solely on continued availability of fumigants. Additional information on the topics in this section may be found in recent reviews (11, 50, 51a).

### Knowledge of Pathogens Constraining Production

Before integrated approaches for disease control can be developed, knowledge of the specific pathogens that are causing production constraints is needed. Lethal pathogens such as *V. dahliae* cause obvious symptoms that indicate a need to control soilborne pests. Other soilborne pests, however, are more nonspecific in the symptoms they cause, but can have a significant influence on crop productivity. A good example of this are root-rotting pathogens such as *Pythium* spp., *Rhizoctonia solani*, binucleate *Rhizoctonia* spp., and *Cylindrocarpon* spp. Although these pathogens are generally not lethal to a mature plant, they can cause reductions in plant growth and vigor that ultimately reduces yield. These pathogens have broad host ranges and are associated with black root rot of strawberry in nonfumigated production systems (50). Recent research suggests that general root-rotting pathogens can also contribute to reduced growth in pepper and tomato in Florida (13) and replant disorders for fruit and nut crops such as apple (51), grape vines (84), and possibly peach (6). Additional work is needed to explore more fully the involvement of these and other pathogens in constraining yields in production systems that currently use MB. This research will likely need to be site specific, as differences in the pests associated with the disorder may vary in different areas. For example, the lesion nematode *Pratylenchus penetrans* has not been associated

with strawberry black root rot in California but it is one of the primary causes of disease in the northeastern United States (87).

## Soil Microbiology

Although dramatic changes in soil microflora can be observed following fumigation with MB + Pic, such as higher populations of fluorescent pseudomonads (88), the soil is far from sterilized. Ibekwe et al. (42) observed that the Shannon-Weaver diversity index of microbial community diversity was lowest for MB fumigated soil 1 week after application compared to chloropicrin, 1,3-D, and MITC; this index remained lower than the other treatments even after 12 weeks of incubation. For all fumigants, there appeared to be a shift to gram-negative bacteria predominating the community structure after fumigation. Likewise, Schutter & Ajwa (personal communication) observed a reduction in nitrification potential in fumigated soils, with recovery in chloropicrin-fumigated soils sooner than MB, IM, 1,3-D, or propargyl bromide. While these examples have focused on soil microbial populations, preliminary work with strawberry rhizosphere colonizers in fumigated compared to native soils suggests that there may be differences in deleterious and beneficial rhizosphere colonizers following soil fumigation (50; F. Martin, unpublished). However, much more detailed quantitative research is needed before conclusions can be drawn.

## Biological Control and Plant Growth Promotion

A basic understanding of the soil and rhizosphere microbiology can simplify the identification of specific microorganisms that can be used directly for disease management, enhancement of plant growth or altered crop management practices to enhance their populations. One excellent example is the identification of specific bacterial rhizosphere colonizers that are capable of protecting apple roots from pathogens associated with apple replant disease and enhancing their soil populations by cropping specific cultivars of wheat (51a, 51b). Research in that program is currently examining how other cultural practices and selection of apple germplasm can be used to modify the community structure of fluorescent pseudomonads to enhance the proportion of specific beneficial genotypes in the rhizosphere (M. Mazzola, personal communication). Another example is the work of Larkin et al. (46, 47a) with the identification of isolates of *Fusarium oxysporum* from disease-suppressive soils generated by monoculture of a specific watermelon cultivar. These isolates are nonpathogenic on watermelon and capable of protecting watermelon and several other crops against pathogenic *Fusarium oxysporum* by induced systemic resistance. Knowledge of the soil microbial ecology of these pathosystems contributed to the development of these biological approaches to disease management. Similar approaches should facilitate the development of biological alternatives to other pest management problems currently controlled by soil fumigation.

Many production systems that currently utilize soil fumigation also use transplants (bare root or plug) for planting material and drip systems for field irrigation.

This provides opportunities for addition of biological control agents to seedlings prior to transplanting either by inoculation of seedling beds or plug transplants as well as field applications through the drip lines (50). For example, Kokalis-Burelle et al. (44) observed that application of plant growth-promoting rhizobacteria to tomato and pepper seedlings prior to transplanting into the field enhanced yield over untreated seedlings. Research on modeling water flow through the bed profile during drip applications of fumigants by Ajwa et al. (3) should facilitate development of the irrigation system to deliver biological control agents in the field. This delivery approach has the advantage that antagonists can be altered throughout the production cycle to address seasonal changes in the pathogens contributing to yield reductions. The efficacy of growth enhancement or biological control may be enhanced by applying the organisms after treatment with low rates of pesticides to reduce the pathogen pressures in the soil and perhaps alter the microbial complexity in the soil, which may enhance establishment of the introduced isolates.

## Host Resistance

Perhaps the most effective strategy to reduce the need for soilborne pest control measures is the development of cultivars that are resistant, or at least have some tolerance, to disease. With the widespread use of MB + Pic soil fumigation in several crop production systems, the focus of breeding programs has been on horticultural traits rather than disease resistance. Many examples of host tolerance are described in the literature and there is little doubt that breeding directed to pathogen control will attenuate the need for soil fumigation. To use strawberry as an example, field and greenhouse trials have shown that there is a range in cultivar susceptibility and field performance in response to general root pathogens such as *Pythium* and binucleate *Rhizoctonia* spp. (50; F. Martin, unpublished). These pathogens can cause severe root rot and reduce yields in the field of some cultivars by more than 50% (cv. Diamante) whereas other cultivars exhibit minor root pruning in greenhouse trials and a 25% yield reduction in the field (cv. Aromas). A similar type of a differential cultivar response to pathogens has been observed for *Phytophthora* spp. (5). Although breeding efforts should enable development of strawberry cultivars tolerant to these pathogens, selection of resistance to *V. dahliae* is more problematic; despite years of research, there are no commercial cultivars resistant to this pathogen. Examples of the contribution of host resistance for management of tomato diseases were reviewed by Chellemi (11).

An impediment to developing disease-resistant cultivars is the complexity of introgressing the resistance into cultivars that have already undergone a rigorous selection for horticultural traits. One approach used in fruit and nut tree crops to circumvent this problem is to graft horticulturally desirable scions onto rootstock that has resistance to specific diseases. Although not widespread in the United States, this approach has been used in the Mediterranean region and Japan with tomato and cucurbit production to enhance yield and manage some soilborne diseases. For example, grafting is used in Israel to manage sudden wilt of melon

caused by *Monosporascus cannonballus* (19, 22) or Fusarium wilt (18) and in Greece to manage root and stem rot of cucumber (67). Interestingly, Paplomatas et al. (66) tested root stock-scion combinations for tolerance to *V. dahliae* and found several tomato cultivar combinations, as well as cucurbit cultivar combinations, that exhibited resistance in the greenhouse. A limiting factor preventing more widespread application of this approach is the added plant cost associated with plant grafting; however, robotic techniques for grafting may reduce this problem.

## Solarization

Solarization has been used for management of soilborne pathogens since 1976 (43) and is still widely used in many areas of the world (11). There may be limits to its effectiveness in some areas where warm temperatures coincide with rainfall since cloud cover and rain will reduce the solar radiation under the plastic (Florida, for example). However, selection of appropriate plastics for covering the soil may improve efficiency in these locations; Chase et al. (10) observed that a thermal-infrared absorbing film kept soil temperatures higher than polyethylene plastic in Florida. Solarization was evaluated in large- and small-scale tomato trials in Florida and was found to provide disease control and yield that was intermediate between MB + Pic and nonfumigated controls when used as a stand-alone treatment (58). However, in other tomato trials in Florida, Chellemi et al. (15) reported that solarization of raised beds provided tomato yields similar to standard MB + Pic fumigation treatments and this treatment was compatible with the standard production practices of the growers. Although control of some fungal pathogens was observed, the results were more variable for nematode control requiring application of 1,3-D under VIF to enhance the efficacy of the treatment. Other reports from Florida have indicated variability in fungal pathogen control at 25 cm depths following solarization (14, 17).

Solarization was reported to be an economically effective means for reducing root diseases in raspberry and strawberry in Oregon (68, 69). Treatment of raised beds was more effective than flat treatment with a treatment period from mid-July through mid-September providing temperatures high enough to reduce populations of several fungal soilborne pathogens. In some areas, however, the field fruit production cycle, high cost of land rents, and local weather conditions may prevent this from becoming a viable option for disease management (for example, strawberry growers in the central coastal production area of California). One approach that might exhibit some beneficial effect is the combination of solarization of tarped preformed beds prior to fumigant applications through the drip lines. Eshel et al. (23) observed that solarization for 8 days followed by applications of reduced rates of metam sodium or MB provided better pathogen control than either treatment individually. Gamliel et al. (30) observed similar enhanced efficacy of combined bed solarization and fumigation treatments for control of Fusarium crown rot of tomato and sudden wilt of melon. The enhanced efficacy was believed

to be due to sublethal heating from solarization weakening pathogen propagules and making them more susceptible to the fumigant (23).

## Crop Rotation and Soil Amendment

Crop rotation is useful for management of soilborne diseases. Although it may not be effective for all pathogens, there have been some successes in managing pathogens as recalcitrant to control as *V. dahliae*. For example, Xiao et al. (89) observed that broccoli residues flail-mowed and allowed to dry on the soil surface for several days prior to incorporation were effective in reducing soil populations of *V. dahliae* in cauliflower fields. When tested in the strawberry production system in California, broccoli rotations were found to reduce soil populations of *V. dahliae*, Verticillium wilt disease incidence, and improve yields (K. Subbarao, F. Martin & S. Koike, unpublished). Although the degree of control was not equal to fumigation, it was significantly better than lettuce rotations and might be a means for managing the severity of the disease in a field. The economic feasibility of broccoli rotations as a disease management tool in the Salinas Valley is subject to question due to the high production costs and low economic return to the grower. Some growers have tried to alleviate this difficulty by growing broccoli as a standard cover crop with limited inputs and not harvesting to reduce production costs. Trials with other *Brassica* spp. that are high in glucosinolates grown as a cover crop are also under evaluation. However, since a number of these species are hosts to *V. dahliae* [reviewed in (4)], pathogenicity tests should be conducted to determine if these cover crops actually enhance soil populations of this pathogen.

Organic amendments may also be useful for management of diseases commonly controlled by soil fumigation, although questions of cost effectiveness and field scale practicality may need to be addressed before they are commercially feasible. In greenhouse trials evaluating methods for management of apple replant disorder, Mazzola et al. (51c) observed that soil amendment with *Brassica napus* seed meal reduced the incidence of apple root infection by *Rhizoctonia* spp. and the lesion nematode *Pratylenchus penetrans*, but in some cases it increased soil populations of *Pythium* spp. and the incidence of disease they caused. Since differences in the level of control of *Rhizoctonia* spp. was not observed with seed meal higher in glucosinolates compared to another cultivar that was lower, it was suggested that the mechanism of suppression was not due to the degradation products of glucosinolates. Likewise, Lazarovitis et al. (47a) reported that soil amendments with high nitrogen-containing organic byproducts reduced the incidence of several soilborne pests, including *V. dahliae*. Some site specificity of efficacy was observed with certain amendments, which was related to the mechanism by which the amendments functioned. For example, ammonia and nitrous acid are generated by decomposition of meat and bone meal and both are toxic to *V. dahliae* microsclerotia (79a). Soil pH can influence the generation and stability of these degradation products in the soil, but it is believed that organic matter content, nitrification rate and buffering capacity of the soil can play a role as well. Likewise, volatile fatty acids were

the component of liquefied swine manure that were toxic to *V. dahliae* in acidic soil; however, in neutral or alkaline soils these fatty acids were ionized and were no longer toxic (79b).

## INTEGRATED CONTROL

Given the broad spectrum of soilborne pests that need to be controlled, the non-chemical control approaches described above should be viewed with an eye toward development of integrated methods for disease management rather than an individual approach for pest control. A similar argument for integrated control also could be made for combining nonchemical treatment and alternative fumigants with the intention of broadening the spectrum of pest control, reducing rates of fumigant application, and minimizing the emission of fumigants into the atmosphere. Additional comments on integrated nonchemical control of soilborne pests may be found in Chellemi (11).

## LIFE AFTER 2005

The current status of research suggest that there are indeed alternatives to replace methyl bromide for management of soilborne pests. However, the picture is less clear when evaluating economically viable alternatives that can be implemented at the farm level, especially for annual production systems. Perhaps the primary reason is that none of the currently registered alternative fumigants is a drop-in replacement for methyl bromide; they will require at least some modification of the current crop production system to maintain control of soilborne pests. These modifications have not yet been perfected in all the different production areas or soil types. A complicating factor is that the crop production practices and pest control needs for a specific crop can vary depending on where the crop is grown. To use strawberry production as an example, alternative fumigation and production strategies developed for production in southern California will likely be different from those used in the central coast. Furthermore, many of the trials with alternative fumigants have been conducted on land that was relatively free of lethal pathogens such as *V. dahliae* due to previous treatment with MB + Pic. While some trials have followed the efficacy of alternative fumigants for several years, the long-term ability of these treatments to manage the pathogens is unknown. Despite the frantic pace of research and conduct of field trials evaluating efficacy, the question of economic viability of alternative fumigants will be addressed over the next few years with more large-scale evaluations in commercial production systems.

One problem that growers may encounter as they switch to alternative fumigants is the consistency of control attained relative to the standard MB + Pic fumigation. This highlights the need for continued research on understanding how fumigants move through soil and their degradation when they are applied to different soil

types using a variety of application methods. Research also is needed to improve application technologies to enhance fumigant distribution to the target sites in soil and reduce potential problems with groundwater contamination or field emissions. This in turn should lead to a more site-specific fumigation strategy using rates that control the specific pests present at the site while minimizing the environmental effect of the application. This knowledge will also assist in developing application strategies that will reduce impediments such as plant back intervals that may limit the utility of some alternative fumigants in specific crop production systems.

Given the current environmental temper and regulatory constraints on fumigant applications, and the possibility that they may become more restrictive in the future, it would be prudent to continue research on the development of integrated nonchemical approaches for pest management. This would include clarification of pathogen complexes that are leading to reductions in yield, insight into how cropping practices influence pathogen inoculum density in the soil and its ability to cause disease, breeding strategies to enhance crop resistance to diseases, a better understanding of rhizosphere microbial ecology and approaches that can be used to enhance beneficial colonizers, and the development of plant growth-promoting rhizobacteria or biological control agents capable of ameliorating the effects of pathogen infection. Although it is unlikely that these approaches will lead to pest control efficacy equal to that of methyl bromide, it is possible that by combining these approaches an economically viable alternative crop production system can be developed. If this objective is not pursued, at some point in the future we may well be addressing the same problems that the research and grower communities have been grappling with since the phase-out of methyl bromide was first announced.

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## ERRATA

An online log of corrections to *Annual Review of Phytopathology* chapters (if any, 1997 to the present) may be found at <http://phyto.annualreviews.org/>