United States
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Office of Air and Radiation
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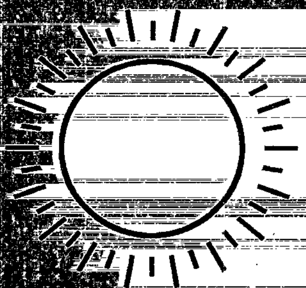
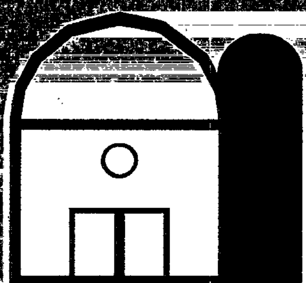
EPA **Stratospheric Ozone Protection**

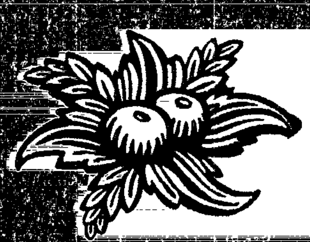


Alternatives to Methyl Bromide

Ten Case Studies

Soil, Commodity, and Structural Use





— Volume Three —

EPA

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Stratospheric Ozone Protection

Methyl Bromide *Alternatives*
10 Case Studies --- Volume 3

Foreword

This is the third EPA publication of case studies describing alternatives to the use of the pesticide, methyl bromide. As with the first two volumes of case studies, the alternatives listed here were chosen because of their level of development and availability, and should not be construed to be the only alternatives to methyl bromide.

The alternatives described in this document are in response to the fact that methyl bromide is a significant stratospheric ozone depleting chemical, and therefore contributes to environmental degradation. Because of this, methyl bromide will soon be phased out both in the United States and internationally. This pesticide has been used since the early 1960's, primarily as a pre-plant soil fumigant (often for high-value crops such as strawberries and tomatoes), as well as a post-harvest (commodity) and structural treatment.

In it's current use pattern, methyl bromide is an important production component for many in the agricultural community. Since effective pest management is essential to field agricultural production, commodity storage, natural resource protection, and public health, alternatives to methyl bromide which are efficacious, cost effective, and environmentally sound must be available before methyl bromide is phased out. To assist in this effort, EPA has published this document, as well as the first two sets of case studies, and has committed to publish additional case studies.

The alternative materials and methods discussed in these case studies are not intended to be complete replacements for methyl bromide, but tools which are efficacious against the pests that are currently controlled by this pesticide. Many of the alternatives described herein are part of an overall integrated pest management system, and must be combined with other pest control tools to achieve an economically viable level of management.

All efforts were made to insure that the information in this document is correct and factual. Comments on this document, as well as your experiences with these and other alternatives to methyl bromide, are welcome via the contacts listed below.

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Methyl Bromide *Alternative* Case Study

Disease Suppressive Compost as an Alternative to Methyl Bromide

Disease suppressive compost can be an effective and viable alternative to methyl bromide use in some nursery production systems, and when used in combination with integrated pest management practices. Disease suppressive compost also has potential for replacing methyl bromide use in the production of fruit and vegetable crops. Diseases that have been shown to be effectively suppressed by compost use include those caused by *Fusarium*, *Phytophthora, Pythium*, and *Rhizoctonia solani.* In addition to suppressing the spread of disease at nurseries and in field crops, disease suppressive compost mixes provide nutrients and organic matter, thereby eliminating or reducing the need for fertilizer additions or use of expensive peat mixes. Compost can also create soil which allows for better water transmission, thereby decreasing the potential for disease development. Use of compost is particularly valuable as a way to utilize what would often be considered waste products: tree barks, municipal solid waste components, green wastes, peanut hulls, and sewage sludge. While compost generally does not contain toxic or potentially harmful substances, it is critical that compost made from sewage sludge and related municipal or animal waste must undergo testing on a regular basis, and its use carefully monitored to ensure that it will not pose any risks to human health or environmental quality. However, in general, disease suppressive compost does not require any special care during use and handling, and therefore eliminates the need for the re-entry period necessary when using methyl bromide.

While the use of disease suppressive compost as a pest control tool is theoretically sound, the science is still new and not clearly understood. It should be noted that most greenhouse operations do not have the equipment necessary to fully adopt this technology. In addition, large-scale field operations may not give consistent results, as a number of factors (including the amount of compost necessary to suppress disease) need additional research.

Benefits of Disease Suppressive Compost

- ✓ *Can replace methyl bromide use in container mixes*
- ✓ *Inexpensive and readily available*
- ✓ *Utilizes materials that would normally be landfilled*
- ✓ *Reduces need for fertilizers and peat*
- ✓ *Provides better porosity than soil*
- ✓ *Does not normally pose risks to human health during use or handling*

Disease suppressive compost is available to a limited extent, and is currently in use in some greenhouses and nurseries in the United States. Several companies sell disease suppressive compost growing media mixes that already include necessary fertilizers and wetting agents. These mixes have virtually eradicated the use of expensive fungicide drenches and fumigants like methyl bromide in the greenhouses and nurseries which are using these materials. Research is currently being conducted to determine the specific interactions that make compost effective and to determine its usefulness in field applications.

Although there are currently no standards regulating the manufacture of disease suppressive compost, the process by which it is made and the inoculations some mixes receive have been shown to be critical to their effectiveness against certain pathogens. For disease suppressive composts to be marketed as natural pesticides, the U.S. Environmental Protection Agency is requiring that they be registered and undergo health and safety testing (Segall 1995). In addition, compost sources tend to be extemely variable with regard to beneficial microorganism abundance, pathogen presence, and salinity.

Development of Disease Suppressive Compost

There are three main phases in the production of compost. The first phase occurs during the first few days when temperatures rise and sugars and other easily biodegradable substances are consumed. Over the next several weeks, in the second phase, the temperature range increases and cellulose and other less biodegradable substances, pathogens, and some biocontrol agents are destroyed. In the third phase, temperatures and decomposition rates decline as the supply of readily biodegradable substances becomes limited. The drop in temperature allows for microorganisms (e.g. *Bacillus*, *Enterobacter*, *Flavobacterium balustinum*, *Pseudomonas*, and *Streptomyces)* to recolonize the compost's interior layers, thereby creating the natural suppressiveness.

There are two primary mechanisms by which the colonies of biocontrol organisms in compost combat disease: general suppression and specific suppression. General suppression occurs when a high-microbial activity environment is created in which the germination of pathogen propagules is inhibited. Specific suppression involves the action of a specific microbial agent in suppressing a specific pathogen. This can be achieved by inoculating the compost with the desired microbial agent (Hoitink 1993).

To ensure that compost will provide the required suppressive qualities, it has been determined that the composting process must be carefully monitored (Hoitink 1991 and 1993, Hoitink and Grebus 1994). Heat levels and anaerobic conditions must be maintained throughout the composting cycle and the compost should be allowed to mature properly before use. Studies have shown that immature compost is generally not as effective as mature compost at suppressing disease (Quarles and Grossman 1995). Assays currently exist that allow the compost to be monitored and evaluated for its disease suppressive capabilities. In addition, some states, most notably Georgia are taking steps to regulate the compost industry by creating standards that all compost manufacturers must meet in order to ensure the quality and performance of their compost.

Research Findings

The discovery that compost can be naturally disease suppressive was made when some nurseries began using composted wood wastes in an effort to reduce their use of expensive and increasingly scarce peat. As a result, plants grown in the composted mixes showed more vigorous growth and *Phytophthora* appeared to be suppressed (Hoitink and Grebus 1994). These findings triggered formal research that further showed the effectiveness of disease suppressive compost as a viable replacement for methyl bromide and other fungicides. Composted mixes that have been shown to have disease suppressive qualities include those based on tree barks, green wastes, and sewage sludge (Quarles and Grossman 1995).

Because disease suppressive compost growing media has been found to be a viable alternative to chemical fungicides (methyl bromide) at nurseries, extensive research is now being conducted to determine whether or not disease suppressive composts can also replace fungicide use in field fruit and vegetable crops. Preliminary research is already showing that this is a reasonable possibility. Some of the findings in this area are summarized below:

- Dr. Sally Miller of Ohio State University has observed that use of composted yard waste can cause pepper plants to grow more vigorously. She believes that use of compost in combination with hilling will suppress *Phytophthora* in peppers (Logsdon 1993).

- Nancy Roe of the University of Florida has experimented with various composts and found that peppers grown using a municipal solid waste or wood chip compost as a mulch have higher survival rates than those grown on white polyethylene (Logsdon 1993). This finding is supported by an additional study by Kim et al. that showed that chitosan and crab shell waste can be effective at controlling *Phytophthora* stem rot in bell pepper (Kim *et al.* 1996).

- Results from a study in a San Joaquin Valley peach orchard showed that incidence of brown rot was notably higher in peach tree plots unamended or grown conventionally than in plots that were amended with urban yard waste compost (Anonymous 1995).

- Vegetable seedlings grown in composted media were found to develop faster and become stronger more productive plants than plants grown with conventional methods in a study performed by Dr. Herbert Bryan at the University of Florida (Logsdon 1993).

Cost of Disease Suppressive Compost

Costs associated with growing plants in nurseries are attributable to the purchase of growing media, fertilizer, wetting agents, fungicides and herbicides, including methyl bromide, and to labor. Using disease suppressive compost generally reduces fertilizer inputs and often results in a reduction in labor costs due to the elimination of labor needed to utilize fumigants and the subsequent elimination of a re-entry period in which workers must wait to have access to a fumigated field or area. Therefore, the primary difference in cost between use of disease suppressive composts versus other growing media is the cost of the material itself. Fumigated container media range in cost from $18 to $60 per cubic yard plus the cost of methyl bromide which is $1.64 per cubic yard (Asgrow 1995, Great Lakes 1995). A cubic yard of disease suppressive compost growing media costs approximately $38 per cubic yard. Cost information is summarized in Table 1. Manufacturers of disease suppressive compost are attempting to ensure that their products are approximately equal or less in cost to other growing media that require fumigation (Southern Importers Inc 1996).

Table 1. Comparison of Costs Among Container Media Used at Nurseries

	Composted Mix	Uncomposted Bark Mix	Uncomposted Peat Mix
Typical price per cu.yd.	$30	$12	$56
Plus:			
Fertilizer	$6	$10	$6
Methyl bromide	$0	$1.64	$1.64
Lime	$0	$1	$0
Shrinkage	$2 (6%)	$4 (30%)	$14 (25%)
Actual cost per cu. yd.	$38.00	$28.64	$77.64

Sources: BioComp 1996, Asgrow 1995, Great Lakes 1995.

Costs associated with using disease suppressive composts in field applications include the cost of the compost plus costs resulting from implementation of integrated pest management and other low-input organic practices. Studies by Gliessman et al. (1990, 1994, 1996) compare conventional and organic methods to grow strawberries. The conventional method includes using methyl bromide to fumigate the soil. The organic method includes using compost in combination with integrated pest management approaches to take the place of the methyl bromide. Results from this study to date show that organic yields relative to conventional yields of strawberries were 39 percent lower in the first year, 30 percent in the second year, and 28 percent in the third year (Gliessman *et al.* 1996).

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Methyl Bromide *Alternative* Case Study

Flooding As An Alternative to Pre-plant Methyl Bromide Fumigation

Flooding can be a viable alternative to methyl bromide as a preplant soil fumigation in flat, low-lying areas rich in mineral soils where there are seasonally high water tables (at least 4-6 feet from the surface) and abundant water supplies (e.g., Florida and in some parts of California). Approximately 66 percent of Florida soils have high water tables, of which an estimated 30 to 50 percent would be amenable to water table/flooding management practices (20 percent of all the land surface in Florida) (Buol 1973). Areas in Florida where flooding could be used as an alternative to methyl bromide include the Florida Peninsula (e.g., potatoes, tomatoes, bell peppers, and eggplants in Hastings and Bradenton, Florida) and east coast areas south of Vero Beach. Areas not suitable for flooding include northwest Florida and the Florida panhandle (Allen and Sotomayor 1996).

Benefits of Flooding

- ✓ *Highly effective against soil-borne pests and pathogens*
- ✓ *Eliminates the need for soil fumigants*
- ✓ *Conserves soil carbon*
- ✓ *Increases levels of mineral nutrients in soils*
- ✓ *Promotes biological control*
- ✓ *Leaves no toxic residues*
- ✓ *Highly efficient and cost-effective pest control method*
- ✓ *Can be combined with other pest management practices*

Flooding is believed to be as effective as methyl bromide for the control of some soil-borne pests and pathogens, particularly nematodes and non-aquatic weeds. Flooding also leaves no toxic residues. With the proper soil and water-availability conditions, flooding can be used to create anaerobic (little to no available oxygen) soil conditions which are followed by drainage to provide an aerated (available oxygen) root environment. This sufficiently will alter the soil environment in way that results in conditions which are unfavorable to pests. It will also conserve carbon in organic matter by slowing decomposition, increases the availability of certain micronutrients (e.g., magnesium and iodine) to crop plants, and changes the soil microflora to favor biological pest control (Snyder 1987). Flooding could be used in conjunction with other control practices, including organic soil amendments and soil solarization. As an added benefit, instead of leaving flooded fields fallow, it may be possible to grow cash crops (such as rice) on flooded fields (Allen and Sotomayor 1996).

In general, the flooding of soils significantly decreases soil oxygen supplies, causing an unfavorable environment for most pests, pathogens, and weeds (Maas 1987). Alternating anaerobic and aerobic conditions through periodic flooding, can cause a decrease in nematode populations (Dunn and Noling 1995, Wallace 1956), while longer periods of flooding have been found to be more effective in the control of weeds (Reddy and Patrick 1975 and 1976). Stover (1979) achieved nematode control by flooding and noted that for Florida organic soils, two weeks of flooding followed by two weeks of drainage, drying, and disking was as effective in controlling nematodes as continuous flooding for 9 months.

Flooding has been recognized as a viable means for controlling plant parasitic nematodes for more than 70 years. As early as 1907, Ernst Bessey (1911) observed control of root-knot nematodes on vegetables in flooded fields on islands which once existed in Lake Okeechobee (Synder 1987). More recent research indicates that proper water management and flooding practices can reduce nematodes and other pests in a variety of crops, including rice, bananas, corn, soybean, milo, sugarcane, tomatoes, bell papers, and eggplant (Hollis and Rodriguez-Kabana 1966, Rodriguez-Kabana and Hollis 1965, Muller *et al.* 1992, Muller and Van Aartrijk 1992). For example, flooding has been shown to be effective in the control of Panama disease and nematodes in bananas (Stover 1962, Maas 1969).

Many vegetable crops in Florida (e.g., eggplants, tomatoes) are grown in high water table soils that must be drained and managed to prevent anoxic rooting conditions. These high-value crops are produced in Florida during the fall, winter, and spring seasons. In the summer, however, fields are either fallowed or managed at a low scale because of seasonally heavy rainfall. This system of cropping followed by fallow may provide an opportunity for the development of specific management technologies during the summer off-season, including prolonged soil flooding (possibly with a water tolerant crop such as rice).

Current Research

Researchers at the USDA, Agricultural Research Service (ARS) in Gainesville, Florida are conducting experiments to assess the efficacy of soil water-logging for the control of root-knot nematodes (*Meloidogyne arenaria*) and purple nutsedge (*Cyperus rotundus L.*) populations. Specific issues being investigated regarding the effectiveness of flooding for the control of nutsedge include: 1) how water-logging affects sprouting of the nutsedge tuber, and 2) once the nutsedge is established, what becomes of it after flooding. Researchers are working to determine if tubers remain in a dormant, but viable stage during flooding (after which they can proliferate when appropriate conditions occur) or if the tubers die because of low soil redox potentials and unsuitable soil conditions resulting from flooding. Recent results indicate that purple nutsedge is suppressed in flooded rice fields. Additional research will be necessary to determine if nutsedge will still be suppressed during the subsequent cropping periods.

Because nematodes are aerobic organisms, they are controlled by asphyxiation in flooded fields, and by a build-up of H_2S and other chemicals produced under anaerobic soil conditions that result from microbial fermentation reactions (Maas 1987, Hollis and Rodriguez-Kabana 1966).

Other changes in soil ecology can occur that limit root-knot nematode reproduction or stimulate predation by beneficial soil organisms (Sotomayor and Allen 1996, Allen and Sotomayor 1996), however, additional research is needed to determine the exact response of nematodes to long-term flooding. Since high temperatures during flooding are more effective in controlling root-knot nematodes than lower temperatures (Stover 1979), combinations of treatments (alternate flooding, solarization, and high applications of fresh or composted organic matter) may prove to be more effective than long-term flooding alone in the control of nematodes.

Important Considerations for Flooding

When using flooding as a pest control measure, some basic processes should be considered (Snyder 1987):

- ***Time or Season of Flooding:*** In general, flooding is more effective at higher ambient air and soil temperatures. This places seasonal and geographic constraints on flooding. For example, flooding will require additional time to be effective at temperatures below 20°C (68°F) -- four to 6 weeks of flooding is effective in warm weather, while 6 to 10 weeks may be required to achieve effective control in cooler seasons.
- ***Alternate Flooding with Disking:*** Because some pathogens can survive flooding by persisting on plant debris in the soil-water interface or on the soil surface during draining; pests may be more easily eliminated if they are disked deep into soils before fields are reflooded.
- ***Water Depth:*** Most fallow flooding involves flooding to a depth of 10 cm (4 inches) to 40 cm (16 inches).
- ***Rice Culture:*** Because rice can be grown on fields flooded for pest and pathogen control, flooded fields can both generate revenue and provide opportunities for more efficient land/water use.

Costs

Flooding can be a viable and cost-effective alternative to methyl bromide in some situations. Flooding can be many times less expensive than methyl bromide fumigation, however, capital costs which may be necessary to achieve good pest control from flooding include those associated construction of retention/detention ponds, digging perimeter ditches and leveling fields, installing subsurface drains for reversible-flow drainage/irrigation/flooding water control, installing vertical barriers of low-density-polyethylene around the water management unit perimeters (i.e., land fill liners 3 to 5 feet below the soil surface to contain the flood waters), and installing power, pumps, and a pipe system (Allen and Sotomayor 1996). In considering the costs associated with this technique, it is also important to consider that water costs vary considerably from region to region. Regions with readily available water supplies will have lower costs, than areas where water must be pumped from wells or transported long distances.

Table 1. Cost of Flooding vs. Methyl Bromide as a Preplant Fumigant.

Costs ($/acre)	Treatment #1 Flooding	Treatment #2 Methyl Bromide
Capital	60	54
Labor/Operating	4-39	436
Materials (Water/Chemical)	0-41	1,936
TOTAL	64-140	2,426

Sources: Allen and Sotomayor 1996, Williams *et al.* 1992, Cooke *et al.* 1996, Gregory and Winn 1996, Giesler and Salassi 1995, Lagunas-Solar 1996, Onitsuka Greenhouse 1996.

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Methyl Bromide *Alternative* Case Study

Plant Grafting as a Tool to Help Reduce the Need for Soil Fumigation with Methyl Bromide

Expanding the use of resistant rootstocks, in combination with Integrated Pest Management (IPM) practices, may help to reduce the need for soil fumigation with methyl bromide for many crops. Grafting currently is used in commercial agricultural production to achieve higher yielding field and greenhouse crops, repair damaged sections of a plant, increase temperature or salinity tolerance, produce higher yielding varieties (including dwarf varieties), and extend the duration of economical harvest time. Research is being conducted to identify disease resistant germplasm for a variety of crops that currently receive methyl bromide treatments at planting. It is believed that germplasm with resistant traits may be useful for grafting, as well as the development of new cultivars. Specifically, with regard to reducing the need for soil fumigation, the primary use of grafting will be to increase disease and nematode resistance through the use of select rootstock with known resistance to soilborne pests.

Benefits of Grafting

- ✓ *Increases disease and nematode resistance*
- ✓ *Helps to increase yields, extend plant life, and increase tolerance to temperature and salinity*
- ✓ *Is useful in both nursery and vegetable applications*
- ✓ *Can be used in conjunction with Integrated Pest Management (IPM) practices*

Commercialization of cultivars with resistance to diseases caused by nematodes (e.g., *Meloidogyne incognita*) and fungi (e.g., *Fusarium oxysporum*) has been achieved by screening various plant species to identify traits of potentially resistant stocks that may be useful for grafting, and through breeding programs. In addition, field trials have been conducted to assess whether identified germplasm increases the ability of crops to withstand soil infestation as well as whether the crop performance will be commercially acceptable (i.e., yield, compatibility, anchorage). Finally, commercialization has been advanced through cooperation with nurseries and growers to determine the factors affecting commercial adoption of new rootstocks. Current research efforts to develop additional resistant germplasm for use in grafting for many of the crops currently treated with methyl bromide may lead to an increased ability to minimize or prevent yield losses from soil pest pressure (Ledbetter 1996b, Ledbetter 1996a, McKenry and Kretsch 1995, Lee 1994).

Grafting Techniques and Applications

Plant grafting is a propagation technique whereby two portions of plant which have similar organic texture are joined in such a manner so as to continue their development as a single plant. There are many methods of grafting plants, each involving the joining of the leaf-bearing part (scion) of one plant with the rootstock of another. Grafting methods include such techniques as apical-wedge grafting, whip-and-tongue grafting, splice grafting, flat grafting, saddle grafting, bud grafting, hole insertion grafting, tongue approach grafting, and cleft grafting.

Grafting can be used for nursery, orchard, vineyard, and vegetable crops. The technique can be particularly useful when there is a specific infestation problem that can be controlled with available rootstocks, and in situations where disease problems arise after the orchard or vineyard has already been established (McKenry 1995). In general, grafting is a technology that is readily accessible to commercial suppliers of nursery and vegetable transplants, can be easily taught to field technicians, and has a relatively low cost (Ledbetter 1996b, Rodriguez-Kabana 1995). To enhance the use of grafting, commercial nurseries and growers will need continued access to new resistant germplasm for field testing and commercial trials. In addition, mechanized grafting approaches are being developed that rely on small portable machines that can perform the basic cutting and joining procedures (Maynard 1996).

Currently, grafted plants are widely used in the United States for a variety of orchard and vineyard crops (e.g., apples, grapes). Other countries also have experience with grafting techniques. For example, in Japan, where land use is intensive and the availability of new farmland is scarce, almost 95 percent of the watermelons (*Citrullus lamanis*), Oriental melons (*Cucumis melo* var. *makuwa*), greenhouse cucumbers (*Cucumis sativus*), and solanaceous crops are grafted before being transplanted to the field or greenhouse. In 1992, Japan cultivated almost 24,000 hectares of grafted watermelon seedlings in the field, and over 3,000 hectares in the greenhouse. Most of the Oriental melons are grafted to squash rootstocks (*Curcurbita* spp.). Watermelons and cucumbers are grafted with either gourd stocks (*Lagernaria siceraria* or *C. ficifolia*) or mixed hybrids (e.g., *C. maxima* x *C. moschata*) (Lee 1994).

Research, Development, and Use of Resistant Rootstocks

The following research programs and commercial applications further demonstrate the potential for commercial use of grafting as a means to reduce soil fumigation with methyl bromide:

- At the U.S. Department of Agriculture/Agricultural Research Service (USDA/ARS) Horticultural Crops Research Laboratory in Fresno, California, over 200 *Prunus* accessions were screened for resistance traits that showed promise for grafting. Germplasm with resistance to root lesion nematodes (*Pratylenchus vulnus*) were identified. To determine the acceptability of these rootstocks for commercial production, several additional factors are being considered, including rootstock performance in the nursery (e.g., vigor, tree anchorage, water use efficiency, and fruit production) and graft compatibility between the rootstock and the fruit bearing portion of the tree (Ledbetter 1996).

- At the USDA/ARS in Davis, California, researchers are evaluating clones, selections, and hybrids of various germplasm to identify superior resistance to *Phytophthora* spp. for walnut. Scientists have determined that chinese wingnut is highly resistant to *Phytophthora* affecting walnuts in California. Additional research is being conducted to evaluate graft compatibility and potential for hybridization of Chinese wingnut with English walnut (Anonymous1996).

- At the USDA/ARS in Byron, Georgia, researchers are investigating rootstock resistance to nematodes, including the ring and root-knot nematodes (*Criconemella xenoplax* and *Meloidogyne* spp.), that frequently cause yield losses in peach orchards. To combat diseases caused by these pests and to help reduce reliance on soil fumigation with methyl bromide, researchers have identified a resistant rootstock that has performed well in research and commercial field trials. Results indicate that the efficacy (in terms of tree survival) of the Guardian rootstock on non-fumigated plots was comparable to results on fumigated plots grown with the currently available rootstocks (e.g., Lovell and Nemaguard) (Nyczepir 1995).

- At the University of California, Davis, Dr. H. Andrew Walker and Dr. Jeffrey Granett have evaluated grape rootstocks for resistance to phylloxera in research and commercial settings. The insect pest *Phylloxera vastratix* feeds on grape roots, is quite prolific, and, once established, can rapidly destroy a vineyard. The primary method of controlling this insect in vineyards is through the use of resistant rootstocks (Bentley *et al.* 1996). As a result, numerous rootstocks with proven resistance to phylloxera have been developed and are widely used commercially (Walker and Butzke 1997, Wolpert *et al.* 1992, Walker 1997). According to Walker (1997), "almost all phylloxera resistant rootstocks are composed of *Vitis berlandieri*, *V. riparia* and *V. rupestris* in various combinations. The primary stocks in California are 5C, 110R, 3309C, 101-14Mgt, 1103P, and Freedom. In addition, there are about ten more in general use. Rootstocks are selected based upon the soils, climate and viticultural needs of a particular area."

- Between 1982 and 1991, Dr. Alberto Gomez conducted several extensive grafting studies on melon plants for the University of Valencia in Spain. The studies showed that, for melon plants, grafting will produce a larger yield and enable plants to live longer. These results were based upon a study prepared in 1982, using *Roget* melons grafted over *Curcurbita moschata,* and on a study in 1984 that evaluated the performance of *Tetsukabuto* grafted over *Just* melons. The yield increases achieved through grafting ranged from 30 to 35 percent. Additionally, Dr. Gomez prepared a study to demonstrate the benefits of grafting for watermelons. In 1982, he found that watermelons can be grafted to have a superior resistance to *Fusarium oxysporum niveau* (Gomez 1992).

Costs

Table 1 presents a cost comparison for grafting and standard methyl bromide fumigation for vegetable, orchard, and vineyard crops. The grafting cost estimates are for activities conducted by nurseries to prepare transplant stock for sale to growers. Typically, grafting is performed by agricultural technicians that can process up to 1,000 grafts per day, therefore, the relative impact on the price of the transplant to the grower is small (Ledbetter 1996b). The majority of the costs to nurseries would be to conduct research and development activities after the completion of university research trials. As shown in Table 1, the costs for grafting orchard and vineyard rootstocks is less than the cost of fumigation with methyl bromide. This suggests that grafting technology can be an economical technology to help reduce the need for methyl bromide fumigation for these crops. Costs of grafting for vegetable crops is more expensive than fumigation, however, vegetable grafting costs are expected to decrease as the mechanized grafting technology becomes increasingly commercialized (Maynard 1996).

Table 1. Costs of Grafting and Fumigation for Vegetable and Nursery Crops

Crop	Cost of Grafting (U.S. dollars/plant)	Cost of MeBr Fumigation (U.S. dollars/plant)
Vegetables	1.80 - 2.28	0.41 - 0.92
Orchard	0.05 - 0.06	1.79 - 6.07
Vineyard	1.75	2.14 - 3.33

Sources: Gomez 1992, Ledbetter 1996b, Anonymous 1993, Anonymous 1992.

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Methyl Bromide *Alternative* Case Study

Hydroponics and Soilless Cultures on Artificial Substrates as an Alternative to Methyl Bromide Soil Fumigation

The use of hydroponic technology can be a viable alternative to methyl bromide soil fumigation for greenhouse grown tomatoes, strawberries, cucumbers, peppers, eggplants, and some flowers. Hydroponics allows crop culturing without soil fumigation by providing a system where a majority of a plants nutrient needs are met by mixing water soluble nutrients with water, and eliminating requirements for soil. Hydroponic systems that use only a nutrient solution, are categorized as water culture or solution culture, however, if the nutrient solution is used in combination with solid inert matter (i.e., Rockwool, turf stone, clay granules, sawdust, flexible polyurethane foaming blocks, composed hardwood bark, or peat) to physically support root systems and hold the hydroponic solution, it is categorized as a substrate culture or aggregate culture.

Benefits of Hydroponics and Artificial Substrates

- ✓ *Eliminates the need for soil fumigants*
- ✓ *Absence of competing weeds and soil-borne pests*
- ✓ *Leaves no toxic residues*
- ✓ *Conserves water*
- ✓ *Control over nutrient and oxygen conditions*
- ✓ *Highly efficient and cost-effective pest control method*
- ✓ *Increases crop quality and yield*

If the nutrient solution is recycled, then the system is considered to be a closed hydroponic system. If the solution is discharged after use, it is considered to be an open hydroponic system (Cropking 1996). Hydroponic systems are usually utilized in indoor greenhouses in non-tropical climates, allowing the grower to have control over climate conditions. Specialized hydroponic farming systems in the U.S., Canada, and Europe have demonstrated the technical and economic feasibility of eliminating methyl bromide use in greenhouses and (under certian climate conditions) in open fields (Braun and Supkoff 1994, Anonymous 1992b, Anonymous 1992c).

The advantages of hydroponic or soilless cultures on artificial substrates are: 1) an absence of completing weeds and soilborne pests and toxic residues; 2) water conservation (with recycling systems, hydroponic systems use one tenth the amount of water used in irrigated agriculture); and 3) conditions that can be altered quickly to suit specific crops, various growth stages, and environmental/climate conditions. In addition to nutrients, hydroponics also brings fresh oxygen to the root zone and takes away "off-gases," the waste by-product of the root zone, making it a highly efficient and cost-effective technology (Anonymous 1992a, Cropking 1996). Because nutrients are readily available in hydroponic systems, plants have smaller, more efficient root systems and can spend more energy growing the more valuable above ground stems, foliage, and fruit. Furthermore, growers can space plants closer together, thus producing more agricultural products per a given area, while avoiding competition for scarce nutrients in the rootzone (Hydro Aquatic Technologies 1995, Resh 1993).

All hydroponic systems provide water, nutrients, and oxygen to plants; however, hydroponic systems differ significantly. Several of the many types of hydroponic systems include the following: static air techniques, aeroponic systems, nutrient flow techniques, rockwool slab systems, aquaponic systems, ebb and flow, deep flow techniques, aerated flow techniques, nutrient flow techniques, drip irrigation techniques, root mist techniques, fog feed techniques, subaeration methods, gravity flow feeds, and peat bag culture (Hydro Aquatic Technologies 1996).

Hydroponics in the Netherlands

In 1980, the Netherlands decided to phase-out the use of methyl bromide as a soil fumigant by 1992. The work that was done to achieve this and the alternatives developed provides an important model for phasing out methyl bromide, as well as a number of good alternatives to this pesticide (Anonymous 1992a). The Netherlands was formerly one of Europe's largest users of methyl bromide for soil fumigation. Using this pesticide to control soilborne pests on greenhouse-grown crops such as tomatoes, lettuce, strawberries, cucumbers, sweet peppers, eggplants, as well as nursery crops and cut flowers (only a small amount was used to fumigate soils in field crops). By using alternative cropping methods, such as hydroponics and soilless culture on artificial substrates, growers in the Netherlands have successfully eliminated the risk of infestation by soilborne pests, while increasing crop yield and quality (Methyl Bromide Task Force 1995).

The phase out of methyl bromide allowed the Netherlands to develop greenhouse crop production systems with a number of economic and environmental advantages. For example, both strawberries and cucurbits are successfully grown in greenhouses in the Netherlands using artificial substrates (i.e., peat and Rockwool, respectively) on hanging shelves or on raised shelves outdoors (Sneh *et al.* 1983, Braun and Supkoff 1994). Planting densities in greenhouses are doubled by hanging each tightly-spaced row from cables attached to winches. Alternating rows are then raised and lowered to gain access for tending or harvesting (Methyl Bromide Task Force 1995, Liebman 1994). The hydroponic solution (nutrient rich water) is pumped to the plants using a regulated trickle/drip irrigation system. The wastewater from the roots is recaptured, sterilized, and reused to reduce environmental waste and contamination, and to conserve water. Growers sterilize the recycled nutrient water by heating it to about 90°C (194°F) (Anonymous 1992b, Anonymous 1992c). Substrates are sterilized for reuse using steam (USDA 1996, Liebman 1994).

Strawberries

There are approximately 2,072 ha of strawberries grown in the Netherlands. In 1993, production of greenhouse strawberries in the Netherlands was approximately 31,000 tonnes, of which almost half (14,000 tonnes) was from greenhouse production. Peat bags are primarily used in the production of greenhouse strawberries and to cultivate new runners. Young plants are exposed to short-day lighting to stimulate bud formation, and are then either placed in greenhouse substrates (or outdoors) to fruit or are stored for up to eight months at -2°C in a dormant state poised for flower development (Methyl Bromide Task Force 1995). In warmer weather, mature plants may produce strawberries within 60 days without the use of methyl bromide or any other soil fumigant (Anonymous 1992b, Anonymous 1992c).

Cucurbits

Approximately 1,020 ha of cucurbits (i.e., cucumbers, eggplant, and melons) are grown in the Netherlands. In the current post methyl bromide period, more than 90 percent of the cucurbits were grown on artificial substrates in temperature controlled greenhouses, while the remainder were grown in steam sterilized soil. The main cucurbit crop is cucumber, of which 484,720 tonnes were produced in greenhouses in 1993. The area used to grow cucumbers has remained constant since 1970, however, the area of crops grown on artificial substrates has increased from 272 ha in 1991 to 935 ha in 1994 (Banks 1993).

Costs

Hydroponics is an economically viable alternative to methyl bromide fumigation for a number of crops, including strawberries and cucumbers (See Table 1a and b). Although materials and total costs are higher for hydroponic systems compared to methyl bromide fumigation, operating costs are generally lower (except for double crops of strawberries) and overall crop yields far exceed those obtained with methyl bromide. In general, strawberry and cucurbit yields using artificial substrates are double those obtained using soil. In fact, production on one greenhouse acre is equivalent to that on 8 to 10 field acres with long term production costs being much lower (Rosselle 1996). Adjusting costs ($/kg yield) to take into account crop yield renders costs comparable to that of methyl bromide fumigation. Furthermore, hydroponic costs are expected to decrease as sales continue to increase and these systems become more commercialized (Rosselle 1996, USDA 1996).

Other economic advantages of hydroponics include a potentially fast and flexible hydroponic cropping period, which allows growers to quickly change production to take advantage of market conditions. Because of the short cropping period (4 months total) and the development of cold storage techniques, growers can increase or decrease production depending on prices, or select alternative crops if crop prices are not favorable. By marketing produce when the prices are at a premium, growers can pay off the initial capital investments in as little as 3 years (Methyl Bromide Task Force 1995, Liebman 1994). In fact, Dutch growers have already reported a 10 to 20 percent increase in cash income with the use of these artificial substrates (USDA 1996, Banks 1993). Lastly, unlike conventional crops, growers also have the option of "double cropping" to produce 2 crops/year from one planting, thereby halving the cost of crop establishment (Banks 1993, Anonymous 1992b, Anonymous 1992c).

Table 1a. Strawberries: Cost of Hydroponics vs. Methyl Bromide as a Preplant Fumigant.

Cost Factors ($/acre/year)	Greenhouse Hydroponic/Artificial Substrate		Greenhouse Methyl Bromide
	Single Crop	Double Crop	
Labor/Operating	4,692	15,602	8,455
Materials (Water/Chemical)	25,844	28,604	14,553
Total	30,536	44,211	23,008
Yield (kg/acre)	20,235	36,423	23,008
Adjusted Cost ($/kg)	1.51	1.21	1.14

Source: Banks 1993.

Table 1b. Cucumbers: Cost of Hydroponics vs. Methyl Bromide as a Preplant Fumigant.

Cost Factors ($/acre/year)	Greenhouse Hydroponic/Artificial Substrate	Greenhouse Methyl Bromide
Labor/Operating	11,818	12,696
Materials (Water/Chemical)	70,381	18,216
Total	82,199	30,912
Yield (kg/acre)	274,791	107,650
Adjusted Cost ($/kg)	0.30	0.29

Source: Banks 1993.

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Methyl Bromide *Alternative* Case Study

Metam Sodium as an Alternative to Methyl Bromide for Fruit and Vegetable Production and Orchard Replanting

This is an update of a July 1995 EPA report (Alternatives to Methyl Bromide, Ten Case Studies) entitled "Metam Sodium as an Alternative to Methyl Bromide for Fruit and Vegetable Production". Additional information on this materials, including new data from field tests, is reported here. This report contains information on the use of this pesticides in the production of crops where methyl bromide is currently used.

First marketed in the 1950's, metam sodium is a soil pesticide that has been sold under the trade names Amvac Metam Sodium®, Busan®, Metam CLR™ 42%, Sectagon 42®, and Vapam®. Once in the soil, this pesticide degrades rapidly to methylisothiocyanate (MITC), the product's primary bioactive agent (Budavari 1994). Metam sodium is a broad spectrum soil fumigant that can be used to control plant parasitic nematodes, weeds, germinating weed seeds, and soil-borne plant pathogenic fungi affecting a variety of economically important fruit and vegetable crops. This pest control tool can be a cost effective, technically viable alternative to methyl bromide for controlling soil pests affecting high value fruit, vegetable, and orchard crops.

Benefits of Metam Sodium

- *Registered for use of many of the crops methyl bromide is used*
- *Widely availability*
- *Proven effectiveness*
- *Low cost*
- *Wide-range of control*

Metam sodium is registered and available to growers. It has no effect on the stratospheric ozone layer, and with current use patterns there are no residues left on crops. For over four decades, metam sodium has been used in a variety of experimental and commercial applications for the control of annual weeds, reduce nematode populations, and control soil-borne pathogens. In California, over 15 million pounds of metam sodium were used in 1995 for the production of melons, peppers, tomatoes, potatoes, strawberries, nurseries, ornamentals, cut flowers, container plants, forest tree seedlings, citrus, grapes, almonds, artichokes, asparagus, and carrots (CDPR 1997).

However, it should be noted that metam sodium has a reputation with some growers of being unforgiving and unreliable if not used carefully. Growers that have used this material note that correct application procedures are critical to insure success in the control of pest, especially nematodes and fungi. Current methyl bromide users should bear this in mind as they consider future utilization of this material.

Commercially Viable Alternative to Methyl Bromide

Table 1 compares methyl bromide and metam sodium soil fumigation use for grapes, peppers, tomatoes, processed tomatoes and strawberries for California in 1995 (CDPR 1997). As indicated in table 1, methyl bromide is not used in processing tomatoes --- this crop is shown in this report to show a successful and established use pattern, not to imply substitution in this or any other crop.

Table 1. 1995 Pesticide Use in California: Lbs active ingredient

Crop	Methyl Bromide	Metam Sodium
Grapes	575,000	15,500
Peppers	49,000	7,600
Tomatoes	266,000	243,000
Processed Tomatoes	-0-	2,888,000
Strawberries	4,200,000	30,000

Source: CDPR pesticide use summary database, April 1997.

Many researchers have cited metam sodium as a potential alternative to methyl bromide fumigation, and metam sodium's low cost and wide-range of control makes it a strong candidate for fumigation on many crops (Braun and Supkoff 1994, Noling and Becker 1994, Yarkin 1994). Metam sodium is registered for use in controlling a wide array of soil-borne pests, and can be used to control weeds (e.g., annual bluegrass, bermuda grass, chickweed, dandelion, ragweed, henbit, nutsedge, and wild morningglory.), nematodes (e.g. root knot, lesion, dagger, lance, needle, pin, reniform, stunt, stubby root, sting, spiral), and soil diseases caused by species of *Rhizoctonia, Fusarium, Pythium, Phytopthora, Verticillium, Sclerotinia*. Metam sodium is also useful in Integrated Pest Management systems, as it can be used in conjunction with resistant varieties, improved sanitation techniques, biological control agents, and soil pasteurization (i.e., solarization, hot water or steam) (Noling and Becker 1994). It is possible, based upon current metam sodium use patterns, to see expanded across a wide range of fruit and vegetable crops including tomatoes, strawberries, and peppers which currently utilize methyl bromide for soil pest control.

Fruit and Vegetable Production

Note that not all the crops listed in this section currently utilize methyl bromide in their production. However, a description of metam sodium efficacy is provided to illustrate the kind of pest control that can be acheived with this material. While this document assumes that such pest control efficacy is transferrable to crops that use methyl bromide, this must be established with field trials where applicaiton methods and production timing can be established. This is especially important with metam sodium, where application techniques are absolutely critical to success.

Carrots -

In comparisons with methyl bromide, metam sodium has shown good growth responses and yield increases (Olson and Noling 1994, Cook and Keinath 1994, ICI 1992). In the production of carrots and tomatoes, metam sodium has been used to significantly reduce populations of stubby root (*Paratrichodorous sp.*) and root-knot nematode (*Meloidogyne sp.*) prior to planting (ICI 1992). Application through drip irrigation on California tomato and carrot beds before planting significantly reduced nematodes in the soil as well as root gall ratings at mid-season and harvest and increased yields in most cases (Roberts et. al. 1988). In Florida, use resulted in improved plant vigor and stand, reduced root-knot nematode damage and increased yields (Johnston et. al. 1991).

Tomatoes -

A fresh market tomato study comparing metam sodium and methyl bromide fumigation to an untreated control reported that yields and fruit quality obtained with metam sodium were equivalent to those achieved with methyl bromide fumigation (Cook and Keinath 1994). In the production of tomatoes in southwest Florida, Fusarium crown and root rot has been the most prevalent soilborne disease. Metam sodium has been demonstrated to significantly reduce crown rot incidence and when combined with solarization, control was equivalent to methyl bromide + chloropicrin (McGovern et. al. 1996).

Strawberries -

In California strawberry production, methyl bromide and metam sodium are rated comparable in chemical effectiveness to control annual and perennial weeds (UC 1996). Field experiments conducted by the UC Cooperative Extension over a three year period on broccoli, cauliflower and strawberries demonstrated that metam sodium will effectively control several annual weeds common in these crops (Agamalian 1990).

In two registrant-supported strawberry field trials, Metam sodium was applied at 240 lbs per acre through sprinkler system; methyl bromide/chloropicrin was applied at 325 lbs per acre. Overall, during the early part of the season, yields achieved with metam sodium were 26% greater than those obtained with methyl bromide. Although methyl bromide yields for the overall season were 14% greater than yields achieved with Metam sodium, because metam sodium treatment costs were 1/3 less than methyl bromide costs and higher early season yields achieved by metam sodium received significantly higher prices, economic returns with metam sodium were greater than those achieved by using methyl bromide (ICI 1992).

Weed Control -

Hairy nightshade (*Solanum sarachoides* Sendter) and black nightshade (*Solanum nigrum* L.) are widespread major weed problems in California processing tomatoes causing severe economic loss to growers. This loss amounts to greater than $68 million due to hand hoeing costs and yield reductions. A three year study of *Solanum* species control in processing tomatoes conducted by University of California Cooperative Extension Farm Advisor, Mullen, show metam applied preplant subsurface can be effective for control of *Solanum* and other weed species (Mullen). It must be noted that processing tomatoes do not currently use methyl bromide. Reference to this crop is to establish metam sodium as a good weed control tool, with the broad (and very likely) assumption that such effective weed control will be transferrable to other cropping situations.

Nematode Control -

A statewide investigation into the potential of various nematicidal materials for controlling root-knot nematodes (*Meloidogyne* spp.) on processing tomatoes was conducted in California during 1985. Metam sodium applied via drip irrigation at both 64 and 128 pounds active per acre significantly reduced root galling throughout the season and had significantly reduced numbers of root-knot nematode second stage juveniles in soil assessed at planting time. These two treatments gave the highest yields in these experiments (Roberts and Matthews 1985). Again, it must be noted that processing tomatoes do not currently used methyl bromide, and reference to this crop establishes metam sodium as a good nematode control agent, with the assumption that such control may be transferrable to other cropping situations, such as those where methyl bromide is currently used.

Plant Disease Control -

Metam sodium applied at rates of 10 to 40 gallons per acre greatly reduced pythium and Fusarium soil levels and root infection in processing tomatoes. Metam sodium also significantly reduced the "corky-root like" banded lesions on roots in midseason. It was concluded that the control of these common soil fungi by metam sodium may have contributed, along with nematode control, to the overall plant growth increase and yield increase that occurred in most of these experiments.

Fusarium oxysporum causes serious losses in yield and quality of celery. It attacks the fibrous root system and spreads through the xylem into the crowns. The initial symptom is a retardation of growth, usually followed by yellowing of the foliage. Field evaluations conducted during 1989 in California revealed that fumigation of soil with metam sodium promoted early plant growth and increased yield in fields infected with this disease (Becker et. al. 1990). Very little celery production currently uses methyl bromide, so here again, reference to this crop establishes the pesticidal effects of metam sodium, with the assumption that such control will be transferrable to cropping situations where methyl bromide is currently used.

In 1990, Johnston and Phillips evaluated soil fumigants for control of Phytophthora and Pythium blight of peppers. The incidence of Pythium blight was high in this test and this test was considered definitive. Metam sodium applied via drip irrigation at 160 to 320 pounds active per acre provided significant reduction in Pythium blight and a significant increase in total yield (Johnston and Phillips 1991).

Orchard Replant Sites -

Pathogenic soil organisms present in the soils of most mature orchards often reduce root growth of young fruit trees when the site is replanted. Poor root development leads to reduced vegetative growth and poor fruit yields throughout the life of the replanted orchard. While many soil fumigants, fungicides, fertilizers and soil amendments have been tested for effect on the orchard replant disease, only three have shown long-term growth and yield benefits in Washington orchard trials: methyl bromide, metam sodium, and fumigants containing chloropicrin (WSU 1996).

To evaluate control of southern blight in apples, UC Farm Advisor Joseph Grant and Greg Browne, USDA-ARS are evaluating alternatives to methyl bromide + chloropicrin. In year one of the experiment, metam sodium performed as well as the methyl bromide/chloropicrin mixture for control of the disease at tree replant sites (USDA 1996).

Trials conducted to evaluate the use of methyl bromide alternatives on orchard replant sites demonstrated that metam sodium can provide comparable control as methyl bromide (McKenry 1994). However, the study also noted that metam sodium does not always penetrate deep roots, and thus may not control nematodes in old roots if the proper soil conditions are not present. A vineyard with root lesion and root knot nematodes was replanted to strawberries. Results of this trial revealed that soil drenching replant sites with 300 lbs of metam sodium gave equivalent nematode control for 24 months. A 20 year old plum site, with root lesion and ring nematodes, was replanted to nectarines. Soil drenching with 330 lbs of metam sodium gave equivalent nematode control for 24 months. At another site, soil drenching a 15 year old peach and plum orchard, infested with root lesion and citrus nematode, with metam sodium gave comparable nematode control. Additionally, at an old almond orchard, infested with root lesion and ring nematode, replanted to grapes was treated with metam sodium at 327 lbs. Results showed comparable nematode control and plant growth when compared to methyl bromide.

Successfully Applying Metam Sodium

Although some growers have been frustrated with metam sodium's soil distribution characteristics and variations in pest control, research and advances in application techniques have the potential to increase the consistency and efficacy of metam sodium as a soil fumigant. Effectively using metam sodium to control pests currently treated with methyl bromide will require some low-cost modifications of cropping systems, including, in some cases, the adoption of drip irrigation systems, narrower bed widths, multiple drip tubes per bed, and planting practices which place plants closer to drip tubes (Noling and Becker 1994).

To use metam sodium effectively, the applicator must follow the recommendations provided by the product label, including considerations of the soil conditions, methods of application, application rates, and the factors influencing the release rate. The release rate of metam sodium depends on several factors including soil temperature, texture, moisture and pH.

Prior to application, the seedbed must be prepared by ensuring that it is free of clods and by receiving a preplant fertilizer treatment. Additionally, soil moisture must be at least 50 to 75 percent of field capacity, and soil temperatures must be between 40° F and 90° F in the top 2 to 3 inches (ICI 1992).

In most cases, 80 to 320 pounds active of metam sodium are applied per treated acre as a liquid and then incorporated into the soil through tilling and irrigation (Braun and Supkoff 1994).

Metam sodium can also be applied through sprinkler, flood or drip irrigation. Research trials indicate that application of metam sodium through overhead irrigation water may be a more effective way to obtain uniform distribution than by injecting with chisels (Adams and Johnson 1983, Adams et. al. 1983, Ben-Yephet and Frank 1984). Additionally, University of Georgia researchers demonstrated that metam sodium was more effective against Rhizoctonia and Pythium when applied through overhead sprinkler irrigation than when injected with chisels in a fall experiment (Sumner and Phatak 1988).

University of Georgia researchers demonstrated that proper placement through adequate water is important for the efficacy of metam sodium (Sumner and Phatak 1988). Metam sodium moves in the water phase (opposed to methyl bromide which moves in the air phase) so adequate watering is essential. Failure to appreciate this fact is one of the major causes of inconsistency in metam sodium application. These trials demonstrated that the application of metam sodium in 2.5 cm of water was more effective in controlling root diseases in deep-rooted vegetables such as okra than in 1.3 cm of water. Application in 0.6 cm of water were ineffective. Metam sodium is most effectively applied through drip tape if it is applied no more than 6 inches off center and 2 to 3 inches deep.

Cost Effective Alternative to Methyl Bromide

An advantage to the use of metam sodium is the low cost. Although supplemental pest control activities may be required under certain circumstances and may increase the total application costs, metam sodium is considered by many to be safer and easier to use than methyl bromide. Table 2. compares the costs of metam sodium and methyl bromide for soil fumigation treatments. The average cost of metam sodium ranges from $0.41 to $0.88 per pound active (Johnson Mercantile Co. 1997, Western Farm Service 1997), with typical application rates ranging from 240 to 320 pounds active per acre (Braun and Supkoff 1994). Total metam sodium costs can average between $141 to $282 per acre. In comparison, the average cost of methyl bromide ranges from $3.13 to $4.25 per pound (Shore Chemical 1997, Helena Chemical 1997, Cal Ag Industrial Supply 1996). Methyl bromide costs are estimated to range from $560 to $1,700 per acre.

TABLE 2. Relative Costs of Methyl Bromide and Metam Sodium Fumigation			
Fumigant	**Cost Per Unit ($)**	**Units Per Acre**	**Estimated Cost Per Acre**
Metam sodium	$0.41 - $0.88 per pound	240 - 320 pounds	$141 - $282
Methyl Bromide	$3.13 - $4.25 per pound	180 -400 pounds	$560 - $1,700

Source: Shore Chemical 1997, Helena Chemical 1997, Cal Ag Industrial Supply 1996, Johnson Mercantile Co. 1997, Western Farm Service 1997.

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Stratospheric Ozone Protection

Methyl Bromide *Alternative* Case Study

Steam as an Alternative to Methyl Bromide in Nursery Crops

Steaming can be a viable alternative to methyl bromide for soil and growth media in greenhouses and some small-scale field nurseries. Steam effectively kills pathogens by heating the soil to levels that cause protein coagulation or enzyme inactivation (Langhans 1990). Soil steam sterilization was first discovered in 1888 (by Frank in Germany) and was first commercially used in the United States (by Rudd) in 1893 (Baker 1962). Since then, a wide variety of steam machines have been built to disinfest both commercial greenhouse and nursery field soils (Grossman and Liebman 1995). In the 1950s, for example, steam sterilization technologies expanded from disinfestation of potting soil and greenhouse mixes to commercial production of steam rakes and tractor-drawn steam blades for fumigating small acres of cut flowers and other high-value field crops (Langedijk 1959). Today, even more effective steam technologies are being developed.

Benefits of Steam Sterilization

- ✓ *Highly efficient and cost-effective control method*
- ✓ *Eliminates the need for tarps and soil fumigants*
- ✓ *Neat, clean, and easy-to-use*
- ✓ *Leaves no toxic residues or fumes*
- ✓ *Requires little aeration time*
- ✓ *Can disinfest non-soil substances*
- ✓ *Can be combined with other pest control practices*

The advantages of steam sterilization are that it can be a highly efficient, cost effective technology for the control of soil-borne pathogens, pests, and weeds; it eliminates the need of tarps and fumigants; it can be a neat, clean, and easy-to-use control technology, leaving no toxic residues or fumes and therefore less harmful to other greenhouse crops and growers (with no toxic fumes, workers can harvest or plant new cuttings in adjacent fields). In addition, it is non-selective (lethal to all pests). Steam requires little aeration time (steamed soils can be planted as soon as they cool, whereas chemically treated soils can have a relatively long treatment and aeration period). Steam can also be used to disinfest non-soil substances such as perlite, peat, and compost (Szmidt *et al.* 1989) and can be adaptable to many situations (i.e., most types of boilers used to heat greenhouses can be adapted to supply steam for sterilizing benches or soil bins).

However, it should be noted that while there are a number of positives aspects to using steam as a pest control tool, there are potential pitfalls and shortcomings. This method does not currently appear to be operationally feasible for large outdoor nursery crops due slow application speed as well as high energy and capital investment costs. Due to limited steam penetration in the field, surface application may not reach pests in deep rooted trees or crops. It is a very inefficient methods when soils are very wet (similar with most other fumigants, including methyl bromide). In addition, steam that is too hot (85°C to 100°C) may increase soil aggregation and destroy soil structure. A number of these issues may well be resolvable, and efforts by researchers to refine this technology should continue.

If deemed necessary, steam sterilization can be used in combination with other control mechanisms, such as nematicides, botanicals, soil amendments, and biological control agents (Stephens *et al.* 1983). For example, one possible biocontrol agent is the fungal antagonist, *Trichoderma*, which has been shown to increase biological control and horticultural productivity. *Tricoderm*a spp. can hasten flowering of periwinkle, increase the number of blooms in petunias and chrysanthemums, and increase dry weights of flowers and vegetables such as tomato, pepper, and cucumber (Baker 1992, Chang *et al.* 1986, Locke *et al.* 1985, Horst and Lawson 1982).

Nursery crops account for 20 percent of the worldwide use of methyl bromide for soil fumigation (Anonymous 1995a). Steam sterilization can be an effective pest control method for many nursery crops, including ornamental bedding plants, potted foliage and flowering house plants, fresh cut flowers and greens, bulbs, container perennials, propagating material, vegetable starts, greenhouse grown vegetables, garden seeds, and sod. Soil used to grow cut Christmas trees and seedlings for orchards, vine-yards, and forests can also be effectively treated with steam technologies, depending upon crop value and size of area to be treated. In 1991, the value of crops produced by floriculture and on environmental horticulture farms was $8.7 billion, or 11 percent of total cash receipt from all crops (Johnson and Johnson 1993). In California, these industries are worth $2 billion in gross receipts, or about 10 percent of the total value of California's agricultural commodities (Anonymous 1993).

Steam Pasteurization

To effectively steam treat soils, soil temperatures of at least 70°C must be achieved for 30 minutes. Temperatures below 70°C will not kill all soil-borne pathogens and steaming for periods exceeding 30 minutes after the desired temperature has been reached does not further benefit the soil (Horst and Lawson 1982). Sterilization does not guarantee that disease causing organisms will not recontaminate the soil, therefore if the soil is not used immediately after it is treated it should be protected from reintroduced pathogens (i.e., by avoiding contact with non-sterilized soil and practicing standard sanitation procedures in the greenhouse) (Horst and Lawson 1982).

Steaming Greenhouse and Potting Soils

The use of steam for greenhouse and potting soil mixes is quick and efficient. Boilers used to heat greenhouses can often be adapted to supply steam for sterilizing greenhouse benches or soil bins. Bulk and container soils can be easily loaded into steam boxes with removable fronts and steam pipe grids for treatment. Alternatively, forklifts can load pallets of soil into pressurized autoclaves for steaming. Another way of disinfesting greenhouse and nursery soils is to cover perforated steam pipes with soil to be treated (Newhall 1955). Bed or bench treatments are most effective when perforated pipes are laid in the bottom of the bed because steam supplied from the top of the bed has limited penetration to about 8 inches depth (Bartok 1993). More recently, small portable steam generators have been developed and used for greenhouse benches in the U.S. and the Netherlands (Grossman and Liebman 1995).

Open Fields and Steam

Sheet Steaming

In addition to greenhouses, it is also possible to use steam technologies on small nursery fields. For example, movable steam applicators, such as the steam rake and the steam blade have been used extensively in nursery fields. Both are pulled through the soil either by a winch or by a self-propelled unit containing a boiler to produce steam. In Florida, several small steam machines have been developed for field use. Using these machines can be less expensive and in some conditions may be more effective than methyl bromide fumigation (Grossman and Liebman 1995) and can disinfest a quarter of an acre of planting bed per work shift. Steam cultivation is also used in the Netherlands, where methyl bromide soil fumigation has been banned for several years and where large mobile boilers (that can be moved from farm-to-farm on trucks) have been developed and used in fields (Grossman and Liebman 1995). To aid steam penetration, soil is cultivated as deeply as possible. Typically steam is blown under a sheet covering the soil and left to penetrate. Clay is very easy to disinfest with this steam system, while slightly more energy is required to achieve high enough soil temperatures in sand, loams, and peat soils because of their water retaining capacity. To raise the temperature in these soils or in deeper soil layers, steaming sheets are sometimes covered with nylon nets or bubble foil , so that the pressure under the sheets can be increased and heat loss can be kept at a minimum. For high value Dutch crops such as carnations and cut flowers, field soils have also been disinfested by embedded steam pipes directly in the field. Though fuel costs for steam systems using embedded pipes are less than sheet steaming, material costs are often higher (Runia 1983).

Negative Pressure Steaming

Negative pressure steaming, the most recent advance in applied steam technologies for soils, was introduced to the Netherlands in 1981. Using this method, steam is introduced under the steam sheet and pulled into the soil by negative pressures created by a fan. Specifically, the fan draws air out of the soil through buried perforated polypropylene pipes (Runia 1983). The fans continue to move heat from the upper to lower soil layers for several hours after steam treatment. Deep soil temperatures achieved with negative pressure steaming are considerably higher than those obtained with sheet steaming, averaging 85 to 100°C (185°F to 212°F) down to 35 cm deep (sheet steaming produces an average temperature of only 26°C (78°F) at the same depth). This method was found to be more energy efficient, economical (by up to 50 percent), and more reliable for the cultivation of some crops (i.e., chrysanthemums) than the conventional steaming methods used to disinfest soil in the Netherlands (Anonymous 1992). By 1982, over 100 nurseries in the Netherlands were using negative pressure steaming (Runia 1983, Banks 1995).

Cool Steaming

Although high-temperature negative pressure steaming has its advocates, some researchers believe that steam at 85°C to 100°C (185°F to 212°F) kills too many beneficial soil organisms (i.e., mycrorhizal fungi) along with the pathogens and can lead to the production of phytotoxic compounds harmful to crop plants. As a result, these researchers advocate the use of lower temperatures (70°C) (152°F)or cool steam, which does not kill beneficial organisms (i.e., nitrifying bacteria) and is less phytotoxic (Langhans 1990, Grossman and Liebman 1995, Baker 1970). To cool steam to the desired temperature (i.e., typically 70°C for 30 minutes), it is mixed with a stream of air. Since lower temperatures are required, aerated steam is faster and approximately 40 percent cheaper than hot steam (Baker 1962, Bartok 1993). Likewise, Baker (1957) calculated that the cost of aerated steaming is 30 to 50 percent cheaper than methyl bromide (including the boiler costs).

Costs

Steam sterilization can be an economically viable alternative to methyl bromide fumigation in a number of crops (i.e., ornamental bedding plants, potted foliage and flowering house plants, fresh cut flowers and greens, bulbs, container perennials, vegetable starts, greenhouse grown vegetables, and garden seeds). Tables 1 and 2 present a cost analysis for steam compared to methyl bromide for cucumbers and chrysanthemums, respectively. The formula for calculating the cost of soil steam sterilization vs. methyl bromide takes into account soil volume and permeability, soil heat exchange efficiency, boiler efficiency, units of fuel required, the BTU constraints of the fuel, and water prices (Lawson and Horst 1982). Total steam sterilization costs ($/kg yield or $/bench) were comparable to that of methyl bromide fumigation for both crops analyzed (Anonymous 1995a). Furthermore, steaming has the extra advantage of allowing growers to replant up to three weeks sooner than methyl bromide treated fields (an important economic advantage in cool climates) (Grossman and Liebman 1995).

Since large steam boilers can cost up to $150,000, it is likely not practical for growers not currently using boilers to heat their greenhouses to buy new boilers to steam soil once a year. Instead, outside contractors can be hired for steam treatments (Grossman and Liebman 1995). This is especially common in the Netherlands, where in addition to stationary on-site boilers, growers commonly rent or contract for truck-mounted steam generators on an as need basis (Anonymous 1992 and Anonymous 1995b). As a result, the capital cost to purchase a boiler was not included in the cost estimates presented in the tables below. Likewise, in Table 2, the cost of tarps, plastic, canvas, metal pipes, and labor were excluded from analysis since these costs were found to vary significantly from greenhouse to greenhouse depending on the current material prices and labor rates (Lawson and Horst 1982).

Steam costs are expected to decrease as these systems become more commercialized and less expensive energy/water sources are utilized. For example, greenhouse heating costs can be kept at a minimum by tapping alternative fuels such as sawdust, rubber from old tires, methane from landfills, wind, hot water from electric power plants, and geothermal vests (Davis 1994).

Table 1. Cucumbers: Annual Cost of Steam vs. Methyl Bromide as a Preplant Fumigant.

Costs Factors	Greenhouse Steam ($/acre/year)	Greenhouse Methyl Bromide ($/acre/year)
Labor/Operating	11,818	12,696
Materials	18,969	18,216
Total	30,787	30,912
Yield (kg/acre)	107,650	107,650
Adjusted Cost ($/kg)	0.28	0.29

Source: Banks 1995.

Table 2. Chrysanthemums: Annual Cost of Steam vs. Methyl Bromide as a Preplant Fumigant.

Cost Factors	Greenhouse Steam ($/bench/year)	Greenhouse Methyl Bromide ($/bench/year)
Application	8.60	20.00

Note: One bench equals 200 square feet.
Source: Lawson and Horst 1982.

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Stratospheric Ozone Protection

Methyl Bromide *Alternative* Case Study

Replacing Methyl Bromide for Preplant Soil Fumigation With Telone®, Chloropicrin and Tillam® Combination Treatments

This is an update of a July 1995 EPA report (Alternatives to Methyl Bromide, Ten Case Studies) entitled "Telone C-17 and Tillam Use on Florida Fresh Market Tomatoes". Considerable work has been done since that report with regard to these materials, and new data from field tests is reported here. This report contains information on the use of these pesticides in the production of tomatoes and other crops where methyl bromide is currently used.

Telone® C-17, a DowElanco product registered for preplant fumigation, contains 77.9 percent 1,3-dichloropropene (1,3-D) and 16.5 percent chloropicrin (an effective fungicide). Telone® C-17 and other Telone® products are recognized as effective preplant nematicides (Youngson *et al.* 1981) and have been proven to suppress some plant diseases (e.g., Fusarium wilt of cotton, Verticillium wilt of mint, and southern stem blight) (Melichar 1994, Dickson 1996). Tillam® 6E, a selective herbicide containing the active ingredient pebulate, is often used in conjunction with Telone® products for control of weeds (especially nutsedge) (Gilreath 1994, Gilreath 1996). Used together, these chemicals can achieve control of nematodes, weeds and a variety of diseases at levels comparable to those achieved with methyl bromide and chloropicrin combinations (Melichar 1994, Gilreath 1994, Olson *et al.* 1996, Gilreath 1996).

Benefits of Telone® C-17 and Tillam® Combinations

- ✓ *reduces incidence of diseases, especially Fusarium wilt of cotton, Verticillium wilt of mint, and southern stem blight*
- ✓ *achieves nematode control similar to that of methyl bromide*
- ✓ *reduces both yellow and purple nutsedge populations as effectively as methyl bromide*

In a recent study, Telone® C-17 controlled root-knot nematodes and several diseases, and achieved yields similar to those obtained by fumigation with methyl bromide for tomatoes, peppers, and strawberries in Florida (Melichar *et al.* 1996b). Another study conducted at the University of Florida found that a combination treatment of Telone® C-17 and Tillam® on Florida tomatoes produced a significantly higher yield of medium and large fruit than methyl bromide/chloropicrin (67/33). There were no significant differences among treatments for yield of extra large fruit or for total yield in the study (Olson *et al.* 1996). In these and at least 4 other recent studies, Telone® C-17 was found to be as effective as, if not more effective than, methyl bromide and chloropicrin in controlling nematodes and certain soil-borne diseases (Chellemi *et al.* 1996, Dickson 1996, Noling *et al.* 1996, Duniway and Gubler 1996).

Telone® C-17 is a restricted use pesticide licensed for control of nematodes, symphylans, wireworms and certain soil borne diseases in the preplant fumigation of tomatoes, peppers, strawberries, melons, grapes, and 112 other crops. Telone® C-17 is also approved for use on nursery crops. This fumigant may be broadcast or row applied and should be sealed immediately after application. Sealing may be accomplished by uniformly mixing the soil to a depth of 3 or 4 inches and compacting the soil surface (broadcast fumigation) or by disrupting the chisel trace using press sealers, ring rollers or by reforming the beds and then using such equipment (row fumigation). In both application techniques, sealing can be improved by applying polyethylene film over the entire area or in strips (DowElanco 1994).

Research Summary

Several studies have been conducted comparing control of soil borne pests obtained with methyl bromide fumigation to that obtained by formulations containing Telone® products. Highlights of 1,3-D/chloropicrin research are presented in the two subsections below. The first section describes other formulations of Telone®, and the second section presents information on combination treatments consisting of Telone® C-17 with certain herbicides or integrated pest management (IPM) techniques.

Other Formulations of Telone®

Researchers have been investigating formulations of Telone® with varying percentages of chloropicrin for control of root-knot nematode, soil-borne diseases, and weeds. For example, Telone® C-25, Telone® C-30, and Telone® C-35 contain 25, 30, and 35 percent respectively in combination with Telone®, while Telone® II contains 1,3-D as the sole active ingredient. Increases in the percentage of chloropicrin are intended to raise the level of disease control achievable. In general, these formulations have compared favorably with methyl bromide and chloropicrin formulations, as described in the following bullets:

- Experiments compared the efficacy of Telone® C-17 and Telone® C-35 to methyl bromide/chloropicrin formulations. These experiments were conducted in 1996 at the Agronomy Research Farm at the University of Florida, Gainesville on tomatoes. Researchers found root-knot nematode galling indices to be lower in soil treatments of methyl bromide/chloropicrin (98/2), Telone® C-17 (1,3-D + 17 percent chloropicrin) and all treatments containing Telone® C-35 (1,3-D + 35 percent chloropicrin) than in the control. The study also found wilt caused by *Sclerotium rolfsii* (southern stem blight) was reduced to one or fewer plant hits per plot by methyl bromide/chloropicrin (98/2) and by all but one of the Telone® C-35 treatments (Dickson 1996).

- Telone® II/chloropicrin formulations were tested against methyl bromide/chloropicrin in a study supported by the California Strawberry Commission and ARS-USDA. In this study, Telone® II/chloropicrin formulations were broadcast fumigated and covered with polyethylene tarpaulins for 5 days before raising the beds. Relative to yields (100%) obtained following standard fumigation with methyl bromide/chloropicrin (67/33 @ 325 lb/acre), total yields for 1994 and 1995 trials, respectively, were 98 and 108 percent with Telone® II (1,3-D)/chloropicrin (70/30 @ 454-461 lb/acre), and 109 percent with Telone® II/Chloropicrin (70/30 @ 410 lb/acre, 1995 only) (Duniway and Gubler 1996).

- Telone® C-17, Telone® C-25, and Telone® C-35 were compared with methyl bromide in field tests conducted by the manufacturer of Telone® products in Florida, California and North Carolina. Researchers compared these three formulations of 1,3-D and chloropicrin to methyl bromide for nematode and soil-borne disease control. Telone® C-35 performed similarly to methyl bromide based on measurements of nematode counts, root damage, disease incidence and disease severity (Melichar *et al.* 1996a).

- Research trials compared the efficacy of Telone® C-17 and Telone® C-30 with methyl bromide on tobacco and peppers in Georgia. Researchers applied Telone® C-17 (@ 20 gal/acre), Telone® C-30 (@ 20 gal/acre), and methyl bromide/chloropicrin (@ 9 lbs/300 linear feet) to tobacco beds. They found no significant differences between the treatments for control of soil borne diseases (*Pythium* spp., *Fusarium* spp., *Rhizoctonia solani*), nematodes (root knot larvae, ring, spiral), or weeds (purple cudweed, cutleaf evening primrose, and old field toneflax) (Melichar *et al.* 1995).

Combination Treatments with Telone® C-17

Studies have shown the importance of using an herbicide in conjunction with Telone® C-17 in areas where nutsedge is a problem. For example, a Florida study evaluated the efficacy of Telone® C-17 on nematodes (*Meloidogyne* spp.), diseases (fusarium wilt, *Fusarium oxysporum* f.sp. *lycopersici*, and fusarium crown and root rot, *Fusarium oxysporum* f.sp. *radicis-lycopersici*), and weeds (yellow nutsedge, *Cyperus esculentus*, and purple nutsedge, *Cyperus rotundus*). Telone® C-17 disease and nematode control was equivalent to methyl bromide, however, Telone® C-17 did not provide equivalent weed control (Melichar *et al.* 1996b).

Although combination treatments with Tillam® have been very effective against weeds, researchers have been looking into other herbicides and combination treatments for use with Telone®, because Tillam® is currently registered for only three crops -- tobacco, tomato, and sugarbeets (Helena Chemical Company 1997). Summaries of research results for herbicides including Tillam® and IPM practices that could be used in combination with Telone® products are presented below.

- One of many studies in which a combination treatment of Telone® C-17 and Tillam® was proven to be as effective as treatment with methyl bromide/chloropicrin was conducted at the North Florida Research and Education Center. Telone® C-17 (@ 35 gal/acre) and Tillam® 6E (@ 4 lbs a.i./acre) were applied and covered with black polyethylene mulch immediately after fumigation. Telone® C-17/Tillam® produced the highest yield of medium and large fruit of all the treatments and significantly higher yield of these fruits than methyl bromide (Olson *et al.* 1996).

- Researchers have also combined Telone® C-17 with Vapam®. Experiments conducted at the University of Florida in 1995 compared the efficacy of methyl bromide/chloropicrin (98:2 @ 400 lb/acre), chloropicrin (@ 350 lb/acre), and Telone® C-17 (@ 35 gal/acre). Each plot was then treated with 956 ml Vapam®. Although chloropicrin treatments resulted in numerically higher strawberry yields, no significant differences in January yields were identified in any of the fumigation treatments (Noling *et al.* 1996).

- A 1996 study compared the efficacy of methyl bromide/chloropicrin on peppers to that of Telone® C-17 and Devrinol® (napropamide) herbicide, the only in-bed herbicide labeled for peppers. The trial was conducted late in the season, thereby allowing time for only 2 harvests. Telone® C-17 (@ 21 gal/acre) and Devrinol® (@ 3.4 lb a.i./acre) produced significantly more peppers than the methyl bromide treatment during the first harvest, and resulted in a minor cumulative yield advantage after both harvests (Mueller 1997).

- Another study considered the effects of soil solarization in combination with Telone® C-17. This Florida study compared the efficacy of soil solarization/Telone® C-17 fumigation with those of standard methyl bromide application on tomatoes. Soil solarization in combination with reduced rates of methyl bromide plus chloropicrin or Telone® C-17 provided significantly greater control of root galling than soil solarization alone. In addition, rows treated with soil solarization reduced the incidence of southern blight (*Sclerotium rolfsii*) to less than 0.1 percent, whereas rows treated with only methyl bromide experienced a 3.7 percent incidence of disease (Chellemi *et al.* 1996).

Availability and Regulatory Issues

Telone® products are currently available in Florida. Although regulatory issues (worker exposure health-related concerns) were once a limiting factor in California (Melichar 1995), Telone® II is now available in California. The California Department of Pesticide Regulation draft permit conditions restrict use of Telone® products to 5,000 gallons per township (i.e., 36 square mile range) for application depths less than 18 inches and 9,500 gallons for depths greater than 18 inches (Duniway 1997, Roby 1997).

DowElanco is considering drip irrigation as a means to deliver Telone®, while reducing 1,3-D loss to the atmosphere. Several field studies have proven 1,3-D/chloropicrin combinations to be effective nematicides when applied through drip irrigation. Drip irrigation of Telone® II (1,3-D) is registered for melons in Arizona and studies are underway to determine the extent of disease control achievable when using drip applied 1,3-D/chloropicrin combinations (Mueller 1995).

Costs of Alternative

Because Tillam® is frequently used in combination with Telone® C-17 during tomato production and because both are applied in a manner similar to the application of methyl bromide/chloropicrin, alternative costs reflect the costs of the raw materials, only. Other costs associated with Telone® C-17/Tillam® or methyl bromide/chloropicrin fumigation include labor costs, machinery costs and the costs of time delays associated with protecting against phytotoxicity and addressing human health concerns. An analysis of the raw material costs associated with fumigation for tomatoes in Florida is presented in Table 1. Please note that application rates are presented in terms of bed fumigation rather than broadcast fumigation.

Table 1.
Comparison of Estimated Raw Materials Costs for Row Applications

Cost Factor	Telone® C-17/Tillam®	Methyl bromide/ chloropicrin
Application Rates	Telone® C-17 17.5 gal/acre Tillam® 6E 2 lb a.i./acre	MeBr/Pic (98:2) 200 lb a.i./acre
Cost per Unit	Telone® C-17 $12.75-13.75/gal Tillam® 6E $7.66/lb a.i. ($45.95/gal)	MeBr/Pic (98:2) $1.12/lb
Total Material Cost	$247/acre	$224/acre

Sources: Eger 1997, Gilreath 1997, Helena Chemical 1997, and Asgrow 1995.

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Stratospheric Ozone Protection

Methyl Bromide *Alternative* Case Study

Fumigation with Carbonyl Sulfide for Controlling Pests on Perishable and Non-Perishable Commodities

Carbonyl sulfide (CAS Number 463-58-1) has traditionally been used as a chemical feedstock; however, recent studies suggest that carbonyl sulfide may be a technically and economically viable alternative to methyl bromide for use as a non-perishable and perishable commodity fumigant to control insects (e.g., termites, beetles, and moths) and mites, and possibly as a soil fumigant for control of nematodes. The first research performed on the efficacy of carbonyl sulfide was conducted by the Commonwealth Scientific and Industrial Research Organization (CSIRO), which lodged a patent for carbonyl sulfide as a fumigant in July 1993 (CSIRO 1993). Further, the potential to use carbonyl sulfide to control stored product insects in fruits and nuts is being evaluated through laboratory studies conducted by the United States Department of Agriculture/Agricultural Research Service (USDA/ARS) Horticultural Research Laboratory located in Fresno, California. Additional research needed to complete applications for registering carbonyl sulfide as a pesticide in the U.S. and elsewhere in the world is currently underway (Zettler *et al.* 1997, Banks 1996).

Based on initial research efforts, carbonyl sulfide has been found to be an effective method of disinfesting non-perishable commodities such as timber products. Studies also indicate that it can be used to control pests on perishable commodities (research is being conducted to determine potential effects on commodities and to determine residue characteristics). Research is also being conducted to determine how to use carbonyl sulfide to control soil pests, especially nematodes. Finally, carbonyl sulfide has been found to be efficacious against termites, indicating that structural treatments may be another potential use area. (Banks 1993, Desmarchelier 1993, Zettler *et al.* 1997, Desmarchelier 1994, Plarre and Reichmuth 1996).

Benefits of Carbonyl Sulfide

✓*Effective method of disinfesting non-perishable commodities.*
✓*Good commodity penetration.*
✓*Doesn't harm seed germination.*
✓*Common trace constituent of the atmosphere.*
✓ *Potential quarantine treatment.*
✓ *May be useful for controlling pests on perishable commodities and in soil.*

Research to Support Registration

CSIRO's Stored Grain Research Laboratory in Australia and the USDA/ARS are conducting research to examine the development of carbonyl sulfide as a replacement for methyl bromide. As noted above, research data generated by CSIRO indicate that carbonyl sulfide will be useful as a non-perishable commodity fumigant. Recent data generated by USDA/ARS suggest that carbonyl sulfide could also be useful as a perishable commodity fumigant. Studies are on-going to determine its potential for use as a soil treatment and to determine potential effects on commodity quality, if any. (Desmarchelier 1993, Banks 1996).

A number of tests have been conducted to determine the likelihood that carbonyl sulfide could be used in commodity applications. First, Plarre and Reichmuth (1996) found that a concentration (C) of 32 mg/liter for 72 hours (T) (CxT value of 2,304 mg/hr/liter) effectively controlled all life stages of the granary weevil (*Sitophilus granarius* (L.)). Another study found that with application rates of 25 mg/L combined with exposure periods of 24 hours (CxT value of 600 mg/hr/liter), over 99.8 percent efficacy could be achieved against some immature stages of insects, including the rice weevil and lesser grain borer (*Rhyzopertha dominica).* It was also determined that application rates could be lowered to 8 mg/L while still obtaining a high efficacy (98.1 percent) if exposure periods were increased to 48 hours. It was suggested that the shorter exposure periods with the higher application rates could potentially be used for treating perishable commodities that require rapid fumigations prior to shipment (Desmarchelier 1993).

In addition to studies on grain pests, a recent USDA/ARS study evaluated carbonyl sulfide for use on stored product insects affecting dried fruits and nuts (Zettler *et al.* 1997). The toxicity of carbonyl sulfide for five economically important pest species was determined. The insects tested included larval navel orangeworm, *Amyelois transitella* (Walker); adult sawtooth grain beetle, *Oryzaephilus surinamensis* (L.); adult driedfruit beetle, *Carpophilus hemipterus* (L.); adult cigarette beetle, *Lasioderma serricorne* (F.); and adult confused flour beetle, *Tribolum confusum* (Jacquelin duVal). Each pest had different susceptibilities to fumigation with carbonyl sulfide, with LC_{90} toxicities ranging from 2.66 to 15.4 mg/liter. The CxT value which resulted in complete mortality for the most resistant life stage of the least susceptible insect tested (i.e., the egg and pupal stage of the adult confused flour beetle) ranged from 750 to 1,008 mg/hr/liter for a 24 hour exposure. Based on these results, it was concluded that carbonyl sulfide could be an effective fumigant for dried fruits and nuts.

The CSIRO Stored Grain Research Laboratory has also conducted tests to identify the effects of carbonyl sulfide treatment on the quality of malting barley, wheat (various types), sultanas, chickpeas, and canola (Desmarchelier 1993). The results of these tests are as follows:

- Barley displayed no significant loss of malting quality when treated with carbonyl sulfide. Similarly, no significant effects have been found on wheat or flour properties with the exception of marginal effects on dough properties. None of these commodities displayed a foreign odor.

- Although research on canola and chickpeas is still underway, researchers found little or no sorption after 24 hour exposures and no detectable odor after 24 hours airing.

- Sultanas fumigated with carbonyl sulfide were assessed for quality by taste, odor, and color change. Fumigated fruit had a distinctive odor, which diminished over time. There were no taste or color changes detected.

Additional research (Desmarchelier 1993) on wheat fumigated with carbonyl sulfide has revealed the following.

- Studies of the sorption of carbonyl sulfide by wheat have been conducted, with the detection of very low levels of possibly naturally occurring carbonyl sulfide in untreated controls. As carbonyl sulfide concentrations in fumigated wheat decline, it becomes increasingly difficult to distinguish carbonyl sulfide in fumigated wheat from that in untreated wheat.

- A comparative study on the effects of carbonyl sulfide and hydrogen cyanide (HCN) on germination and plumule length of wheat indicates that carbonyl sulfide can be used to control insect infestation in wheat without affecting seed viability or plumule length (i.e., it has no effect on seedling vigor and thus potentially is a valuable treatment for seed for planting).

Additional studies being conducted to support carbonyl sulfide registration as a fumigant are evaluations of soil and commodity residue potential, flammability, and the potential for worker exposure. Many of the toxicity, emission, and environmental fate studies needed to complete registration have been completed (Banks 1996, Desmarchelier 1993). Studies to more accurately determine the efficacy of carbonyl sulfide for controlling specific insect species are also being initiated (Zettler *et al.* 1997).

Performance Characteristics

With regard to its potential as a commodity fumigant, carbonyl sulfide has what is considered to be excellent physical and chemical characteristics (Banks 1994, Desmarchelier 1993, Kluczewski *et al.* 1985). Its spectrum of activity, mobility and penetration, efficacy, and environmental fate characteristics are briefly discussed below.

- Spectrum of activity – Carbonyl sulfide effectively controls insect pests and mites. It may also be useful for controlling soil borne pests such as nematodes; additional research is pending.

- Mobility and penetration – Carbonyl sulfide has a high penetration and mobility rate; thereby increasing distribution and efficacy. This characteristic may be particularly useful for fumigation of logs and lumber, where its penetration is much superior to methyl bromide.

- Efficacy – In ten comparative efficacy studies using the rice weevil and lesser grain borer, carbonyl sulfide consistently out-performed carbon disulfide at application rates ranging from 8 mg/L to 24 mg/L and exposure periods of up to two days. Data on direct efficacy comparisons with methyl bromide generally are not available. Efficacy comparisons for treatment of logs indicate that carbonyl sulfide may be comparable to methyl bromide. Further, studies evaluating the efficacy of carbonyl sulfide for controlling stored product insects in dried fruits and nuts indicate the potential for carbonyl sulfide to replace methyl bromide in these applications.

- Environmental fate – Carbonyl sulfide is biodegradable, is a natural part of the sulfur-cycle, and has low water solubility.

Cost Comparison Data

Although cost data for the use of carbonyl sulfide are not currently available because research and development is still in the early stages, it is believed that carbonyl sulfide will be both a technically and economically viable alternative to methyl bromide (Banks 1996 and 1994, Desmarchelier 1993).

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Stratospheric Ozone Protection
Methyl Bromide *Alternative* Case Study

Use of Controlled Atmospheres As A Quarantine Treatment for Table Grapes

Controlled atmosphere technology with elevated carbon dioxide and/or reduced oxygen concentrations can be a viable alternative to methyl bromide as a post harvest quarantine treatment for table grapes. It is effective against insect pests and pathogens (Carpenter and Potter 1994) and has the added benefit of improving the quality of grapes and extending their shelf life by lowering respiration rates (Mitcham *et al.* 1994). Other benefits include the prevention of color change and softening and the maintenance of fruit composition and nutritional value. Furthermore, the gas used in this technology are chemically inert and will not corrode handling equipment (Ke and Kader 1992, Calderon and Barkai-Golan 1990). Unlike some other fumigants, controlled atmosphere treatments (with carbon dioxide and/or nitrogen) do not leave toxic residues on grapes. The treatment also penetrates more easily than most fumigants because of its small molecular size (Smith and Newton 1992). Furthermore, grapes are ideally suited for this treatment technique because they produce very little ethylene (a compound emitted from fruit which stimulates ripening) and are highly resistant to its effects (Lamb 1996).

Technological advances have led to the development of refrigerated controlled atmosphere sea transport shipping containers used by commercial exporters for storage treatment. These containers can be equipped with controlled atmosphere units that control insects and other pathogens. As a result, controlled atmosphere technologies could be used as quarantine treatments. By maintaining low oxygen levels and refrigerated temperatures, decreased commodity spoilage and pest control can be accomplished (Gay 1995). Furthermore, because of the demonstrated benefits of sulfur dioxide in combination with carbon dioxide in the control of black widow spiders (Shorey and Wood 1993), omnivorous leafrollers, and other grape pests, it may be possible to combine these two treatments to achieve even more effective control of grape pests (Mitcham *et al.* 1994).

Benefits of Using Controlled Atmospheres on Grapes

- ✔ *Penetrates easily to reduce or eliminate insects and pathogens*
- ✔ *Increases product value by extending shelf life and enhancing fruit quality*
- ✔ *Prevents color change and softening*
- ✔ *Maintains fruit composition and nutritional value*
- ✔ *Does not corrode handling equipment*
- ✔ *Leaves no toxic residues*
- ✔ *Allows use of more economical surface transport for shipping commodities*
- ✔ *Can be used in conjunction with other treatments, such as sulfur dioxide*

Controlled Atmosphere Technologies

Controlled atmosphere technology has been used to control a variety of economically important pest species including thrips, aphids, and beetles infesting a wide variety of fruits and vegetables, including grapes (Anonymous 1993b). Controlled atmosphere technology works by reducing the respiration of grapes, inhibiting pathogen reproduction, and killing insects and pathogens. The greatest impact on insects is achieved by maintaining low oxygen levels for an extended period of time, leading to oxygen depravation in insect body tissues (Gay 1995). Controlled atmospheres are most effective at preserving grapes when they exhibit no signs of senescence or damage from handling; therefore field packaging, purchase of physiologically younger, less ripe commodities, and installation of ripening rooms may reduce difficulties in using controlled atmosphere technologies for grapes (Anonymous 1993b).

The effectiveness of controlled atmospheres varies depending on the insect species and developmental stage, temperature, oxygen and carbon dioxide levels, and relative humidity. Likewise, factors influencing the grapes treated with controlled atmosphere technology include storage temperature, oxygen concentration, respiration rate, resistance of gas diffusion, soluble solids content, and ethanol accumulation rate of the commodity under a low oxygen treatment (Ke and Kader 1992, Calderon and Barkai-Golan 1990).

Current Research

Current research on the use of controlled atmospheres on grapes is being conducted at the University of California at Davis. The main focus of this research is the development of a quarantine treatment technique for export of grapes from California to Australia (although the same research may later be applied to U.S. imported grapes from Chile). Currently, U.S. grapes are not exported to Australia; however, a proposal for use of controlled atmospheres as a quarantine commodity treatment for grapes shipped to Australia is currently under review (Kader 1996, Christie 1996). Pests of quarantine concern to Australia include the omnivorous leaf roller (*Platynota stultana*), western flower thrips (*Frankliniella occidentalis*), spider mites, and grape mealy bug (*Pseudococcus maritimus*) (Mitcham *et al.* 1994).

Initial studies indicate that table grapes can tolerate and are effectively disinfested by carbon dioxide. For example, Mitcham et al. (1995) demonstrated that by increasing the carbon dioxide levels and lowering temperatures to 45 percent and 0°C to 5°C, respectively, over an 8 to 10 day period results in 100 percent mortality of all life stages in the pests of economic concern. Research is still pending for the Grape Mealy Bug. Grapes have also been evaluated for firmness, soluble solids, berry shatter, browning, and weight loss of the cluster. In general, controlled atmospheres have only minimal effects on grape quality. The most notable difference between treated and non-treated grapes was a decrease in titratable acidity in treated grapes; however, there was not consistent effect on berry shatter, weight loss, or soluble solids. Future research will include consumer taste tests (Mitcham *et al.* 1994 and 1995).

Potential to Use Controlled Atmospheres as Quarantine Control Technology in Grapes

Current U.S. regulation requires that grapes be fumigated with methyl bromide as a condition of entry (i.e., Chilean grapes--which undergo treatment because of a mite). Furthermore, grapes exported by the United States must be fumigated with methyl bromide in order to comply with the quarantine requirements of recipient countries (i.e., Japan). Finding alternatives to methyl bromide as a quarantine commodity treatment is critical because large quantities of grapes are both imported to and exported from the United States and may carry non-indigenous insects and pathogens. In 1989 to 1990, for example, the United States imported an annual average of approximately 372,135 tonnes of grapes of which 302,502 tonnes (92 percent) were fumigated with methyl bromide. In fact, grapes fumigated with methyl bromide represented 34 percent of the annual U.S. fresh grape supplies in that same year (Anonymous 1993a). By comparison, currently 80 percent (1,488,540 tonnes) of table grapes are consumed domestically, while 20 percent (372,135 tonnes) are shipped overseas; therefore, the use of controlled atmospheres could increase trade by lowering costs and extending shelf life (Wineman 1996, Anonymous 1993a).

After a disinfestation treatment, the majority of controlled atmosphere shipments do not require methyl bromide fumigation for quarantine control of pests (Gay 1995b). However, controlled atmospheres are not currently recognized by USDA's Animal and Plant Health Inspection Service (APHIS) as a quarantine treatment, and therefore if a quarantine pest was found on the shipment, fumigation with methyl bromide would be required for quarantine purposes (Gay 1995b). Industry, government, and academic partnerships are currently compiling data on pest control efficacy required to secure quarantine approval. If successful, controlled atmosphere technology for grapes may become an important quarantine treatment technology. Continued research is expected to lead to effective methods to achieve insect control that will satisfy strict international quarantine regulations (Gay 1995, Mueller 1994, Delate and Brecht 1989).

Costs

Although controlled atmosphere technologies require significant operating, labor, and capital investments in hardware required to customize containers, the benefits in these investments far outweigh the costs, making it an economically viable alternative to methyl bromide (Anonymous 1993b). Estimating costs for application of controlled atmosphere technology compared to methyl bromide use is presented in Table 1 below. Two standard methods used to conduct controlled atmosphere treatments are presented independently. Although capital, labor, and operating costs vary between these two methods, their total costs are similar. The first method has low capital costs but high labor and operating costs, while the opposite is true for the second method.

In the first treatment method, the controlled atmosphere unit partially displaces air in the container by purging the container with carbon dioxide (usually supplied via a compressor) and closing the system until the container has reached its final destination. The second method is believed to be more effective because it is more automated. The process generates nitrogen from surrounding air, which is then pumped into the chamber. Gas concentrations in the containers are then monitored and maintained throughout transport in an open system which vents gases to the atmosphere (Lamb 1996, Calderon and Barkai-Golan 1990). In general, the cost to adapt a shipping container for controlled atmosphere treatments cost between $800 to $7,000 per container, depending on which type of treatment method is used, the number of containers shipped, the type of commodity, destination, place of origin, and pests of concern (Cea 1996, Gay 1995). Typically controlled atmosphere equipment has a useful life of about 10 years and is used between 6 and 12 times a year. Currently commercial facilities only use controlled atmospheres to improve grape quality and extend shelf life; however, it was assumed that storage treatment costs (operating and labor costs) would be comparable to the costs of disinfestation treatments with controlled atmospheres. As a result, treatment costs range from $800 to $1,200 per container. Fumigating grapes with methyl bromide, on the other hand, costs nearly twice as much as controlled atmosphere treatments. Specifically, operating/labor costs for methyl bromide fumigation represents a large percentage of the total costs, while capital and chemical costs are relatively minor.

If controlled atmosphere technology becomes an approved quarantine treatment, shippers will quickly recover their initial investment as expensive methyl bromide treatments will no longer be required. Furthermore, methyl bromide can often damage, destroy, or shorten the shelf life of grapes. Therefore, the risks associated with reduced inventory due to fumigation can partially offset the costs of using controlled atmosphere technology (Murphy 1995). Lastly, controlled atmosphere treatments add significant value to grapes by extending and improving both their quality and shelf life and enabling them to be shipped using surface transport where aircraft or airlift transport was required previously (Gay 1995).

Table 1. Costs Comparison for Controlled Atmospheres vs. Methyl Bromide.

Cost Factors	Controlled Atmospheres Case #1 and #2 ($/tonne)		Methyl bromide ($/tonne)
Annualized Capital	<1	8	5
Labor & Operating	45-58	66	100-150
Chemical	N/A	N/A	<1
Total	46-59	74	106-156

Notes: N/A = Not applicable.
Sources: Rodde 1996, Lamb 1996, Cea 1996, Folwell 1996.

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Methyl Bromide *Alternative* Case Study

Phosphine/Carbon Dioxide Combinations As Alternatives to Methyl Bromide in Structural and Commodity Fumigation

This is an update of a July 1995 EPA report (Alternatives to Methyl Bromide, Ten Case Studies) entitled "Structural Fumigation Using a Combined Treatment of Phosphine, Heat, and Carbon Dioxide". Considerable work has been done since that report with regard to the described pest control method, as well as two other methods which also use significantly reduced amounts of phosphine combined with carbon dioxide. This report presents these methods as viable alternatives to the use of methyl bromide in appropriate treatment situations.

Currently seven percent of domestic methyl bromide consumption is for commodity and quarantine fumigation (Anonymous 1994b). Phosphine, another fumigant gas, has been used successfully to control insects in a number of plant and animal commodities (especially stored products), and therefore can be a viable alternative to methyl bromide treatments. Compared to methyl bromide, phosphine treatments can be more economical and easier to use in some situations . When used correctly, phosphine can have a broader spectrum of activity, penetrate more effectively and deeper into commodity storages (thus reducing the number of fumigations required and the amount of shut down time needed to perform the fumigation) and can exceed the 95 percent minimum kill rate required for methyl bromide fumigations (Sloane Group 1996).

Benefits of Phosphine Treatments

- ✓ *Economical and easy to use*
- ✓ *Has a broad spectrum of activity*
- ✓ *Penetrates commodities deeply and effectively*
- ✓ *Requires less frequent fumigations*
- ✓ *Leaves very little residue*
- ✓ *Has a high percentage kill rate and eradicates most pest species at most life stages.*

Existing phosphine formulations available on the market include air-tight packages of pellets, tablets and plates (sachets) which contain and inert ingredients. Once the package is opened, the metallic phosphides contacts with moisture in the air, and phosphine gas is slowly produced. The metallic phosphides most commonly used include: magnesium phosphide (used primarily in the United States because it is safer and releases phosphine faster than other phosphine compounds), calcium phosphide, and aluminum phosphide (primarily used in Canada) (Phosphume™ 1996, AAC 1996, Sloane Group 1996). During conventional phosphine commodity treatments, structures are first sealed and then the solid fumigant is placed in the container or structure in several places to assure complete gas dispersion. Phosphine levels reach the desired concentration in 3 to 10 days to achieve the proper effect. Following treatment, the structure is aerated and the inert ingredient residue disposed of properly (Kelley 1997).

Although conventional phosphine treatments are convenient to use, there are use limitations as a commodity treatment. For example, conventional phosphine treatments can take up to two days to reach required concentrations, leave residual dust after the treatment, and can be corrosive to precious metals or alloys (i.e., copper, brass, gold, silver). There are also health and safety concerns associated with handling products that emit phosphine when exposed to the air (sometimes at flammable concentrations leading to unexpected fires and possible explosions) (Phosphume™ 1996, AAC 1996, Kelley 1997, Sloane Group 1996).

Because of these disadvantages to conventional phosphine treatments, recently improved phosphine treatment methods: such as the combination method (using heat, phosphine, and carbon dioxide); the cylinderized phosphine gas ECO_2FUME; and the TURBO HORN (phosphine) GENERATOR, may be more appealing alternatives to methyl bromide treatments in the future. A more detailed description of these treatment techniques is presented below.

Phosphine Treatment Techniques

COMBINATION TREATMENT

Combining heat, phosphine, and carbon dioxide as a commodity treatment technique was first tested in 1992 and refined and patented by David Mueller of Fumigation Service & Supply Inc. (FSS) in Indianapolis. Since then researchers in the United States at Purdue University and Oklahoma State University, and in Canada, South America, and Europe have demonstrated the effectiveness of combination treatments as a pest control method in flour mills (e.g., Hawaiian Flour Mill in Honolulu and the Quaker Oats Company of Canada Limited), food processing plants, and museums (Anonymous 1994a, AAC 1996, McCarthy 1996). The combined treatment consists of 50 to 100 ppm phosphine (9 to 18 percent of the standard phosphine concentration), heat (89.6-98.6°F, 32-37°C), combined with 4 to 6 percent carbon dioxide. Using low concentrations of phosphine reduces the chance of corrosion of metallic materials at facilities, a common problem associated with conventional phosphine treatment techniques. Furthermore, heat and carbon dioxide help reduce moisture, thereby limiting corrosion. The process relies on heat and carbon dioxide to increase the susceptibility of pests to phosphine by interfering with insect metabolism (i.e, by dilating insect spiracles, increasing respiration and interfering with cellular energy cycles). This stress on the insect allows for low levels of phosphine to more effectively kill all insect life stages, including the egg stage (Anonymous 1994a, Mueller 1994a). Experiments have shown that combined treatments can produce 100 percent mortality within 24 hours or less for the egg, larvae, pupae, and adult stages of stored-product insects, including the *Angoumois* grain moth, red flour beetle, warehouse beetle, and rice weevil (Mueller 1994b).

Over the last five years, more than 40 successful combination fumigations have been performed. Twenty-four of these have been for flour mills, resulting in use reductions of over 100,000 lbs. of methyl bromide (Mueller 1994b, Mueller 1994c, Mueller 1996a). This patented process is less expensive than heat, more practical than carbon dioxide, and safer and more effective than phosphine alone (AAC 1996, Mueller 1994c). As a result, the combination technique shows promise as a replacement for methyl bromide in flour mills and food processing facilities (Anonymous 1994a).

ECO₂FUME

BOC Gases Group has developed and patented ECO_2FUME, a gaseous phosphine fumigation mixture that can be used as an alternative to in-situ generation of phosphine from metallic phosphides. It consists of 2.6 percent by volume of phosphine in carbon dioxide premixed in a cylinder and can be used on a wide variety of products, including foods, tobacco, timber and cane products, buildings, and other structures (Phosphume™ 1996, Carmi *et al.* 1995, Sloane Group 1996).

Eco_2Fume appears to offer many advantages over other phosphine fumigation techniques, including improved health and worker safety, environmental benefits, and product quality (Ryan 1991, Phosphume™ 1996, Carmi *et al.* 1995, Sloane Group 1996). Since Eco_2Fume is premixed and ready to use, the need for on-site mixing is eliminated. The gas is dispensed directly from the cylinder into a sealed structure to be fumigated. The technique achieves the required concentration in a matter of hours, allowing for greater and more immediate control of phosphine concentrations during the entire fumigation period. Because the gas is dispersed quickly and reaches the desired concentration in a short period of time, the treatment itself is shorter, and may result in less frequent fumigations, thus reducing the risk of corrosion. The treatment prevents incomplete or variable phosphine generation (such as that acquired with the use of metallic phosphides), eliminates the need for disposal of residual product, and reduces worker exposure.

As of the date of this publication, Eco_2Fume does not have a label which allows use as a commodity or quarantine treatment technique in the United States. However researchers are collecting data and developing the necessary information to meet regulatory requirements. Studies are also being conducted on the use of Eco_2Fume in quarantine situations (e.g. pre-shipment, pre-marketing fumigations). Furthermore, BOC has initiated plans for plant production and sourcing of phosphine. The registration process to receive use labels has been initiated in the U.S., Canada, Europe, and other parts of the world. The product is expected to be available on the global market by the end of 1997, registered as Eco_2Fume in the U.S. and Canada, and Phosfume™ in Australia and Europe (Mueller 1996b, Anonymous 1997). Although Eco_2Fume has not been used extensively in the United States, over 9 million metric tons of grain are fumigated in Australia each year using the Phosfume™ process (Sloane Group 1996, Anonymous 1997). Eco_2Fume also has proven to be highly effective and beneficial to the cut flower industry (MacDonald and Mills 1995), and as a result, this pest control tool has good potential to be a viable substitute for methyl bromide in this and other commodity fumigation applications (Mueller 1996b, Kelley 1997, Carmi *et al.* 1995)).

TURBO HORN GENERATOR

A new method of generating phosphine gas, the Turbo Horn Generator (manufactured by Fosfoquim S.A. in Santiago, Chile) has been developed, field tested, and patented by Degesch de Chile. The method involves an apparatus that rapidly produces phosphine on site when magnesium phosphide granules (a new product) are placed in the unit with water, producing hydrogen phosphide under controlled conditions. The gas is then mixed in the apparatus with air and carbon dioxide until hydrogen phosphide concentrations reach approximately 2.5 percent. The gas then is pumped directly into the structure to be fumigated, while air is drawn from the structure and recirculated through the system to maintain a constant pressure and distribution. The system quickly produces large amounts of gas from a relatively small amount of reactants and can quickly be reloaded to produce more gas if necessary. Residues or any remaining reaction products remain in the apparatus and can easily be disposed of following treatment. Lastly, the generator is computerized to operate automatically or manually and will stop automatically if any irregularity or technical problems occur (Fosfoquim S.A. and Degesch De Chile Ltda 1996).

Advantages of the Turbo Horn Generator include a flexible system where gas concentrations can be adjusted at any time during the fumigation, and allows gas generation under various temperatures and humidities. Furthermore, the system is easy to use and cost effective. This technique has already been successfully utilized in several flour mills, granaries, and silos (Fosfoquim S.A. and Degesch De Chile Ltda. 1996).

Costs

In general, the cost of phosphine treatments are only slightly higher than those using methyl bromide. This is attributed to the fact that phosphine treatments require marginally more equipment, labor, and technical expertise than methyl bromide treatments (Table 1). However, phosphine treatment costs are expected to decrease in the future as new advances in phosphine gas generation technology are made. For example, after initial capital costs, the Turbo Horn Generator is less expensive than conventional phosphine treatment techniques. Furthermore, because much of the cost for conventional fumigations is that associated with the facility shutdown time necessary to complete disinfestation, phosphine treatments, when correctly applied, are cost effective because they can require a shorter shutdown than required for methyl bromide treatments (Mueller 1994c).

Table 1. Comparison of Phosphine and Methyl Bromide Treatment Costs
($ per 1,000 cubic feet)

Cost Factor	Methyl Bromide	TURBO HORN Generator	ECO_2FUME	Combination Treatment	Aluminum Phosphide Tablets	Magnesium Phosphide Plates
Labor	$4.25	$4.50	NA	$4.50	$4.75	$5.10
Equipment	$0.25	$0.75	NA	$1.25	—	—
Chemical	$1.15	$1.00	NA	$1.50	$2.00	$4.50
Additional	$1.75	$1.85	NA	$2.00	$1.50	$1.50
TOTAL	$7.40	$8.15	NA	$9.25	$8.25	$11.10

Notes: NA = not available at this time.
Source: Mueller 1994c, Sullivan 1997.

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