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Agriculture, Methyl Bromide, and the Ozone Hole

Can We Fill the Gaps?

Methyl bromide is a widely used fumigant in U.S. agriculture and is one of the five most used pesticides in the United States (68). Between 25,000 and 27,000 t of methyl bromide are applied annually (70). More than 75% of the use of methyl bromide is for preplant fumigation of soil (68) (Fig. 1A). In addition, methyl bromide is used for postharvest treatment of nonperishables (13%) and perishables (8.6%), and for quarantine purposes (<1%). The compound also occurs as an intermediate in chemical manufacturing and is used as a medical sterilant. Methyl bromide is an effective herbicide, nematicide, insecticide, and fungicide and has been used commercially in the United States for soil fumigation and quarantine purposes for most of the twentieth century (53).

Considerable evidence has accumulated that methyl bromide is a potent ozone depletor, and the compound is scheduled to be phased out in the United States by 2001 under the Clean Air Act (71). The use of methyl bromide was a critical factor in dramatic changes in crop production systems in California, Florida, North Carolina, and elsewhere. Crop rotations were once standard methods of pest management before widespread use of soil fumigation and plastic mulching. Production of crops such as strawberries and fresh market tomatoes has become highly dependent on methyl bromide use, leading to reductions in crop rotation and in diversification of production practices (7). The economic viability of specific crops in Florida, California, North Carolina, and other states could be affected by the loss of this compound if no alternatives are available (9,62,69). The purpose of this article is to review the scientific, trade, regulatory, and policy issues that will affect the use of methyl bromide in agriculture and to discuss methyl bromide alternatives.

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Is There an Ozone Depletion Problem?

Ozone is a rare form of oxygen containing three atoms per molecule (O_3) and is highly reactive. Most ozone is found in the lower two layers of the earth's atmosphere: the troposphere and stratosphere. Ozone present in the troposphere is normally found at concentrations of 10 to 30 parts per billion. Tropospheric ozone has increased in recent decades in the Northern Hemisphere due to photochemical production from anthropogenic precursors (77). Over 90% of the earth's ozone is present in the stratosphere, which contains ozone concentrations of 10,000 parts per billion (77). The stratosphere extends from 16 to 160 km (10 to 100 miles) above the earth's surface. The ozone layer refers to the region of the stratosphere where ozone concentrations are greatest, about 25 km above the earth's surface. Stratospheric ozone provides a protective layer for the earth's surface and is essential for life on this planet. Ozone is known to play a key function in moderating the climate of the earth by absorbing ultraviolet radiation from the sun (UV-B) and essentially acts as a sunscreen for the planet (57). There is a strong correlation between decreased stratospheric ozone and increased UV-B at the earth's surface (77). Increases in sunburn, skin cancer, eye damage, crop damage, and other negative environmental impacts can result from increased UV-B. Absorption of UV radiation by ozone in the earth's stratosphere also creates heat, which moderates the earth's temperature (57,77).

The episodic loss of ozone each spring over the Antarctic continent was demonstrated by Farman et al. (19). The low temperatures that occur between midwinter and spring make the Antarctic stratosphere sensitive to growth of inorganic chlorine, which depletes ozone (3,19,41). Mapping of the recurring and worsening ozone depletion event has been monitored with satellite data each year since 1985 (Fig. 1B) (45). Within 4 years, ozone loss in a region the size of the Antarctic continent occurred, and 70% of the total ozone column content was lost during September and October 1989 (64). The size of the ozone "hole" varies from year to year, but increases in the size of the hole over time have occurred (64). The ozone holes of 1992 and 1993 were the most severe on record (24,77). In 1995, the ozone layer hole over Antarctica was twice the size of the previous year and lasted three and a half months longer than previous records of depletion (45). Springtime depletion of stratospheric ozone was recorded over the Northern Hemisphere in the Arctic in March 1996 (45). Ozone levels were 20 to 25% lower over Siberia, Europe, and parts of Canada than previous recorded levels (45).

Atmospheric pollutants such as chlorofluorocarbons and bromine react chemically with ozone molecules (41). Halogenated hydrocarbons have been used as propellants and refrigerants, and they include compounds such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), the Halons, methyl chloroform, and carbon tetrachloride (77). These compounds remain in the atmosphere for 40 to 150 years (41). Chlorofluorocarbons undergo photolysis in the stratosphere and produce significant amounts of chlorine (77). Chlorine reacts with ozone and breaks down the molecule. Bromine reacts in a similar manner to chlorine and is also a potent ozone depletor (3,77). At least seven organic bromine compounds have been identified in the atmosphere (51). Bromoform, emitted from ocean sources, is a large contributor to atmospheric bromine and has a short lifetime due to photolysis. Methyl bromide is the major carrier of bromine to the stratosphere (51). Methyl bromide breaks down to form bromine, which participates in a series of ozone-depleting chemical reactions (15,67). In fact, bromine is 50 times more reactive than chlorine in depleting ozone because it reacts with reservoir chlorine species, freeing the chlorine to react with additional ozone (77).

A recent analysis by Montzka et al. of air samples from around the world taken between 1991 and 1996 revealed that tropospheric chlorine attributable to anthropogenic halocarbons peaked near the beginning of 1994 and was decreasing at a rate of 25 ppt per year by mid-1995 (42). Bromine from Halons is still increasing, but the summed abundance of the halogens is decreasing. The amount of reactive chlorine and bromine will reach a maximum in the stratosphere between 1997 and 1999 if all limits outlined in the Montreal Protocol on Substances that Deplete the Ozone Layer are not exceeded in future years (42). These results indicate that the regulatory actions on a worldwide basis have made an impact on levels of CFCs in the stratosphere (42). However, most of the CFCs measured in the work of Montzka et al. are still on the increase in the stratosphere. The study did not include methyl bromide in the analysis (42).

The Role of Methyl Bromide in Ozone Depletion

Unlike chlorine, which is present in the stratosphere mostly from human activities, presence of bromine compounds in the atmosphere can result from both natural and anthropogenic sources (77). Four major atmospheric sources of methyl bromide have been identified, including ocean sources, which are a natural source, and three anthropogenic sources, including agriculture, biomass burning from destruction of forests, and automobile exhaust (13). Emissions of bromine from these sources into the atmosphere have been measured. Emissions of methyl bromide from natural ocean sources range from 26 to 100 Gg per year (77). The largest anthropogenic source of methyl bromide in the atmosphere is agricultural use. Estimates of sources of methyl bromide from soil fumigation range from 16 to 47.3 Gg per year. Biomass burning emits 10 to 50 Gg per year of methyl bromide. Emissions from the exhaust of cars using leaded gasoline range from 0.5 to 22 Gg per year (77). Penkett et al. measured concentrations of methyl bromide in the atmosphere and found concentrations were higher in the Northern than in the Southern Hemisphere. These authors suggested that the major source of emissions of methyl bromide entering the atmosphere was anthropogenic (51).

Research to determine the relative magnitudes of natural and anthropogenic sources of methyl bromide has led to much debate, and uncertainties still exist. Early work suggested oceans were a large net source of methyl bromide (59), but recent work suggests that oceans are a small net sink for methyl bromide (32). Annual oceanic sinks for methyl bromide of 142 Gg per year were estimated (32). Most of the methyl bromide produced in the oceans (60 to 75%) is degraded in situ in seawater by nucleophilic substitution by Cl^- and by

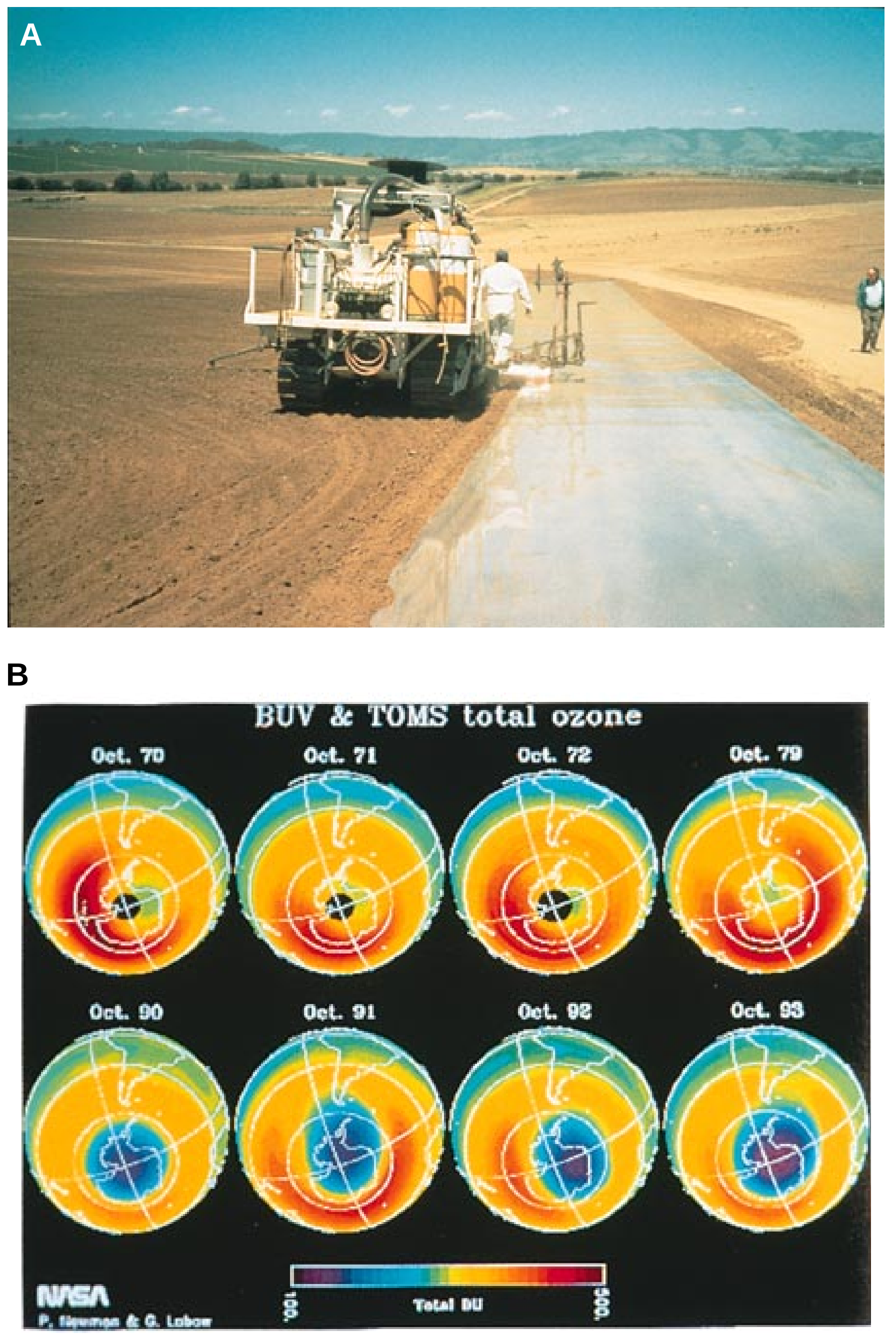

Fig. 1. Methyl bromide and ozone depletion. (A) Commercial fumigation of agricultural soils with methyl bromide. (B) History of the Antarctic ozone hole from 1970 to 1993.

hydrolysis (2,18). The relative amount of methyl bromide emitted to the atmosphere from ocean sources is still a subject of great debate, and estimates from 30 to 90% of total production have been proposed (1,32). The magnitude of the flux of methyl bromide into and out of oceans is important since it affects the atmospheric lifetime of the compound and hence the ozone depleting potential (ODP) (2). Only 8% of the observed interhemispheric differences in methyl bromide concentrations were attributed to oceanic sources and sinks (32). Current data indicate the importance of the oceans in buffering atmospheric bromine concentrations but also emphasize that anthropogenic sources of methyl bromide are significant. Further research is needed on the atmospheric chemistry of methyl bromide and its role in ozone depletion (67).

Is Methyl Bromide from Soil Fumigation Released into the Atmosphere?

The general consensus is that substantial retention and degradation of methyl bromide within agricultural soils is unlikely, and most is released into the atmosphere following soil fumigation (23,79,83). In one study, 87% of the applied methyl bromide was emitted within 7 days after commercial fumigation and plastic removal at 95 h (79). Fumigated fields covered with plastic film released 40% of the applied methyl bromide (79). However, these measurements may be erroneously high due to errors in measurement of the mass balance of the compound and lack of correction for temperature effects on volatilization of the compound (83). In a recent study, after commercial fumigation in an inland valley soil in California, 36% of the methyl bromide was released within 24 h and 63% was released after 18 days (82,83). Addition of irrigation during the fumigation process increased degradation of methyl bromide and reduced emissions to 5%, presumably through hydrolysis of the compound (83). Other management practices, including deep injection of the fumigant and addition of organic matter to the soil prior to fumigation, are being investigated and may substantially reduce emissions of the fumigant to the atmosphere. However, the addition of organic matter may reduce the biocidal properties of the fumigant to soilborne pathogens and pests (44). Increased soil moisture will decrease soil temperatures and could also reduce the effectiveness of the fumigant (44). New plastic films, termed virtually impermeable films (VIF), have been developed and tested in Israel, but controlled field measurements of the mass balance of methyl bromide emitted after fumigation under VIF tarps need to be conducted in the United States. Bromine can accumulate in the groundwater and can be taken up by plants (27). Further experiments on reductions in emissions of the fumigant are needed, with particular emphasis on impacts of new tarping technologies on emissions, improvements in application technology to reduce atmospheric releases, and effects of these new technologies on plant pathogens and crop growth.

Some argue that most of the methyl bromide applied during soil fumigation is degraded or absorbed in soil and that the soil is a large sink for methyl bromide (58). Bacterially mediated uptake of methyl bromide in soils has been reported (58). Methyl bromide can undergo a variety of reversible or irreversible processes in the soil (8). In one study, chemical bonding and decomposition by hydrolysis had little effect on the flow of methyl bromide through soil columns (8). Degradation of methyl bromide and subsequent production of bromine is highly dependent on soil organic matter, with the greatest bromine production in muck soils and the least production in sand (5,8). Hydrolysis and methylation are the two most common means of degradation of methyl bromide in soils (11,32,38). Degradation of methyl bromide in soil decreases with soil depth, mainly due to reduced organic matter (23). In soils with high organic matter, degradation of methyl bromide by methylation predominates over hydrolysis (23). Methyl bromide can also undergo degradation in anaerobic sediments by bacterial metabolism from methanogenic and sulfate-reducing bacteria (49). The resulting methylated sulfur compounds serve as substrates for methanogens and other bacteria present in microbial films in salt marsh communities. Coastal salt marshes containing sulfate-reducing bacteria may constitute a sink for atmospheric methyl bromide, but the size of this sink is not clear at the present time (49).

Regulatory Action

Concern over ozone depletion led to negotiations among countries that resulted in the 1987 drafting of the Montreal Protocol on Substances that Deplete the Ozone Layer (26,67). This ambitious environmental treaty set the standards for reductions of ozone-depleting substances worldwide and was signed by more than 150 countries, including the United States. The treaty governs the production and trade of ozone-depleting substances and requires eventual elimination of production of those substances. The Copenhagen amendments to the Protocol called for a ban on all CFCs by 1996. An ozone depletion potential (ODP) index is used under the Montreal Protocol and the Clean Air Act to gauge a substance's relative potential to deplete stratospheric ozone. The ODP represents the amount of ozone destroyed by the emission of 1 kg of a chosen gas over a particular time scale compared with chlorofluorocarbon-11 (CFC-11), a major ozone depletor (67). The United Nations Environment Programme (UNEP) calculated that methyl bromide had an ODP of 0.6, or 60% of CFC-11's ozone-depleting potential, and the atmospheric lifetime was calculated at 1.7 years (39,61). The ODP of methyl bromide is dependent upon the atmospheric abundance of chlorine. The higher the abundance of chlorine, the higher the ODP of methyl bromide. The relative value of the ODP of methyl bromide is important since gases with ODP greater than 0.2 are listed as Class I ozone depletors and are required to be phased out under the U.S.

Table 1. Schedule of methyl bromide phaseout in the United States and in the international community[a]

Provision	United States	Montreal Protocol
Freeze on production and importation	Production and importation frozen at 1991 levels, effective 1 January 1994	Production and importation frozen at 1991 levels, effective 1 January 1995
Exemptions to the freeze	No exemptions have been granted yet. EPA has authority to grant exemptions for use in medical devices and for export to developing countries.	Preshipment and quarantine uses exempted. Methyl bromide production can exceed their 1991 levels by 10% to export to developing countries.
Ban on production and importation	A ban on production and importation becomes effective January 2001.	Developed countries agreed to phase out use by 2010 with 50% reduction by 2005, 25% reduction by 2001.
		Developing countries agreed to freeze use of methyl bromide in 2002 based on average production levels in 1995 to 1998.

[a] From U.S. Government Accounting Office. 1995. Pesticides: The Phaseout of Methyl Bromide in the United States. GAO/RCED-96-16, Washington, DC.

Clean Air Act and the Montreal Protocol (67,71).

In December 1993, the EPA issued a notice of final rulemaking that added methyl bromide to its list of Class I substances and established a domestic schedule for elimination of production of the compound (Table 1) (43,71). Domestic production of methyl bromide in the United States was capped at 1991 levels as of 1 January 1994, and use of the compound is to be eliminated by 2001 (71). After this date, no new importation or production of methyl bromide can occur in the United States. Stronger international efforts to control methyl bromide emissions have also been developed (77). In December 1995, parties to the Montreal Protocol met, and developed countries agreed to eliminate production of methyl bromide by 2010, with a 50% reduction by 2005 and a 25% reduction by 2001. Developing countries, which currently account for only 18% of the global consumption of methyl bromide, agreed to freeze their use of the compound in 2002 based on the average levels of 1995 to 1998 consumption (43) (Table 1).

Methyl bromide is categorized as a restricted use pesticide, and registration is currently required under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Methyl bromide is currently undergoing reregistration, and data supporting its registration are being supplied by producers. The compound has acute toxicity risks and requires special handling by trained individuals to ensure safe use (53).

Methyl Bromide Sales and Use Since the Montreal Protocol

Sales. Methyl bromide production in the United States increased from 1984 to 1991 and declined thereafter (Fig. 2A) (71). The U.S. schedule for phaseout of methyl bromide called for a freeze on production of methyl bromide at 1991 levels effective January 1994. The EPA's Stratospheric Protection Division in the Office of Air and Radiation is currently tracking the production, import, and export of methyl bromide and calculating consumption rates each year until 2001 (71). Consumption of the chemical is defined as annual production plus imports minus exports. U.S. exports of methyl bromide declined from 5,442 to 2,268 t between 1980 and 1984. Since 1984, U.S. exports of methyl bromide have nearly quadrupled and were 8,526 t in 1995. The largest amount of methyl bromide from the United States is exported to western Europe, Canada, and Asia (68).

Annual worldwide production of methyl bromide has increased over time (Fig. 2B). A worldwide summary of methyl bromide sales by region for 1984 to 1990 indicates that most of the sales of methyl bromide are in North America, Europe, and Asia (Fig. 3A). These regions account for 41.6, 27.8, and 22.3% of the total sales of methyl bromide (68). Mexico and Central American and Caribbean countries are included in the North American estimates of sales, but these countries are not large users of methyl bromide. The United States, Japan, and Italy are the top three user countries of methyl bromide (68). In North America, Europe, and Asia, sales of the product are predominantly for preplant soil fumigation (Fig. 4A). Sales of methyl bromide for preplant use as a soil fumigant have increased to a greater extent in North America than in Europe, Asia, or other parts of the world (Fig. 4A) (68). In Asia, sales of methyl bromide from 1984 to 1990 for postharvest treatment of exports to other Asian countries greatly exceeded the postharvest usage of methyl bromide for treatment in North America (Fig. 4B). In 1990, Asian sales were 5,265 t of methyl bromide; whereas U.S. sales were only 1,219 t. Most methyl bromide used in postharvest fumigation is released to the atmosphere. This indicates that Asian countries should be targeted for recycling and alternative fumigant research and implementation efforts.

Use. Approximately 29,000 t of methyl bromide were used in the United States in 1990. More than 80% of the methyl bromide use in the United States is for agriculturally related purposes. Most of the use of methyl bromide for preplant soil fumigation occurs on 21 small fruit and vegetable crops in California, Florida, Georgia, North Carolina, and South Carolina (Fig. 3B) (69). The largest uses of the fumigant by crop are for tomatoes, strawberries, peppers, ornamentals and nurseries, tobacco, grapes, and melons. California and

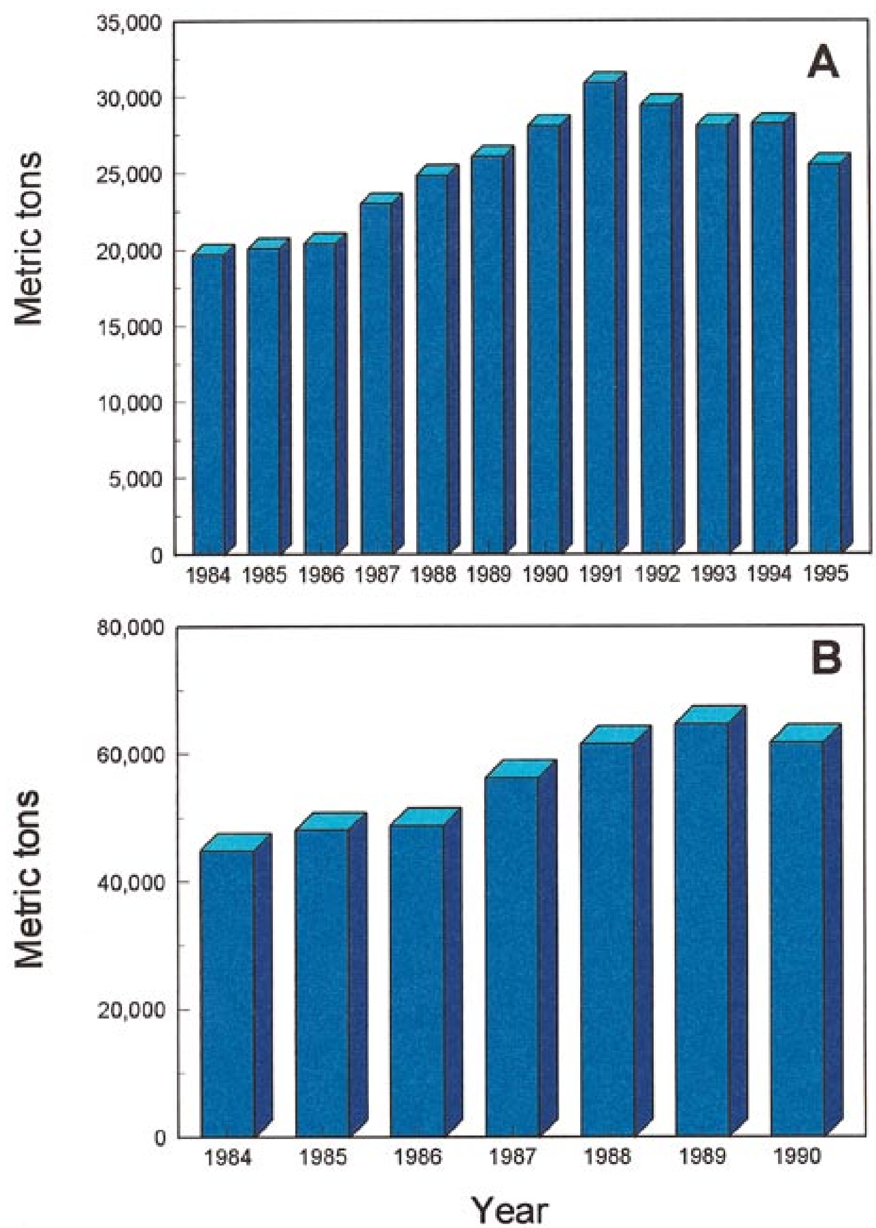

Fig. 2. Methyl bromide production in (A) the United States from 1984 to1995 and (B) worldwide from 1984 to 1990.

Florida are the largest users of methyl bromide in the United States, and most of the use is on strawberries and tomatoes, respectively (69).

Pesticide use data in California collected by the California Department of Pesticide Regulation are the most extensive in the country (10). An increase in methyl bromide use occurred from 1,451.2 t on 49 commodities in 1971 to 8,707 t on 109 commodities in 1992. Methyl bromide was the chemical alternative that replaced organochlorines and other fumigants that were banned in the 1970s and 1980s. From 1990 to 1994, field use of methyl bromide on strawberries in California declined slightly, from 1,966 to 1,879 t, while hectarage of strawberries in California has been stable between 9,430 and 9,470 ha (10). In recent years, use of methyl bromide across all commodities in California declined slightly, from 9,100 to 7,600 t, and number of applications also declined between 1990 and 1994 (10,70).

Economic Impact of the Loss of Methyl Bromide

The National Pesticide Impact Assessment Program (NAPIAP) estimated annual economic losses of $1.3 to 1.5 billion if a ban of methyl bromide use occurred in the United States (69). Most of the losses estimated were due to loss of soil fumigation ($800 to 900 million), and lesser amounts were due to loss of quarantine fumigation for imports ($450 million). NAPIAP estimates indicated that the greatest losses would occur in tomatoes and strawberries. The USDA-NAPIAP study thoroughly identified regional areas of greatest use of methyl bromide and crops that had the greatest dependence on the compound (69). The California Department of Pesticide Regulation also conducted an economic analysis of the loss of methyl bromide and determined that $287 to 346 million in losses would result from the loss of the soil fumigant, and $241 million in trade income would be lost (9). In Florida, a ban of methyl bromide would affect tomatoes, peppers, cucumbers, squash, eggplant, watermelon, and strawberries. Estimated losses of more than $500 million were projected (62). These loss estimates assumed that few or no alternatives would be available or used.

The EPA conducted a cost–benefit analysis of the elimination of methyl bromide (*unpublished data*). The EPA estimated that $1.2 to 2.3 billion in losses could occur if the methyl bromide phaseout did not occur. Additionally, EPA estimated the likely health effect costs of the use of methyl bromide. It was estimated that between $244 and 952 billion in benefits would result primarily from a reduction in 2,800 skin cancer deaths over the period from 1994 to 2010. Estimates of ozone depletion and skin cancer incidence associated with a "no restrictions" scenario, the less restrictive Montreal Protocol, and the most restrictive Copenhagen Amendments have been conducted (60). The no restrictions and Montreal Protocol scenarios produce runaway increase in the incidence of skin cancers, up to quadrupling and doubling, by 2010, respectively. The Copenhagen Amendments scenario leads to an ozone minimum around the year 2000 and a peak relative increase in incidence of skin cancer of almost 10% 60 years later. These results demonstrate the importance of international measures agreed to under the Vienna Convention to phase out ozone-depleting compounds (60).

Estimates on a global scale of the economic costs of reduced ozone need to be calculated as more scientific research is conducted to define the impacts of ozone depletion on specific terrestrial and atmospheric ecosystems. These indirect costs need to be examined so that balanced, sound policy on pesticide use can be developed (52). Indirect costs of methyl bromide use include detrimental human health effects from increased UV-B (60), detrimental effects of increased UV-B on global photosynthetic rates (57), health effects from exposure of workers to the compound (53), increased control expenses resulting from pesticide-related destruction of beneficial organisms (40), yield reductions due to phytotoxicity (40), groundwater contamination (7), and governmental expenditures to reduce the environmental and societal costs of the use of the pesticide, including alternative research and development in the United States and developing countries.

Some workers have proposed that the phaseout of methyl bromide should be based on the value of the use of the compound on specific commodities (80). The economic effect of the elimination of methyl bromide varies by region and crop in California. Strawberries have the highest net return per pound of methyl bromide used, so workers have suggested that elimination of the compound should not be uniform on all crops but staggered by commodity from low- to high-value usage to reflect these net returns (80). Additionally, a tax on usage of the fumigant has been proposed that would result in a price increase and thus reduce usage of the fumigant over time from 8,617 to 2,494 t in California (80). Pesticide use fees have been proposed by others as an alternative

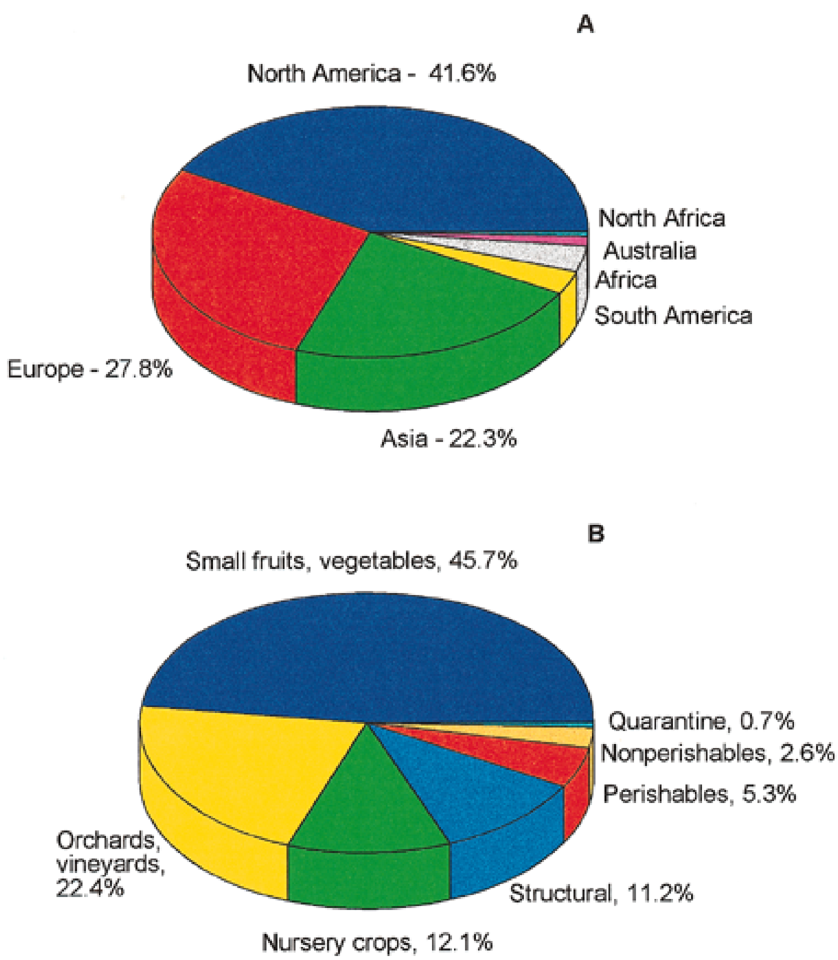

Fig. 3. Methyl bromide (A) total sales (% metric tons) by region of the world from 1984 to 1990 and (B) consumption by end use in 1990.

to outright banning of specific pesticides. Such fees could be used to support IPM research and environmental regulatory activity but might not reduce the actual usage of compounds (50,87). However, risk-adjusted taxes, with higher use fees for compounds with more serious environmental impact, create incentives for users to choose less hazardous and less expensive products, according to Pease et al. (50). Taxation of methyl bromide would require new national legislation (43). Without alternatives, outright pesticide bans result in reduced production levels, higher prices for consumers, and possible use of more toxic compounds by growers (87).

Trade Issues Relevant to Phaseout of Methyl Bromide

U.S. law requires that certain agricultural imports from specified countries be almost completely (99.9968%) pest free prior to entry (69). Methyl bromide fumigation is one of the quarantine treatments accepted by USDA, and it is often the preferred method of treatment at ports of entry into the United States. Many imported fruits and vegetables enter the United States during months when similar commodities are unavailable locally. In addition, more than $400 million worth of exports were fumigated with methyl bromide in 1994 (72). Over 118 million kilograms of cargo was fumigated for import or export in California alone in 1996 (9). Methyl bromide is the fumigant of choice for quarantine purposes since it requires short treatment times, is efficacious, has a low cost, and does not affect quality or flavor of the treated commodity if used correctly (9). The total use of methyl bromide for quarantine treatments in the United States is less than 1% of its use for preplant soil fumigation (Fig. 3B). Whether exemptions will be granted for certain restricted uses of methyl bromide such as quarantine has not yet been determined (72).

If methyl bromide use is banned in the United States as a quarantine treatment, alternative methods of treating import and export commodities will be needed. Alternative treatments are currently being used by USDA Animal Plant Health Inspection Service (APHIS) to treat commodities, and many USDA and university laboratories are working on this issue (Table 2). The pros and cons of the use of alternative fumigants for stored products have been reviewed (65,68,81). Several quick, efficient technologies, including microwaves and irradiation, may prove useful as alternatives for quarantine treatment of stored product pests (20). Movement of pests and pathogens across borders could increase if alternative strategies for quarantine fumigation are less effective than methyl bromide. APHIS is increasing emphasis on pest risk assessment to more precisely estimate risks and reduce the number of phytosanitary applications of fumigants. Tolerance levels for certain pests based on risk need to be developed. Increased use of accurate diagnosis and deployment of molecular detection methods for pests and pathogens into quarantine decision making could significantly reduce the use of fumigation.

The proposed international phaseout of methyl bromide differs from the domestic schedule for phaseout (Table 1). This has led U.S. growers to be concerned that an unfair trade advantage may be gained by other nations if U.S. growers are forced to eliminate methyl bromide use by 2001. In particular, Florida tomato growers are concerned that Mexican growers may develop an even greater competitive edge in fresh-market tomatoes if Florida can no longer fumigate its fields with methyl bromide (62). Over 95% of the tomato fields in Florida are currently fumigated with methyl bromide due to problems from soilborne diseases including the root-knot nematode, *Fusarium*, and bacterial wilt diseases (70). Over 95% of the Mexican fresh-market tomato growers do not currently use methyl bromide since soilborne pathogens are less severe in their tomato-growing areas. Methyl bromide use in Mexico is primarily for strawberries grown in the Baja region (34). Despite their use of the fumigant, Florida shipments of tomatoes account for 45.2% of the market, while Mexican exports have increased dramatically in the United States in the last year and now account for 40.7% of the market (73). Apparently, issues other than methyl bromide use, including reduced labor costs, improved varieties and production practices in Mexico, and consumer

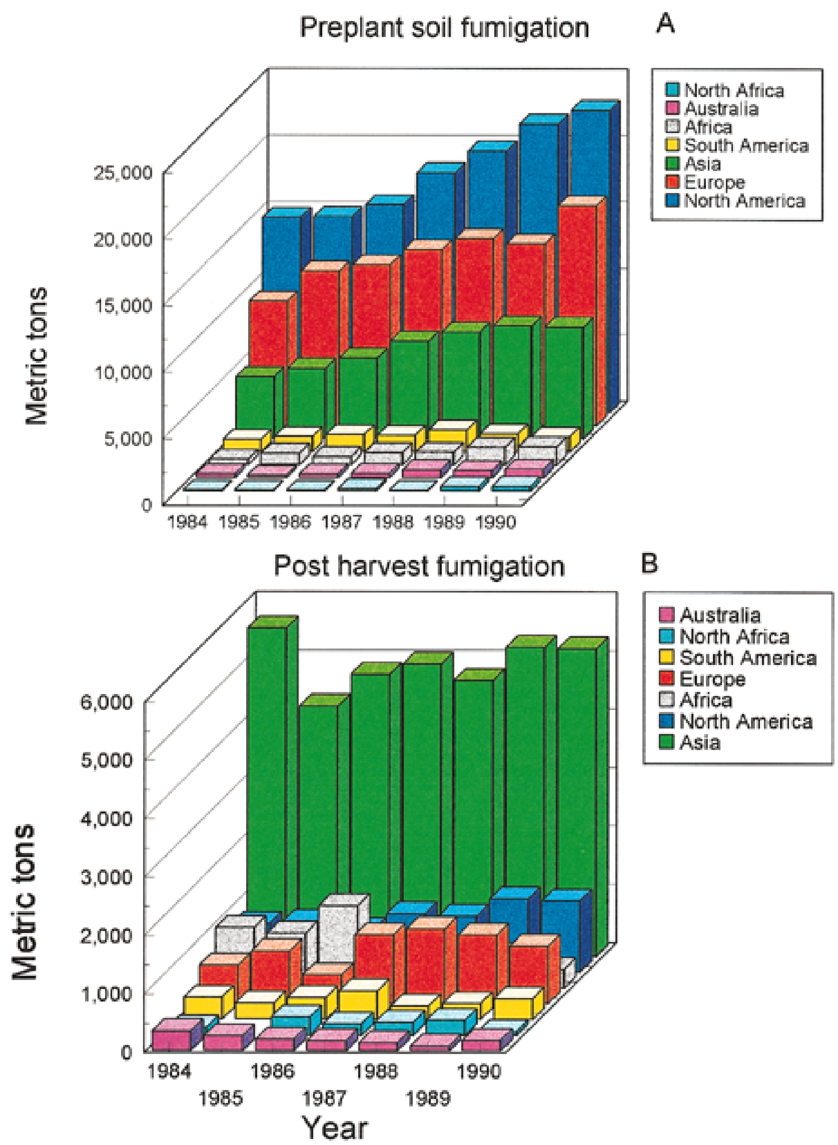

Fig. 4. Methyl bromide sales by region of the world for (A) preplant soil fumigation and (B) postharvest fumigation, from 1984 to 1990.

choice of Mexican tomatoes that are vine ripened rather than gassed, have influenced this increase in Mexican imports (34,73).

Alternatives to Methyl Bromide

Alternative fumigants. The pending elimination of methyl bromide use in the United States has stimulated a great deal of creative research that should improve our ability to manage soilborne pathogens using ecologically based pest management strategies. It is clear from most of the research conducted to date that a single alternative fumigant will not be found to replace methyl bromide, although recently, workers have suggested that methyl iodide might be that new alternative (47). Some would argue that it is not desirable that a single new "magic bullet" fumigant be found that is as efficacious and widely applicable as methyl bromide. Use of a diversity of management practices that include less dependence on single-chemical strategies and greater use of biological and cultural management strategies could enhance grower options (46). On the other hand, if a single chemical method of control that is safe and efficacious could be found to replace methyl bromide, it would be rapidly adopted by growers (53).

Methyl iodide has shown promise as a useful soil fumigant and has not been implicated as an ozone depletor (47) (Table 3). Methyl iodide has an atmospheric lifetime of 1 week in the troposphere and is rapidly oxidized. Methyl iodide was equal to or better than methyl bromide in controlling *Phytophthora citricola*, *P. cinnamomi*, *P. parasitica*, *Rhizoctonia solani*; the nematode *Heterodera schachtii;* and the weed plants *Cyperus rotundus*, *Poa annua*, *Portulaca oleracea*, and *Sisymbrium irio* (47). The compound is not currently registered, although EPA has received some inquiries from prospective registrants about the compound.

Strawberries are susceptible to a number of soilborne and fruit-rotting pathogens, including *Rhizoctonia solani* (Fig. 5A), *Phytophthora fragariae* (Fig. 5B), *P. citricola*, *P. cactorum*, root-knot nematodes *Meloidogyne incognita* and *M. hapla* (Fig. 5C), *Verticillium dahliae*, and black root rot caused by a complex of *Pratylenchus*

Table 2. Postharvest pest control strategies and potential alternatives[a] for methyl bromide

Treatment	Treatment time	Comments and issues
Methyl bromide	3 to 12 h	Ozone depletion, 2001 phaseout. Quick efficacious treatment.
Methyl bromide with recapture	3 to 12 h	Scale up to large-scale recapture difficult, efficacy.
Phosphine	4 to 7 days	Registered. Resistance development, longer time for treatment. Least disruptive to current practices.
Controlled atmosphere ($C0_2$)	3 to 40 days	Slow acting and temperature dependent. May help ripen and disinfect. Storage facilities need upgrading.
Cold	3 to 40 days	Slow acting and energy intensive. Extends product shelf life. Relatively safe.
Dust and diatomacaeous earth	Days to weeks	Inert dust sprayed in empty storage bins and equipment. Crawling insects are desiccated.
Heat	1 to 36 days	Energy intensive. Can affect quality. Vapor, hot water, dry heat.
Microwave	<1 h	Microwave energy applied as grain enters bin. Cost comparable to chemical treatment.
Irradiation	<1 h	Consumer reluctance. Short treatment time of <1 h. Extends shelf life. Expensive process.
Biological	Agent specific	Nontoxic, long-term solution. Control but not eradication. Quarantine issues.
Certified pest-free zone	No treatment required	Requires extensive monitoring, may increase pesticide use. Product shelf life and quality unaffected.

[a] List of alternatives from references 65, 68, and 81.

Table 3. Chemical alternatives to methyl bromide

Chemical name	Crop	Pest or pathogen	Comments
Chloropicrin	Strawberries, fruit and nut crops, Solanaceous, leafy vegetables, forestry and nursery crops	Nematodes, soil insects, soil fungi (*Fusarium, Pythium, Rhizoctonia, Sclerotinia, Verticillium*, and *Colletotrichum*)	Drift problems. Marginal activity against some nematodes and weeds due to poor distribution in soil. Reregistration early 1997.
Dazomet (Basamid)	Solanaceous (tobacco seedbed only), forestry, ornamental and nursery crops	Nematodes, soil insects, soil fungi, and weed seeds	Long period between application and planting. Highly phytotoxic. Registered for nonfood crops use currently. Experimental use permit granted on strawberries, peppers, tomatoes, and broccoli in February 1996. Registration decision, early 1998.
1,3,Dichloropropene (Telone II)	Vegetables, tobacco, and root crops mostly, but labeled for all food and nonfood crops	Nematodes, soil insects, soil fungi	In special review because of cancer concerns. Label changes to mitigate risk agreed to by registrant. Restricted usage in California due to residue problems in air samples around urban areas adjacent to farmland. Special review by EPA will be done in 1997.
Telone C-17	Vegetables, tobacco, and root crops mostly, but labeled for all food and nonfood crops	Nematodes, soil insects, soil fungi	Same as Telone II but with added chloropicrin. Same concerns as above.
Methyl iodide	Not labeled yet for any crop	Soil fungi, nematodes, weeds	Not registered currently. Destroyed rapidly in troposphere. One week atmospheric lifetime.
Metam-sodium (Vapam)	Strawberries, fruit and nut crops, leafy vegetables, forestry, nursery and ornamental crops	Nematodes, weeds, soil fungi, insects	Reregistration scheduled for early 1998. Major spill in Sacramento River caused environmental problems. Not as efficacious as Telone on strawberries. Can be useful at low rates with biological control agents.

penetrans and *Rhizoctonia* and *Pythium* species (Fig. 5D) (86). Strawberry producers in California are among the largest preharvest users of methyl bromide. A number of soil fumigants are available that could provide alternatives to methyl bromide use in specific applications for specific pests or pathogens (Table 3) (4,6,17,31). Field experiments were conducted in commercial fields with five preplant treatments, including methyl bromide/chloropicrin (67/33% at 364 kg/ha), chloropicrin (336.3 kg/ha), Telone II (1,3,dichloropropene)/chloropicrin (70/30% at 509 kg/ha), Vapam (metam-sodium, 993.58 liters/ha), or no treatment (17). Fumigants were broadcast treated under tarpaulins, and after 5 days covers were removed, beds were shaped, and strawberries were planted. In a second test, Vapam was replaced with Telone II (1,3,dichloropropene)/chloropicrin (30/70% at 458 kg/ha). All fumigants tested, with the exception of Vapam, worked equally well, and yields were not different from the methyl bromide–treated plots in 1994 and 1995, when the fumigants were used at high rates in soil with a history of strawberry/vegetable rotations (17). Disease pressure was low in the fields tested, and growth responses were observed in the absence of disease (17). In 1996, in fields where disease pressure was higher, yields were increased over the nonfumigated controls in all fumigant treatments; however, yields were highest with the methyl bromide/chloropicrin mixture (17). These studies on strawberries are currently in progress in California, and abstracts of the work have been published (17). The rates of alternative fumigants and costs are economically feasible for strawberry growers (66). Telone use in California is currently restricted by the California Department of Pesticide Regulation due to toxicity and excessive residues in air samples collected from treated fields near schools (7). Permit conditions allow use of 18,927 liters for shallow injections or 35,961 liters for broadcast or deep injections per township range (93 km^2) per year. Telone II is also currently under special review at EPA. Clearly, some cost-effective alternative soil fumigants will be available by the 2001 phaseout date (Table 3) (66). The best long-term solution for strawberry producers will be the development of resistant varieties, crop rotations, planting of pathogen-free planting materials, and judicious use of low-risk pesticides (17,25,31,66). Use of molecular detection methods for certification of pathogen-free planting materials could also reduce introduction of strawberry pathogens such as *Verticillium* and *Phytophthora* species into fumigated soils.

Resistant varieties. Host resistance is one potential long-term solution for management of the major soilborne pathogens of both strawberry and tomato. Currently, few strawberry varieties grown commercially in California have resistance to the major strawberry pathogens, including *Phytophthora* species and *V. dahliae* (31,75). Research has been conducted in other areas of the United States and is in progress in California to develop host resistance to root-infecting fungi on strawberry (35,75). Most of the breeding efforts in California have focused on development of high-yielding varieties with good shipping qualities and other desirable agronomic traits (31). Currently grown strawberry cultivars have greater differences in levels of resistance to *Phytophthora* species than to *Verticillium* species, but these levels of resistance are not equal to the beneficial effects observed with soil fumigation (75). Further research is needed to develop resistant strawberry cultivars adaptable to growing conditions in California and elsewhere.

Many tomato varieties have resistance to *Fusarium oxysporum*, nematodes, and *V. dahliae*. The challenge is to maintain levels of resistance to these pathogens as new races occur in the field. Some novel approaches using transgenic gene technologies have been developed that may provide more specific resistance to root-infecting nematodes (48). Specific plant genes can be turned on at nematode feeding sites in order to stop giant cell formation in roots (48). Continued research utilizing both traditional and molecular strategies will be needed to develop host resistance to a number of soilborne pathogens to acceptable levels for many vegetable crops.

Biological alternatives and cultural practices. Soil quality is the capacity of soil to function, within ecosystems and land-use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health (16). Mycorrhizal fungi are detrimentally impacted by methyl bromide fumigation in soils from diverse cropping systems (40). Microbial biomass in fumigated forest and pasture soils consistently remains lower than in nonfumigated soils even after 6 months (85). Bacteria are less affected by soil fumigation and recover more rapidly than do fungi in fumigated strawberry field soils (17,85). Diversity of protozoans and nematodes is greatly reduced by the fumigation process (85). Beneficial nematodes including bacterivores, fungivores, omnivores, and predators are major components of the biological soil food web and also play important roles in nutrient cycling in soils (84). In fact, these nematodes can provide a useful indicator of soil health, and their elimination from fumigated soil could lead to negative long-term consequences for soil productivity (84).

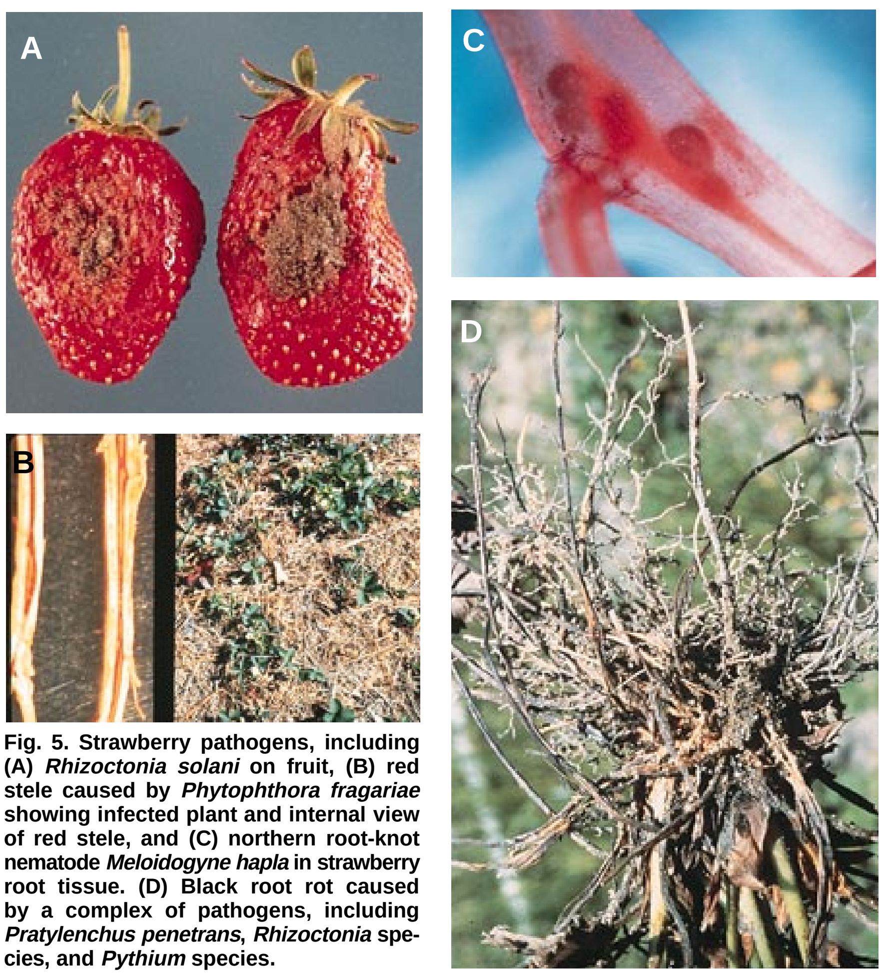

Fig. 5. Strawberry pathogens, including (A) ***Rhizoctonia solani*** on fruit, (B) red stele caused by ***Phytophthora fragariae*** showing infected plant and internal view of red stele, and (C) northern root-knot nematode ***Meloidogyne hapla*** in strawberry root tissue. (D) Black root rot caused by a complex of pathogens, including ***Pratylenchus penetrans***, ***Rhizoctonia*** species, and ***Pythium*** species.

Fumigated soils can also provide open niches for recolonization by pathogenic fungi (37). Introduced pathogens spread rapidly in fumigated soils that are devoid of suppressive biological communities (37). In a typical raised-bed fumigation, soil in furrows is not fumigated and can provide an inoculum source for introduction of pathogens into fumigated soils. *Fusarium* species rapidly colonize fumigated soils and can spread to cause severe disease in the absence of competition from beneficial microorganisms (37). Simple changes in cultural practices, such as the planting of pepper in stubble from a no-till cover crop of wheat or rye-vetch, can substantially suppress the dispersal of *Phytophthora capsici* in fumigated soil (54).

Solarization involves the thermal heating of moistened soil by sunlight under clear plastic mulch to temperatures that are lethal to a broad spectrum of soilborne pathogens, insects, and weeds (29). Solarization is generally conducted for 3 to 6 weeks in the hottest part of the year (29). Beneficial microorganisms such as thermophilic organisms and some bacteria survive solarization and act as antagonists against weakened plant pathogens (55). In containerized soil, solarization may be conducted within 1 week under California conditions (63). Soil solarization is a potential alternative practice for control of soilborne pathogens in southern coastal California, Florida, Texas, and North Carolina (12,28,55). Solarization has been used on a wide variety of crops and is effective against a number of important soilborne pathogens, including *Sclerotium rolfsii* (Fig. 6A), *V. dahliae*, and *Phytophthora* species (29,52). In North Carolina, repeated field tests have demonstrated the efficacy of soil solarization for control of southern blight caused by *S. rolfsii* on bell pepper, carrot, and tomato (55,56).

Solarization was as effective as methyl bromide in reducing baited populations of *P. cactorum* and *P. citricola* in strawberry field soils, but reductions in *V. dahliae* populations were not as large (28). Yields were similar between methyl bromide–treated plots and solarized plots, but higher with the fumigant treatment (28). Strawberries are grown as an annual crop in many areas of the United States, and fields have a summer fallow period that is ideal for solarization. Solarization would probably not be as reliable as chemical fumigation for coastal strawberry production areas in California since regional variations in solar radiation occur in coastal areas. Solarization experiments are needed on a wider scale in marginal areas to confirm or refute this idea. In the San Joaquin Valley, where temperatures are higher, solarization might be a viable alternative; but currently most strawberry acreage in California is in coastal areas (6). Soil temperature modeling studies are currently being conducted on a regional basis in California with a model developed at North Carolina State University (78). This work may potentially increase the use of solarization as a pest control strategy in California and elsewhere (James Stapleton, University of California, Davis, *personal communication*).

Florida uses more methyl bromide in tomato production than any other state for control of a number of soilborne pathogens, including *Fusarium oxysporum* f. sp. *solani* (Fig. 6B), *Pseudomonas solanacearum* (Fig. 6C), root-knot nematodes (Fig. 6D), nutsedge, and other weeds (69). In 1994, soil solarization was compared with methyl bromide/chloropicrin for control of soilborne pathogens of tomato (12). Soil solarization significantly reduced densities of *Phytophthora nicotianae* and *Pseudomonas solanacearum* down to depths of 25 and 15 cm, respectively (12). However, *Fusarium oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *radicis-lycopersici* were reduced only in the upper 5 cm of soil by solarization (12). This poses a problem since the *Fusarium* species can rapidly recolonize soils. In contrast, fumigation with methyl bromide reduced levels of the pathogens to 35 cm (12). Incorporation of biological control organisms into solarized soils after solarization may improve control of *Fusarium* diseases (30). Specific nonpathogenic isolates of *F. oxysporum* consistently reduced disease by 50 to 80% when transplant mixes were treated with the antagonists. These isolates are currently being field tested in Florida in fields with a history of Fusarium wilt (R. Larkin, USDA, Beltsville, MD, *personal communication*).

Solarization of compost-amended soils was highly effective at reducing populations of root-knot nematode on lettuce (22). Soils solarized after incorporation of cabbage residues produced volatile compounds that effectively suppressed *Pythium ultimum* and *S. rolfsii* (22). Alcohols, aldehydes, sulfides, and isothiocyanates were produced in heated soil containing cabbage residues. The cabbage residues were dried and ground and amended to soil prior to heating.

Electrical heating can reduce the incidence of soilborne pathogens in nursery soils. Steam has been traditionally used in nursery production systems but does not kill *Fusarium* spores present deep in soils (36). Ohmic heating involves passing an electrical current between an anode and a cathode in the soil. Heat is generated due to the soil's resistance to the current flow. Steel rods are driven in soil and act as anode and cathode arrays. Preliminary abstracts from the research indicate that Ohmic heating was more effective than steam treatment for reduction of *Fusarium* spores present deep in soil (36). This technology has been used in greenhouse systems, but large-scale applications for field use need further research.

Organic amendments may provide another means of suppressing plant pathogens and improving soil quality (31,74). Organic growers use manures and cover

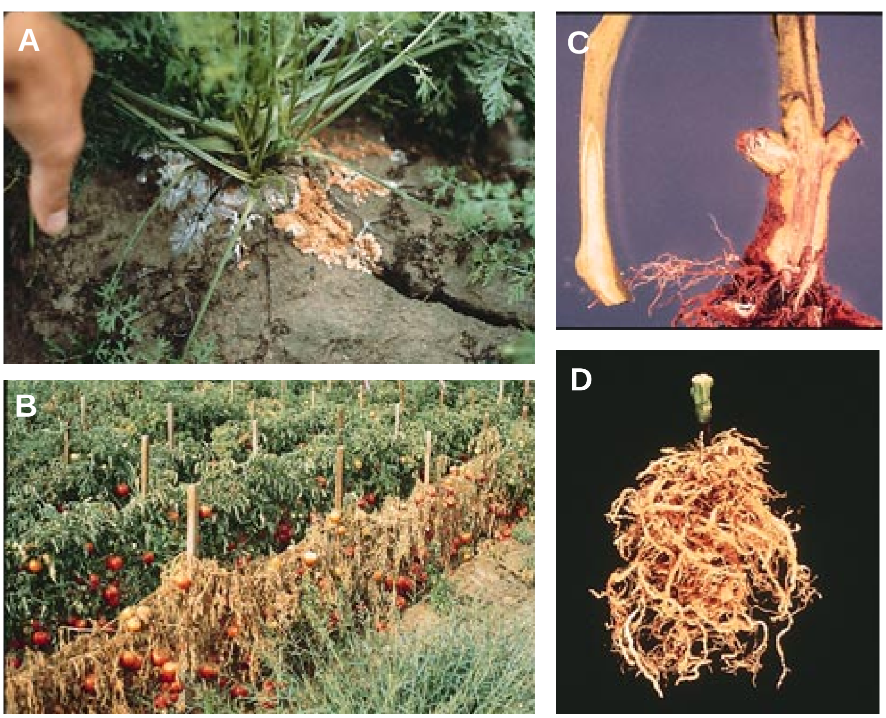

Fig. 6. Disease caused by (A) *Sclerotium rolfsii* on carrots. Sclerotia and mycelium present at the base of the plant. (B) Fusarium wilt caused by *Fusarium oxysporum* f. sp. *lycopersici* on tomato. (C) Internal stem discoloration in tomato caused by the bacterial wilt pathogen *Pseudomonas solanacearum*. (D) Root-knot nematode caused by *Meloidogyne incognita* on tomato roots.

crops as sources of nutrients. Organic strawberry production systems are economically viable since price premiums are obtained even though yields are not as high as in conventional fumigated fields (6,25). In a study of conventional and organic tomato production systems in California, Phytophthora root rot on tomatoes was lowest in soils with highest organic matter content and highest soil microbial activity (74,76). Soils with a diversity of beneficial microorganisms are more suppressive to pathogens and pests than are soils that have little or no biological diversity. In the coastal plains region of North Carolina, large-scale swine production facilities are located adjacent to vegetable farms. Most of these farms contain soil that has been depleted of organic matter. We are currently testing swine manures for suppression of soilborne plant pathogens in tomato production systems (J. Ristaino and L. R. Bulluck, *unpublished*).

Incorporation of biological control organisms into solarized, fumigated, or nontreated soils also shows promise for control of a number of soilborne pathogens (14). Alginate bran prill formulations of *Gliocladium virens* incorporated into nontreated or solarized soils effectively controlled southern blight caused by *S. rolfsii* to depths of 30 cm in field soils in repeated studies (55,56). Application of the antagonists *Talaromyces flavus* and *Gliocladium roseum* in combination with low rates of fumigation with Vapam (metam-sodium) reduced the incidence of Verticillium wilt on eggplant (21).

Table 4. Biopesticides registered by the Division of Biopesticides at the Environmental Protection Agency with efficacy against soilborne and postharvest pathogens

Microbe and trade name	Pest and crop
Agrobacterium radiobacter GallTrol-A	Crown gall caused by *A. tumefaciens* on fruit, nut, and ornamental nursery stock.
Bacillus subtilis GBO3 Kodiak - Gus 2000 Biological fungicide	*Rhizoctonia solani, Fusarium* spp., *Alternaria* spp., and *Aspergillus* spp. - seed treatment on all crop seed.
Bacillus subtilis MBI 600 Epic - Gus 376 Concentrate Biological Fungicide	*Rhizoctonia solani, Fusarium* spp., *Alternaria* spp., and *Aspergillus* spp. - seed treatment on corn, cotton seed, pod vegetables, peanuts, soybean, wheat, and barley.
Candidia oleophila I-182 Aspire	*Botrytis* spp. and *Penicillium* spp. on citrus and pome fruits.
Gliocladium virens GL-21 SoilGard	*Pythium* and *Rhizoctonia* in greenhouse soilless potting mixes and soils. Efficacy also against *Sclerotium rolfsii* in field but not currently registered for this use.
Myrothecium verrucaria DiTerra	Nematodes including *Meloidogyne* spp., *Heterodera/Globodera* (cyst), *Pratylenchus* spp. (Lesion), *Tylenchulus semipenetrans* (citrus), *Trichodorus* spp. (stubby-root), *Xiphinema* spp. (Dagger) and other tylenchid nematodes of all food, fiber, and ornamental crops.
Pseudomonas fluorescens EG-1053 Dagger	*Pythium* and *Rhizoctonia* on cotton.
Pseudomonas fluorescens NCIB 12089 Victus	Bacterial blotch of mushroom caused by *Pseudomonas tolaasii.* Applied to compost beds.
Burkholderia (Pseudomonas) cepacia type Wisconsin Deny (formerly Blue Circle) SMP PcpWi	*Rhizoctonia, Pythium,* and *Fusarium* spp. and lesion, spiral, lance, and sting nematodes on alfalfa, beans, canola, carrot, clovers, cole crops, corn, cotton, grain, lettuce, melons, potatoes, squash, sugar beet, sunflower, sorghum, soybeans, and tomatoes.
Pseudomonas syringae ECC-10, ESC-11 Bio-Save 10 Bio-Save 11	*Penicillium expansum, P. italicum, P. digitatum, Botrytis cinerea, Mucor piriformis,* and *Geotrichum candidum* for use on apples, lemons, grapefruits, pears, and oranges to control fruit rots during storage.
Streptomyces griseoviridis K61 Mycostop	*Fusarium, Alternaria, Botrytis, Phomopsis, Pythium,* and *Phytophthora* spp. on field crops including beans, cotton, peas, sorghum, soybeans, wheat, and on vegetables and ornamental crops in the field and greenhouse.
Trichoderma harzianum T-22 (KRL-AG2) Rootshield Biotrek (formerly F-Stop Biological Fungicide Concentrate and Seed Protectant)	*Pythium, Rhizoctonia solani, Fusarium* spp., and *Sclerotinia homoeocarpa* on beans, cabbage, corn, cotton, cucumbers, greenhouse ornamentals, peanuts, potatoes, sorghum, soybeans, sugar beets, tomatoes, and turf.

There are currently 13 biopesticides registered by the Biopesticides and Pollution Prevention Division of the EPA that are targeted for soilborne or postharvest pathogens (Table 4). In 1995, 20 new biopesticides were registered by EPA, and the agency has placed low-risk pesticides on the fast track for registration. SoilGard (formerly GlioGard) was the first fungal biological control agent registered with the EPA. It contains chlamydospores of the fungus *Gliocladium virens*. This beneficial antagonist has activity against *Pythium* and *Rhizoctonia* in greenhouse potting mixes and against *S. rolfsii* in the field (33). Worldwide, there are 40 biocontrol products commercially available to control plant diseases; however, many of these are not currently registered in the United States (33). Many of these biocontrol organisms have broad-spectrum activity against a wide range of pathogens. For instance, *Trichoderma* species control species of *Armillaria, Botrytis, Chondrostereum, Colletotrichum, Fulvia, Monilia, Nectria, Phytophthora, Plasmopara, Pseudoperonospora, Pythium, Rhizoctonia, Rhizopus, Sclerotinia, Sclerotium, Verticillium,* and wood rot fungi (33). *Myrothecium verrucaria* (DiTerra) is a new biological nematicide with activity against a number of important nematodes species (Table 4). Biological control organisms can be used as part of an integrated pest management program to target specific pathogens and pests. Most of the biological control organisms currently on the market are targeted for soilborne and postharvest diseases. Some of these organisms could be used as alternatives to methyl bromide to target problem areas in fields (33).

Future Outlook

The development of sustainable production practices for strawberries, tomatoes, and other high-value fruit and vegetable crops without reliance on methyl bromide will require the input of knowledgeable and progressive growers, industry representatives, scientists, environmentalists, regulatory agencies, and policymakers. All these groups need to come to the bargaining table and consider the short-term and long-term impacts of their actions on the environment. The courtroom and the conference room are currently being used to resolve issues surrounding the use of methyl bromide. The debate over methyl bromide has often resulted in polarized views by environmentalists, industry groups, grower groups, regulatory agencies, and scientists. Agricultural scientists have an important role to play in providing relevant data to policymakers.

A number of creative, ecologically based approaches to disease and pest management have emerged from the debate over methyl bromide use that may not have been developed without the impending loss of this compound. The formation of the Biopesticides and Pollution Prevention Division in November 1994 at the EPA and the registration of 36 new biopesticides since 1995 are positive signs. Industry incentives are needed to develop low-risk pesticides and biologically based pesticides. The USDA has mobilized research resources to develop alternatives to methyl bromide. Priority registration of low-risk pesticides and biopesticides has been initiated at the EPA. Grower incentives including special subsidies that encourage use of low-risk pesticides and biologically based pest management strategies are also needed. Could green grower awards that utilize "moral persuasion" be enacted by partnerships between the USDA and EPA to reward growers who make the move to alternative, low-risk strategies for disease and pest management?

Research funded by the USDA and EPA has provided opportunities for development of feasible alternatives to methyl bromide. Recently, the agencies have jointly sponsored a yearly Methyl Bromide Alternatives and Emissions Reduction meeting. Many published research projects and abstracts from yet-to-be-published work have been shared at these meetings. Viable alternatives and technologies that lead to reduced emissions are on the horizon. Additional funding is needed to conduct IPM demonstration projects on commercial grower farms. Industry, government, and university partnerships could lead to technological successes that any partner alone might not achieve. These approaches could redirect conventional agriculture toward more sustainable, environmentally friendly methods of food production that minimize global ecosystem impact in the twenty-first century and beyond (46).

Acknowledgments

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