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EPA
United States Environmental Protection Agency
Office of Air and Radiation (6205-J)
December 1996

Stratospheric Ozone Protection

Methyl Bromide Alternatives

10 Case Studies Vol. II

Foreword

This is the second EPA publication of case studies describing alternatives to the pesticide methyl bromide. As with the first volume 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.

It is now clear that methyl bromide is a significant stratospheric ozone depleting chemical, and agricultural use of this material 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.

EPA recognizes the importance of a pest control agent like methyl bromide to 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 set of case studies, and has committed to publish two more volumes of 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. The individual elements are considered in these case studies as a way to define and characterize the wide array of alternatives to methyl bromide.

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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This publication discusses specific proprietary products and pest control methods. Some of these alternatives are now commercially available, while others are in an advanced stage of development. In all cases, the information presented does not constitute a recommendation or an endorsement of these products or methods by the Environmental Protection Agency (EPA) or other involved parties. Neither should the absence of an item or pest control method necessarily be interpreted as EPA disapproval.

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Methyl Bromide Alternatives
10 Case Studies Vol. II

Table of Contents

Note: Page numbers have been purposely excluded from this document to allow individual case studies to be copies and distributed.

EPA

United States
Environmental
Protection Agency

Office of Air and Radiation
(6205-J)

December 1996

Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Using Nematode Resistant Cultivars As An Alternative to Methyl Bromide for Selected Crops

Nematode resistant cultivars can be used as part of an integrated approach to develop an effective alternative to methyl bromide against a wide variety of nematodes for a wide variety of crops, particularly high value vegetable and fruit commodities. Crops for which both nematode resistant cultivars have been developed and for which methyl bromide has been used include both seed crops (tomatoes, bell and hot peppers, and tobacco) and vineyard/orchard crops (grapes, peaches, plums, apricots and nectarines, walnuts, almonds, and citrus) (Slaughter 1996, Fortnum 1996, Noling 1996, McKenry and Kretsch 1995, Thies et al. 1995, Khan and Khan 1991, Lehman and Cochran 1991, Cook and Evans 1987).

Nematode resistant cultivars have a number of distinct non-commodity-specific advantages over the use of methyl bromide, including 1) complete prevention of nematode reproduction, 2) no requirements for special application techniques or equipment, and 3) comparable costs to non-resistant cultivars. Nematode resistant cultivars are particularly effective because they can be used in conjunction with other pest control practices (i.e., sanitation, soil solarization, soil amendments (compost and manure), biological control, crop rotation, and early planting scheduling to reduce or eliminate nematode infestation (Dunn 1993, Lehman and Cochran 1991, Cook and Evans 1987).

Benefits of Nematode Resistant Cultivars

- ✓ *Reduces the need for methyl bromide*
- ✓ *Prevents nematode reproduction*
- ✓ *Requires no special application techniques or equipment*
- ✓ *Comparable costs to non-resistant cultivars*
- ✓ *Can be used in conjunction with other pest control practices*

Nematodes

Nematodes (microscopic unsegmented roundworms) are defined as any member of the Phylum *Nematoda*, including those that are parasitic to plants and animals. Plant parasitic nematodes are extremely common in soil, where they live primarily in a film of water which surrounds soil particles. A single gram of top soil can contain over one thousand of these tiny organisms. Nematodes generally interfere with water/nutrient availability and a plant's feeding mechanisms (i.e., root function and plant growth processes) (Ashwroth 1991). Many species of nematodes exist, and they attack an enormous variety of plant species. The most common are the root knot nematodes, *Meloidogyne arenaria, Meloidogyne incognita, Meloidogyne javanica*, and *Meloidogyne hapla*. Root knot nematodes alone have a host range of over 2,000 plants (McKenry and Roberts 1985).

The response of plants to nematode infestation varies considerably according to the species of nematode/plant and environmental conditions such as host status, soil temperature/moisture/structure, aeration, organic matter, fertility level, nutrients, nematode predators/parasites, etc. (Gaur and Seshadri 1986). Symptoms of nematode-damaged plants are generally non-specific and are characterized by poor growth, plant stunting (through the presence of root galls), crop patchiness, wilting, and chlorosis (yellowing or discoloration of leaves). As a result, preliminary examination of the crop usually does not provide unequivocal diagnosis of nematode damage. For example, plant symptoms indicative of nematode infestation can also result from other variables, such as low or excess fertilizer, low water holding capacity, or poor drainage of soil. Furthermore, plant symptoms in the field may be widespread or patchy, depending on differences in the nematode densities in the field or the placement of infested planting stocks (Lehman and Cochran 1991, McKenry and Roberts 1985). Plants stunted or diseased by nematode related activity may not die, but are likely to produce reduced yields (Hauge and Gowen 1987, McKenry 1987). Plant deaths are generally not attributed directly to nematode damage, but instead to secondary pathogens (i.e., fungi and bacteria), which invade plants weakened by nematodes (McKenry and Roberts 1985).

Outlook for Nematode Resistant Cultivars as a Replacement for Methyl Bromide

Plant breeders have developed nematode resistant cultivars in an effort to prevent the stunted growth and deformed or galled roots of plants commonly infested with nematodes. *Cultivars* are defined as cultivated plants which are produced by breeding programs and are distinguished by characteristics significant for agriculture, forestry, or horticulture, and which, when reproduced, retain their distinguishing characteristics (Lehman and Cochran 1991, Cook and Evans 1987). *Level of resistance* describes the effect of the host on nematode reproduction. A *completely resistant* plant allows no nematode reproduction, *non-resistant* or *susceptible* plant allows nematodes to multiply freely, and *partially resistant* plants support intermediate levels of reproduction (Cook and Evans 1987). *Nematode resistant cultivars* are plants bred specifically to inhibit nematode reproduction and resist the impact of nematodes on plant growth and production, while nematode resistant vineyard and orchard crops also can be developed by grafting high yield cultivars to resistant rootstocks (Titts 1996). Ideally nematode resistance cultivars are bred for both *resistance* (suppressed nematode reproduction) and *tolerance* (nematode feeding will have little impact on plant growth and crop yield).

Resistant cultivars are already widely used for specific crops in the United States, particularly in California and Florida. No fruit or vegetable nematode resistant cultivars are resistant to all nematodes; however, many have resistance to the most common nematodes, and often in combination with resistance to one or more other pathogens. If they are otherwise suitable, nematode resistant cultivars are typically planted when no nematicide is used, but are desirable even when other chemical treatments are used (Dunn 1993). Crops where pre-plant fumigation with methyl bromide is used and nematode resistance cultivars developed include both seed crops (tomatoes, bell and hot peppers, and tobacco) and vineyard/orchard crops (grapes, peaches, plums, apricots, nectarines, walnuts, almonds, and citrus). Crops frequently fumigated with methyl bromide for which there are no nematode resistant cultivars in significant commercial use to date include: eggplant, cucurbits, carrots, broccoli, cauliflower, melons, and strawberries (Becker 1996). However, currently there are significant research efforts underway to develop nematode resistant cultivars for many of these crops. For example, Scientists at North Carolina State University have tested five cultivars of cucumber for resistance to root knot nematodes, these cultivars (*C. metuliferus* and 'Sumter') account for approximately 12% of the cucumber crop grown annually in North Carolina. Preliminary results indicate that the cultivars vary in their resistance to the four root-knot nematode species (Wehner et al. 1991). Likewise, Canadian scientists are conducting research on the resistance and tolerance of strawberry cultivars to the lesion nematode, *Pratylenchus penetrans* (Potter 1995).

Costs

Currently, a large percentage of crop production where nematode resistance has been commercialized utilizes nematode resistant cultivars (e.g., up to 90 percent for seed crops, 95-100 percent for orchard crops, and 70-85 percent for vineyards), often in conjunction with pre-plant methyl bromide fumigation. For these crops, gains in plant vigor and yield have been achieved through use of resistant cultivars. Applications of methyl bromide are utilized in order to protect the crop from competition from weeds, diseases from fungi, and damage caused by non-susceptible nematode species. For crops where nematode resistant technology is currently not available, development and commercialization of resistant cultivars, as part of an integrated system utilizing substitute fumigants (e.g., metam sodium) or non-chemical alternatives (e.g., solarization), may enable growers to achieve yields currently realized under production systems utilizing methyl bromide fumigation. It should be noted that other pests, such as weeds, will need to be managed on an as needed basis, which may add costs to both resistant and non-resistant crop production.

Production costs under a system that uses nematode resistant cultivars in conjunction with an alternative fumigant can be compared to a system that utilizes methyl bromide with no crop resistance (table 1). A comparison of these cost estimates is provided in Table 1. Although the cost of resistant cultivars may be slightly higher, yield increases and lower fumigant treatment costs may help to offset these increases. Furthermore, the costs of nematode resistant cultivars are expected to decrease in the future as a wider variety of cultivars become available on the commercial market. In addition, there are other financial benefits of nematode resistant cultivars including cost savings from growing crops on land most suited to their production (rather than letting the presence of nematodes in a field be the deciding factor for which crops to grow). Finally, through breeding for resistance, seed producers are also able to combine resistance with other traits including better marketability, longer shelf life, and increased yields. (Seals 1996, McKenry 1996, Slaughter 1996, Titts 1996, Emershad 1996, Cook and Evans 1987, Cotton 1996).

More research dedicated to the future development of nematode resistant cultivars is needed. The successes in the development of nematode resistant cultivars discussed earlier in this document are promising; however, more varied nematode resistant cultivars must be developed in order for this practice to develop into a broadly applicable alternative to methyl bromide.

Table 1. Comparative Costs of Resistant versus Non-Resistant Cultivars

Cost Factors	Treatment #1: Alternative Fumigant[a]/ Resistant Cultivar ($/acre)	Treatment #2: Methyl Bromide/ Non-Resistant Cultivar ($/acre)
Treatment Cost	750-1,000	1,200-1,500
Cultivar Costs[b]	50-1,000[c]	10-40[c]
Total	1,050-1,750	1,240-1,510

[a] Alternative fumigant is metam sodium (Vapam®).
[b] Assumes 1 pound of seed planted per acre.
[c] Based on a hybrid cost range of $50-75 for cucurbits and $500-1000 for tomatoes and eggplants; and a open pollinated cost range of $10-40 for cucurbits, tomatoes, and eggplants.

Sources: Seals 1996, McKenry 1996, Slaughter 1996, Titts 1996, Emershad 1996, Noling 1996, VanSickle 1996, Cotton 1996.

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Stratospheric Ozone Protection
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Methyl Bromide Alternative

Chloropicrin Applications for California Strawberries

Preplant soil treatment with chloropicrin (trichloronitromethane), alone, or in combination with other soil fumigants and pest control measures, can be used by strawberry growers as an alternative methyl bromide. Currently, there is widespread use of methyl bromide formulations that typically contain 33 percent chloropicrin for preplant fumigation treatments of strawberry nursery and production fields. These fumigation treatments are performed prior to planting and typically provide significant season-long control of a broad spectrum of soilborne pests, including a variety of fungal and nematode pathogens and weeds (USDA 1996).

The strawberry industry in California has favored the use of methyl bromide formulations that contain chloropicrin because of the synergistic effects of these two compounds. Tests and field experience have verified these effects and have shown that chloropicrin offers superior control of fungal pests, whereas methyl bromide is a better broad spectrum fumigant with efficacy against a wide range of pathogens, including weeds and nematodes (Liebman 1994, Wilhelm and Storkan 1990).

Benefits of Chloropicrin

- ✔ *Effectively controls soilborne fungal pathogens.*
- ✔ *Its effectiveness is increased when used in combination with other soil fumigants.*
- ✔ *Is commercially available as the sole active ingredient or in formulations with Telone®.*

Recent interest in developing effective alternatives to the use of methyl bromide as a preplant fumigant in the California strawberry industry has led to design of experiments and field trials which test the effectiveness of chloropicrin in both nursery and field settings, alone, and in combination with fumigants such as Vapam® and Telone®. The results of field studies suggest that the use of chloropicrin will offer strawberry nursery and fruit producers in California a pest management tool for combating soil diseases caused by soilborne fungal pathogens (Duniway and Gubler 1996, Duniway et al. 1994, Coffey et al. 1994, Welch and Gubler 1994). Furthermore, in situations where soil fungi are the principle pests of concern, and other pests such as weeds and nematodes are controlled through other measures (e.g., alternative fumigants), it is possible that the use of chloropicrin will allow strawberry producers to effectively control soilborne fungal pathogens thereby promoting strawberry plant growth and crop yields similar to those achieved with methyl bromide fumigation.

The Importance of Fumigation to Strawberry Production in California

Finding alternative soil pest control measures has been a priority for the California strawberry industry because of its reliance on methyl bromide/chloropicrin fumigation to achieve superior yields and high quality fruit. California produces 75 to 80 percent of the nation's strawberries on less than half of the total U.S. strawberry acreage planted each year (Welch 1989). Average yields in California range from 24 to 40 tonnes per acre, values that are several times higher than those found in other parts of the country (i.e., Florida, Oregon, and North Carolina). In 1995, there were 23,600 acres of strawberry production in California yielding 1.19 billion pounds of strawberries with an average wholesale price of $46.30/100 lbs. Overall, the 1995 California strawberry crop was valued at $552 million (Hill 1996).

California's high strawberry yield can be attributed to the fact that California has adopted an annual planting system, developed highly productive strawberry cultivars, and has a cool climate to enhance strawberry production (USDA 1994). Because plants are grown as annuals, strawberry production in California occurs throughout most of the year (Welch 1989). Nearly all strawberry acreage in California is fumigated to control weeds, fungi, and nematodes, and use clear plastic mulch, irrigation, and fertilizers. Approximately 4.5 million pounds of methyl bromide are used annually in California for pre-plant fumigant of strawberries, representing roughly 35 percent of the total use of methyl bromide in California, 7 percent of United States use, and 4 percent of world use (DPR 1990-1992, NAPIAP 1993, UNEP 1992, EPA 1995).

In addition to its widespread use in fruiting fields, methyl bromide is considered to be a critical part of current produciton practices for strawberry nurseries to ensure the cleanliness of transplanted nursery stocks. Strawberry runners (transplants) are produced in nurseries and are then shipped to the fruiting fields throughout coastal and southern California each year where they are transplanted. All California strawberry growers depend on clean nursery stocks each year because there is a high risk that pathogens can be transplanted from the nurseries to the fruiting fields. In addition, researchers depend on nursery stock that has been produced using pre-plant fumigation with methyl bromide/chloropicrin (Larson 1996).

In California, fumigation with methyl bromide/chloropicrin is typically performed by contract applicators. Fields are covered with a clear plastic during the fumigant application process to hold the gas in the soil and increase efficacy (Voth et al. 1973). The tarp is removed after at least 24 hours and a clear polyethylene mulch is applied (usually in November) to warm the soil and promote early plant growth. Plants are then set into the planting beds in pre-moistened soil. If bed fumigation is used, the fumigation plastic remains in place for the duration of the crop cycle (USDA 1994).

Advantages of Chloropicrin

Chloropicrin currently appears to offer advantages as a soil fumigant because its use parameters are relatively familiar to applicators and its efficacy on economically important pests has been well documented. Despite the proven benefits of chloropicrin, the long-term effect of soil fumigation with higher dosages chloropicrin, community exposure concerns, and requisite dosages are still being evaluated.

Chloropicrin is a restricted use pesticide and is available in formulations with Telone® or as the sole active ingredient. Chloropicrin is typically injected six to eleven inches into the soil as a liquid 14 days or more before planting. It is a clear, colorless, nonflammable liquid with a moderate vapor pressure, and it rapidly diffuses through the soil profile and is toxic to common root destroying fungi. Chloropicrin is not considered to pose a threat to the ozone layer, it undergoes rapid degradation in sunlight, it is metabolized in soil to form carbon dioxide, and is not expected to accumulate in plant tissue. In addition, it is not soluble in water and therefore is not expected to pose a threat to groundwater. Finally, it is not expected to accumulate in animal cells. (USDA 1996).

Research on the efficacy of chloropicrin for strawberry production has been conducted and is ongoing. Chloropicrin is best known for its wide spectrum effectiveness in controlling soilborne fungi; however, it has particular effectiveness in controlling several genera, including *Ceratobasidium, Colletotrichum, Cylindrocarpon, Fusarium, Idriella, Phytophthora, Pyrenochaeta, Pythium, Rhizoctonia, and Verticillium,* all of which are known to cause root rot and/or wilt diseases in strawberries (Wilhelm and Westerlund 1993, Maas 1984). Chloropicrin may also have some degree of control of root destroying insects, slugs, snails, earwigs, root weevils, grubs and root lesion types of nematodes (Wilhelm and Westerlund 1993, USDA 1996).

Although some studies have shown that chloropicrin, when used as the sole active ingredient, is not as effective as methyl bromide/chloropicrin for fruit production or for the production of certified nursery stock (Shaw 1996, Larson 1996), a number of studies have indicated that strawberries treated with chloropicrin achieve yields similar to those attained with methyl bromide. For example, one California study demonstrated that strawberries planted in soil treated with 20 gallons chloropicrin per acre resulted in higher yields (6,428 trays/acre) compared to those grown with methyl bromide/chloropicrin (6,265 trays/acre) (Welch and Gubler 1994). Likewise, a similar study by Larson and Shaw (1994) found that approximately 100 pounds of chloropicrin applied produced higher yields

(2,322 trays/acre) compared to that produced with methyl bromide/chloropicrin (2,303 trays/acre). The positive results of these studies support the findings that chloropicrin is an excellent fumigant for the control of soilborne fungi.

However, because the use of chloropicrin is not as effective as other compounds (e.g., Telone®) in controlling weeds and nematodes, research is now being conducted to further evaluate the effectiveness of chloropicrin when it is used in conjunction with other chemicals (Coffey, et al. 1994, Duniway and Gubler 1996). Results from these studies suggest that by combining chloropicrin treatments with other treatments, especially Telone®, control of many of the nematode and weed pests currently controlled with methyl bromide/chloropicrin fumigation treatments may be possible. In addition, the development of fumigant formulations that contain higher levels of chloropicrin may provide excellent pathogen control without requiring alterations to existing cultivation methods (USDA 1996).

Costs

Strawberries are among the most expensive crops to grow, with annual production costs as high as $24,600 per acre (attributed primarily to materials and harvesting costs) (Gliessman et al. 1990). Although profits and losses vary considerably depending on the size of the crop and fluctuations in market price, profits of $3,500 to $5,000 per acre or more have been reported (Gliessman et al. 1990, Webb 1994, Cochran 1994).

Although costs resulting from the need to perform additional pest control measures may be incurred (e.g., application of Telone®), the actual costs associated with applying chloropicrin (e.g., injection and tarping) will be similar to those for methyl bromide (Wilhelm 1995). However, one of the principle differences in the cost of chloropicrin versus methyl bromide/chloropicrin use in the California strawberry industry will be the material cost of the chemical (i.e., $675/acre for chloropicrin compared to $615/acre for methyl bromide/chloropicrin (67:33)). A material cost comparison is provided in Table 1 below:

Table 1. Raw Materials Cost Comparison

Cost Factor	Treatment #1 Chloropicrin	Treatment #2 Telone®/ Chloropicrin (70:30)	Treatment #3 Methyl bromide/ Chloropicrin (67:33)
Application Rate	100 to 300 lbs. a.i./acre	350 to 450 lbs. a.i./acre	300 to 375 lbs. a.i./acre
Cost per Pound	$2.25/lb.	$1.59/lb.	$1.64/lb.
Total Material Cost	$225 to $675/acre	$556 to $715/acre	$492 to $615/acre

Sources: Wilhelm 1995, Asgrow 1995, Coffey, et al. 1994, Duniway et al. 1994, Fowler 1996.

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Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Organic Strawberry Production As An Alternative to Methyl Bromide

Organic strawberry production is an effective integrated approach that offers an alternative to methyl bromide use for California strawberries. Organic producers do not use methyl bromide or any other synthetic pesticide or fertilizer in the production of certified organic strawberries (MBRTF 1995). Instead they use organically acceptable production methods to control or suppress weeds, plant pathogens, and nematodes including the use of plastic mulches coupled with supplemental hand weeding to suppress weeds, release of mass-reared beneficial insects, soil solarization, good sanitation practices, resistant cultivars, biological control fungi and/or organic matter, hot water treatments, crop rotation, various cultural controls, and irrigation management practices (Liebman 1994, University of California 1993, Liebhardt et al. 1989). These techniques are part of an overall integrated pest management (IPM) program.

There are several advantages to converting conventional, high-input strawberry production systems to organic systems, including elimination of synthetic fertilizers and pesticides and the building of healthy soil. Recent improvements in organic strawberry production have resulted in yields as high as 89 percent of that obtained from conventional strawberry production. Furthermore, organically grown strawberries can be sold at a higher price than conventional strawberries, thus offsetting any yield reductions (Cochran 1995). While only a small percentage of the California strawberry crop is produced organically, price premiums of as much as 50 to 100 percent for certified organic strawberries provide a considerable incentive for growers to consider organic production techniques in the future (Gliessman et al. 1994). Organic strawberry production also eliminates environmental stress caused by pesticide use, thus increasing soil biotic diversity and beneficial organisms (i.e., a complex of natural predators and parasites) (Liebman 1994, Baker 1996).

Benefits of Organic Strawberry Production

- ✓ *Allows for elimination of synthetic fertilizer and pesticide inputs*
- ✓ *Produces yields as high as 89 percent of that obtained from conventional strawberry production*
- ✓ *Increases price premiums by 50 to 100 percent over that for conventional production practices.*
- ✓ *Reduces environmental stresses and permits an increase in biotic diversity and beneficial organisms*
- ✓ *Reduces the need for methyl bromide and other synthetic pesticides and fertilizers*

Despite the advantages of organic production as an alternative to methyl bromide, it is unlikely that all strawberry farms will switch to organic production. If all large growers did shift to organic production practices, the price differential between conventional vs. organic strawberries would decrease along with some of the price incentives to convert to organic production practices (Baker 1996, Cochran 1996). Instead, without methyl bromide, most conventional (non-organic) California strawberry producers probably would be able to use a variety of other pesticides to help improve yields over those obtained under organic systems alone. For example, the use of chloropicrin, and other synthetic chemical treatments applied in addition to the "organic" approaches discussed here can further improve yields (Gliessman et al. 1996).

California Fresh Market Strawberries

California strawberry growers produce 75 percent of the fresh market strawberries and 80 percent of the processed strawberries in the United States (Welch 1989) on only about 19,250 acres of land (mainly in Central Coastal counties in California) (Gliessman et al. 1996, Larson and Shaw 1994). Strawberry production in California typically occurs all year long (Welch 1989) with yields steadily increasing over time for the last four decades, making it one of the most valuable and stable crops in the state (Wilhelm and Paulus 1980). However, strawberries are also one of the most expensive/labor intensive crops to grow (Gliessman et al. 1990 and 1996, Webb 1994, and Cochran 1995). Although strawberries are a perennial crop, commercial growers in California treat them as annuals, planting new transplants from nurseries in the Sierra foothills each year (Liebman 1994). Californian farmers routinely obtain superior yields over producers in other states (i.e., Oregon, Florida, Louisiana, and North Carolina). For example, California strawberry production yields average 24 tons per acre, with some growers obtaining between 35 to 40 tons per acre, several times higher than that achieved in other states (Wilhelm and Paulus 1980).

The loss of methyl bromide will also have an impact on strawberry nurseries. Because California strawberries are grown as annuals, nurseries must grow transplants for the entire crop each year. In the past, methyl bromide has been the key to producing clean planting stocks. However, without methyl bromide, careful monitoring for pests, vigilant sanitation efforts, and the use of other soil disinfestation techniques (i.e., steam and biocontrol inoculants) will be needed in the future. In addition, it may be necessary to grow plants in bags of sterilized peat or rock wool, similar to that used for strawberry production in The Netherlands and for other nursery crops in the U.S. (Liebman 1994).

Overview of Methyl Bromide Use in Conventional California Strawberry Production

Methyl bromide has been used extensively as a preplant fumigant in California strawberry production and is one of the keys to the stability and economic viability of the California strawberry market (Wilhelm and Paulus 1980). In 1992, about 85 percent of the state's crop was planted on land that was fumigated with a total of 4.5 million pounds of methyl bromide (USDA 1993), representing approximately 25 percent of all methyl bromide applied in California and about 10 percent of the total annual domestic use of methyl bromide (Liebman 1994). The only strawberry land that is not fumigated are those plots certified for organic production (less than 100 acres in the state) or crops left in the ground for a second year (10-20 percent of California's strawberry acreage) (Westerlund 1994, Liebman 1994).

In conventional California strawberry production, growers fumigate land to be planted to strawberries with a mixture of methyl bromide and chloropicrin (2:1 ratio) for the control of most plant pathogens, nematodes, and weeds (Braun and Supkoff 1994, Welch et al. 1985). Because of the need for specialized application equipment and concerns for worker safety, methyl bromide can only be applied by licensed applicators (University of California 1993). Application rates range from 300 to 400 pounds per acre with associated treatment costs of approximately $1,200 to $1,400 per acre (Liebman 1994). The frequency of fumigation is determined by the rotation sequence practiced by the grower. Some growers, especially in Southern California, plant strawberries each year and fumigate before each crop is planted. On the Central Coast near Watsonville, growers often rotate crops (i.e., bellbean, barley, lettuce, broccoli, cauliflower, or celery) and fumigate alternating years (Westerlund 1994 & 1996, Liebman 1994).

Organic Production Techniques as a Replacement for Methyl Bromide

Twenty-two of the 600 strawberry farms in California are certified as organic according to The California Certified Organic Farmers Directory. Unlike conventional strawberry farmers, organic farmers use a rotation of 1 to 2 berry crops every 4 to 5 years and do not use methyl bromide or any other synthetic pesticides or fertilizers (Gliessman et al. 1990, Cochran 1995, Webb 1994). An example of successful organic strawberry production is Swanton Berry Farms in the central coastal area of California, which has profitably grown strawberries without synthetic inputs (including methyl bromide) since 1986 (Cochran 1995). Weeds, soilborne pests, and diseases are controlled or suppressed using a combination of organically acceptable methods, including crop rotation and cover crops, plastic mulch, compost, cultural controls, and careful management of naturally occurring beneficial predators with supplementary releases of mass-reared beneficials when needed (Gliessman et al. 1996, Cochran 1995).

Costs Associated with Organic Strawberry Production

Limited research has been conducted on organic strawberry production costs and techniques and the conversion from conventional strawberry production to organic production in California (Gliessman et al., 1994, Liebman 1994). In one three-year university sponsored, on-farm research trial conducted at Swanton Berry Farms, University of California researchers initially achieved strawberry yields that were 68 percent of strawberries produced with conventional chemicals (Gliessman et al. 1994). While yields were lower for organically produced strawberries, they steadily improved over the study period from 2,068 trays per acre in the first year, to 2,388 trays per acre (79 percent) in the third year. Specifically, organic yields relative to those of conventional 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). Similar studies on conversion to organic production of strawberries and other crops support these findings -- i.e. that yields increase over time (Sances and Ingham 1995, Liebhardt et al. 1989). More recently, Swanton Berry Farms has been able to achieve yields as high as 3,100 trays per acre, a 13 percent improvement over yields attained in the previous 3 year study and 89 percent of the yield using conventional techniques (Cochran 1995). However, when comparing these yields to those of conventional strawberry growers, it must be noted that the variety of strawberries planted at Swanton Berry Farms are grown primarily for taste, and are not considered to be a high yielding variety. In addition, the area where the farm is located is not conducive for achieving the highest yields possible with the variety currently grown.

Slightly lower yields are offset by higher prices paid for certified organic strawberries (Gliessman et al. 1990). For example, production costs range from $18,919 to $23,668 and $20,480 to $24,437 per acre for organic vs. conventional strawberry production practices (See Table 1). In the first two years, input costs associated with pesticides, fertilizers, and fuel were higher in conventional strawberry production; however, organic production practices require more hours of tractor work for mechanical weeding and longer picking times, resulting in higher labor costs for organic strawberry production (Gliessman et al. 1996). Price premiums of up to 50 percent or more have been attained by Swanton Berry Farms. As a result, profits range from $3,039 to $9,738 for organic strawberries compared to $2,303 to $6,087 per acre for conventional strawberries (Gliessman et al. 1996). As demonstrated by these values, organic strawberry production can be profitable. In fact, compared with traditional, chemical-intensive production practices, results indicate that organic strawberries were 83 percent and 60 percent more profitable in the second and third years, respectively (Liebman 1994).

Table 1. Comparative Strawberry Production Costs and Returns ($/acre)

	Cultural labor	Materials & field power	Interest on working capital	Total costs
Organic	($/Acre)			
Year 1	9,613	10,770	1,397	21,780
Year 2	10,094	12,176	1,397	23,668
Year 3	8,377	9,144	1,397	18,919
Conventional	($/Acre)			
Year 1	8,194	13,474	1,534	23,346
Year 2	8,755	14,148	1,534	24,437
Year 3	8,446	10,500	1,534	20,480

Source: Gliessman et al. 1996

The labor and material costs for each of the three years were based on a combination of grower estimates and University of California Cooperative Extension standard cost-of-production data for winter planted strawberries on the Central Coast. Adjustments were made to account for management changes in the second and third years in addition to a 5 percent annual increase in operating costs over baseline for both production practices. Yield and income were calculated by combining the observed yields on a plot basis with average market prices for the season reported by the grower (Gliessman et al. 1996).

The relatively high return on organic strawberries (especially in the third year) must be considered in light of the fact that 1) the study took place when growing conditions (land which was not previously used for strawberry production) and prices for organic strawberries were favorable, 2) costs and returns were based on relatively small-scale operations, which may not translate to larger operations with current production timing and practices, and 3) the cost and returns reported do not reflect the cost of fallow periods typically used in organic strawberry production (i.e., when land is cover cropped and no returns are realized). However, planting marketable cover crops on fallowed fields may compensate for lost revenue. Furthermore, cost savings were realized in the absence of fallow periods in both conventional and organic crops. For example, leaving plants in the ground for several years, as opposed to fallowing the fields, saves on replanting and weeding costs. Additionally, costs were saved by not having to fumigate conventional crops with methyl bromide (Gliessman et al. 1996).

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Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Solarization for Controlling Soilborne Pests and Pathogens in Field Crop Cultivation

Solarization is a method in which clear plastic is laid on the soil surface to trap solar radiation and heat the soil. Solarization as a preplant soil treatment to control soilborne pathogens and pests can be a viable alternative to methyl bromide for shallow-rooted, short-season crops (Katan and DeVay 1991, Stapleton 1996). Solarization is a hydrothermal process that can be used in moist soils covered with clear plastic tarps and exposed to direct sunlight in tropical climates or during warm summer months in more temperate regions. Solarization traps solar radiation, and thereby heat, in the soil in order to raise temperatures sufficiently to suppress or eliminate soil-borne pests and pathogens (Katan 1981 and 1991). It can be effective against a broad spectrum of soil diseases, fungi, weeds, nematodes, insect pests and most soilborne bacteria. Solarization also causes complex changes in the biological, physical, and chemical properties of the soil that improve plant development, growth, quality, and yield for up to several years (Stapleton 1994, Katan 1981 and 1991, DeVay et al. 1990). In areas with a suitable climate, solarization can be used alone, or in combination with lethal or sublethal fumigation or biological control, to provide an effective substitute to methyl bromide (Hartz et al. 1993).

In addition to disinfecting the soil while reducing or eliminating the need for fumigants, solarization leaves no toxic residues, increases the levels of available mineral nutrients in soils by breaking down soluble organic matter and making it more bioavailable, changes the soil microflora to favor beneficial organisms, conserves water, and can serve as a mulch when maintained as a row cover during the growing season (Stapleton 1994, Katan and DeVay 1991). However, solarization appears only to be effective in warm climates and requires that cultivated land be left fallow for short periods of time (Katan and DeVay 1991).

Benefits of Solarization

- ✓ *Can be combined with other pest management practices*
- ✓ *Can provide effective pathogen control for several years*
- ✓ *Stimulates increased plant growth response, resulting in higher crop quality and yield*
- ✓ *Increases levels of mineral nutrients in soils*
- ✓ *Promotes biological control*
- ✓ *Conserves water*

Research

Solarization alone, or in combination with other pest control technologies, could be adopted as a preplant soil pest control measure for a variety of different pathogens and pests in a wide range of climates and different cropping systems. Since its inception in 1976, soil solarization has been tested and modified under local conditions in more than 50 countries, including the United States (Florida, California, North Carolina and other states), Israel, Greece, Morocco, and Japan, for the control of nematodes, weeds, and disease organisms affecting a variety of vegetable and fruit crops (Hartz et al. 1993, Katan 1984 and 1981, Ristaino et al. 1996 and 1991, Stapleton 1994, Wu 1996). Studies have shown that 1) solarization reduces or eliminates pathogens and pests prior to planting, 2) crop yields can be significantly increased, and 3) the effects of solarization can extend through several growing seasons (Afek et al. 1991). Solarization has already proven to be an effective pest control tool for tomato, pepper, and eggplant production in the northern part of Florida and North Carolina, strawberry and lettuce production in California (Gamliel and Stapleton 1993, Hartz et al. 1993, Ristaino et al. 1991), tree nursery production in the southeastern U.S., and orchard crops in California (Chellemi 1994, DeVay et al. 1990, Littke 1994a, Littke 1994b, Stapleton 1994). Solarization also has proven effective in controlling pests (pathogens) for a variety of other crops including pistachios, almonds, carrots, garlic, peanuts, potatoes, watermelon, onions, artichokes, and beans (Katan and DeVay 1991). It must be noted that the effectiveness of this pest control tool is directly linked to climate - that is, the amount of sunlight received during the solarization process. In addition, as with other pest control tools, the effectiveness of solarization is related to how well it is applied and the experience of the persons involved in the process.

Because of its passive nature, solarization alone is limited to growing areas in primarily hot, generally cloudless climates. However, it has also shown considerable promise for vegetable production in more humid areas, such as the southeastern United States where average soil temperatures at 5 cm depth are 50°C in solarized plots and 36°C in bare ground. Variations of the principle have also been used in other locations. For example, in the Rio Grade Valley in Texas and in Northern Florida, transparent film used to solarize fields during the hot summer off-season is then painted white and left in place to serve as a mulch for the fall melon and tomato crops. In the Jordan Valley in Israel, black plastic has been used to solarize soil during the extremely hot summer months, and is then left in place to serve as a mulch for the fall vegetable crop. These modifications represent excellent adaptations of the technique for maximizing cost effectiveness (Stapleton 1996). Additionally, while not currently commercially feasible in most cases, the use of recycled/old plastics has been shown to be more effective at heating the soils than new plastics because the photometric properties of transparent polyethylene sheets change significantly during the aging process (Katan and DeVay 1991).

Solarization Techniques

Generally, a layer of clear plastic film is applied to the soil prior to planting and is left in place for 4 to 6 weeks during the hot season in the appropriate climatic region. Optimal use, however, may require a longer period of time and adjustments in scheduling for other production practices. However, this time period may be reduced by combining solarization with chemical or non-chemical pesticides. Proper soil preparation also is essential to provide a smooth, even surface for the tarp and allow water to penetrate evenly and deeply into the soils (Stapleton 1996). To maintain proper soil moisture, irrigation using sprinklers is typically performed 1 to 4 days prior to applying the plastic tarp. Alternatively, drip irrigation lines can be installed underneath the tarp and utilized as necessary (Katan 1981). Plastics may be applied either in strips (usually 2 feet wide) over the planting beds or as continuous sheeting glued, heat fused, or held in place by soil. Because pathogens that survive heat treatment within or at the periphery of treated soils tend to multiply (a phenomenon known as the "edge or boarder effect"), continuous sheeting is thought to be more effective than strip applications, although it is more expensive (Katan and DeVay 1991, CEUC, 1984). However, soil temperatures under bed solarization in the southeastern United States are higher than temperatures achieved under full-field solarization. In addition, the border-effect associated with the lack of pest suppression along the edges of full-field solarization is eliminated by bed solarization (Chellemi, 1996). Currently the most common film types used for solarization are UV-resistant clear polyethylene or polyvinyl chloride film (Katan and DeVay 1991). Double layers of plastic, which simulate solarization of soil under glasshouse conditions, result in even greater temperature increases in soils (i.e., 3 to 10°C higher that achieved under a single layer of plastic) (DeVay et al. 1990).

After solarization, the plastic is either removed or left in place to serve as mulch during the growing season (Katan and DeVay 1991). The physical, biological, and chemical changes that occur during solarization may persist for up to 2 years (Katan and DeVay 1991, DeVay et al. 1990). Because soil temperatures are the highest within the uppermost layers, cultivation after solarization should be kept to a minimum to avoid reinfestation from pests deep in the soils. To achieve lethal soil temperatures at greater depths, solarization must be maintained at higher temperatures for an extended period of time (two months or longer) (Katan 1987). However, the use of double layered plastic may reduce time necessary for this procedure to control pests.

Solarization causes physical, chemical, and biological changes in the soil by raising soil temperatures from 2-15°C above the temperatures of untreated soil. For example, temperatures achieved with solarization in Israel during July and August, at levels between 5 and 20 cm below the soil surface were 45-55°C and 39-45°C, respectively. In California, at a depth of 5 cm, the temperature of tarped soil was recorded at 60°C (Katan 1981). In Florida, at depths of 5, 15, and 25 cm, temperatures of 49.5, 46.0, and 41.5, respectively, were recorded in solarized soil (Chellemi 1994) The success of soil solarization is based on the fact that most plant pathogens and pests are mesophilic or unable to survive for long periods at temperatures above 37°C. The heat sensitivity of these organisms is related to an upper limit in the fluidity of cell membranes, which lose their ability to function at high temperatures. Other causes of death of organisms at high temperatures involve the sustained inactivation of enzyme systems, especially respiratory enzymes (DeVay et al. 1990). Pathogens may be killed either directly by the heat or are weakened by sublethal heat to the extent that they are unable to damage crops (DeVay 1996).

Solarization also promotes increases in plant growth and development and crop quality and yield by increasing the availability of plant nutrients and the relative populations of beneficial organisms such as rhizosphere bacteria *(Bacillus spp.)* and pseudomones species (Ristaino et al. 1991). Heating causes the release of soluble mineral nutrients from soil organic matter and heat killed soil biota and induces the upward movement of mineral nutrients in the soil profile. Reductions in populations of soil borne pathogens also constitute the basis for biological control of plant pathogens and in some cases the development of disease suppressive soils (Katan and DeVay 1991, Stapleton 1996, Ristaino et al. 1991).

The effectiveness of solarization and the heat dosages achieved for disinfesting soil depend on soil moisture and texture; air temperature (maxima, minima, and duration); season; length of day; intensity of sunlight; wind speed and duration; and the type, color, and thickness of the plastic (DeVay et al. 1990, Katan and DeVay 1991). The greater the temperature, the less time is needed to reach a lethal heat dosage. For example, at soil temperatures of 37°C (the lower threshold temperature for lethal and sublethal damage for many mesophilic fungi) exposure may require from 2 to 4 weeks, however at 47°C, 1 to 6 hours of exposure is a lethal dose (Katan and DeVay 1991). Because solarization is a hydrothermal process, its success also depends on moisture for maximum heat transfer to soilborne organisms (Chellemi 1995). However, recently a soil temperature model that predicts temperature under plastic mulch based on above ground meteorological data has been developed (Wu et al. 1996)

Reducing Chemical Usage and Costs

Solarization can be a cost-effective technique for controlling soil-borne pests of fruits, vegetables, nursery, and orchard crops, making it a viable alternative to methyl bromide in many warm climates. This is supported by an economic analysis of 30 single-crop, single-season experiments which suggested that solarization was effective and profitable for numerous shallow-rooted, short season crops (Katan and DeVay 1991). Furthermore, additional benefits of solarization, such as an increased growth response and its long-term effects, strengthen its economic profitability (Katan and DeVay 1991, Stapleton 1994). In addition, solarization can be combined with other chemical, physical, and biological methods (e.g., fertilizers, soil amendments, integrated pest management strategies, limited pesticide use, and biological control agents) for enhanced management of soil and root pests and diseases (DeVay 1996, Katan and DeVay 1991). Cost estimates for solarization compared to methyl bromide fumigation are provided in the Table 1 below. As shown, reduced chemical usage and cost savings can be achieved by using solarization for controlling soil-borne pests. It should be noted however that with strip and bed solarization, costs can be reduced as the application techniques are virtually identical to the standard polyethylene mulch culture without the additional labor costs listed here for solarization (Chellemi, 1996).

Table 1. The Comparative Costs of Solarization and Methyl Bromide Fumigation

Cost Factor	Treatment #1: Solarization ($/acre)	Treatment #2: Methyl Bromide ($/acre)
Tarp	175-180	225-300
Labor	100-160	50-80
Other	25 - 100 (post-treatment white paint or tarp removal)	200-350 (fumigant costs)
Total	300-440	475-730 (broadcast up to $1,500)

Source: Chellemi 1995, DeVay 1996, Olson 1996, Hartz 1996, Katan and DeVay 1991.

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Methyl Bromide Alternative

Soil Solarization as an Alternative to Methyl Bromide In California Orchards

Solarization as a pre- or post-plant soil treatment to control soilborne pathogens and pests is a viable alternative to methyl bromide in orchard crops such as peaches, plums, nectarines, apricots, walnuts, pistachios, almonds, apples, and cherries. Currently, methyl bromide is used to control soilborne bacteria and diseases, weeds, nematodes, and fungi in these crops (DeVay 1995, Stapleton 1995, Pullman et al. 1984). As early as 1981, soil solarization was successfully used in California to control *Verticillium* wilt in pistachio tree groves (Ashworth and Gaona 1982). Since then, extensive soil solarization research has been conducted in orchards and the treatment is being appraised by many large orchard growers (McKenry 1996). In 1992, the top five California orchard uses of methyl bromide (e.g., almonds, nectarines, plums, peaches and walnuts) utilized over 2.5 million pounds of methyl bromide (State of California 1992).

Solarization is a hydrothermal process that can occur in moist soils covered with plastic tarps and exposed to direct sunlight in tropical climates or during warm summer months in more temperate regions. Solarization traps solar radiation, and thereby heat, in the soil and raises temperatures sufficiently to suppress or eliminate soil-borne pests and pathogens (Katan 1981, Katan and DeVay 1991). Solarization also causes complex changes in the biological, physical, and chemical properties of the soil that improve plant development, growth, quality, and yield for several years (Stapleton 1994, Katan and DeVay 1991, DeVay et al. 1990, Katan 1981). In areas with a suitable climate, solarization can be used alone, or in combination with lethal or sublethal fumigation or biological control, to provide an effective substitute to methyl bromide (Hartz et al. 1993).

Benefits of Soil Solarization In Orchards

- ✓ *Can be combined with other pest management practices*
- ✓ *Can provide effective pathogen control for several years*
- ✓ *Leaves no toxic residues*
- ✓ *Conserves water*
- ✓ *Increases levels of mineral nutrients in soils*
- ✓ *Stimulates increased plant growth response*
- ✓ *Promotes biological control*
- ✓ *Serves as a mulch when maintained as a row cover throughout the growing season*

In addition to disinfesting the soil while reducing or eliminating the need for fumigants, solarization leaves no toxic residues and can contribute to water conservation. Furthermore, solarization increases the levels of available mineral nutrients in soils by breaking down soluble organic matter and increasing bioavailablity. In doing so, solarization stimulates an increased growth response in many orchard trees and changes the soil microflora to favor biological pest control. Lastly, polyethylene films used in solarization can serve as mulch to reduce weeds when maintained as a row cover throughout the growing season (Stapleton 1994, Katan and DeVay 1991).

Soil Solarization in California Orchards

Unlike methyl bromide, soil solarization can be used effectively as both a pre- and post-plant treatment in many California (and other regional) orchards. Clear polyethylene films are typically used in pre-plant orchard treatments, while black polyethylene films (which achieve slightly lower temperatures depending on the thickness of the film) are most often used on newly planted or established orchards to gain the benefits of solarization while preventing heat damage to trees (DeVay 1996, Stapleton et al. 1993). Orchard trees have also been successfully established using clear polyethylene mulch as a pre-plant treatment in cooler areas of the San Joaquin and Sacramento Valleys (Stapleton and DeVay 1985, Stapleton et al. 1989).

Solarization causes physical, chemical, and biological changes in the soil by raising soil temperatures from 2-15°C above the temperatures of untreated soil. Soil solarization is successful because most plant pathogens and pests are mesophilic or unable to survive for long periods at temperatures above 37°C. Pathogens may be killed either directly by the heat or are weakened by sublethal heat to the extent that they are unable to damage crops (DeVay 1996). The heat sensitivity of these organisms is directly linked to an upper limit of fluidity in cell membranes, which lose their ability to function at high temperatures. Other methods of inactivation affected by solarization include sustained interference with enzyme systems, especially the respiratory process (DeVay et al. 1990).

In addition to providing pest and pathogen control, solarization conserves water and promotes growth in new orchards or replanted trees in temperate, as well as arid climates (Stapleton et al. 1993, 1991, and 1989, Duncan et al. 1992, Stapleton and Garza-Lopez 1988, Katan 1987, Stapleton and DeVay 1986). Experiments have confirmed that polyethylene films used for solarization conserve irrigation water under arid and drought conditions by preventing evaporation and trapping water. Furthermore, there is significant evidence that even in hot and arid climates, non-mature deciduous fruit and nut trees (e.g., almond, peach, apricot) may be established with no more than pre-plant irrigation and perhaps two or three carefully timed irrigations later in the season if necessary (Stapleton et al. 1993, Duncan et al. 1992, Stapleton et al. 1989, Stapleton and Garza-Lopez 1988). Solarization may also result in an increased growth response (as evidenced by increased trunk diameters) and yield in orchard trees, by increasing the availability of plant nutrients and the relative populations of beneficial organisms (i.e., rhizosphere bacteria (such as *Bacillus spp.* and *Pseudomonas spp.), Trichoderma spp.,* actinomycetes, and mycorrhizal fungi) (Stapleton 1996, Katan and DeVay 1991, Stapleton et al. 1989, Stapleton and Garza-Lopez 1988, Pullman et al. 1984).

Solarization Techniques

The effectiveness of solarization and the heat dosages achieved during solarization depend on soil moisture and texture; air temperature (maxima, minima, and duration); season; length of day; intensity of sunlight; wind speed and duration; and the type, color, and thickness of the plastic (Katan and DeVay 1991, DeVay et al. 1990). Orchard trees create discontinuities in the field so that application of continuous plastic films must either be done manually or semimechanically using plastic-laying machinery. Plastic strips are cut and hand applied around tree bases and then (in the case of semimechanical applications) connected to sheets of machine-applied plastic between tree rows with heat-resistant glue or narrow bands of soil (Pullman et al 1984). While not as effective as the above, in some cases, wide strips of plastic are only placed between tree rows (strip mulching) or are applied by piercing films over young tree shoots in newly planted orchards (DeVay 1996, Katan and DeVay 1991).

In pre-plant orchard treatments, a layer of polyethylene film is applied to the soil prior to planting and is left in place for 4 to 6 weeks or more during the hot season. In post-plant treatment, however, polyethylene films are applied after planting and can remain in place for up to two years (McKenry 1996). Proper soil preparation is also essential to provide a smooth, even surface for the film and allow water to penetrate evenly and deeply into the soils (Stapleton 1996). To maintain proper soil moisture, orchards are irrigated 1 to 4 days prior to applying the plastic tarp. Alternatively, irrigation lines can be installed beneath the tarp and utilized as necessary (Katan 1981). While not currently field feasible, double layers of plastic can simulate solarization under glasshouse conditions, and will result in even greater temperature increases in soils (i.e., 3 to 10°C higher then that achieved under a single layer of plastic) (DeVay et al. 1990, DeVay 1996). Regardless of the technique used, the beneficial effects of solarization may persist for up to 2 years or more after the plastic is removed (Katan and DeVay 1991, DeVay et al. 1990).

Solarization Research In Orchards

A number of researchers have reported successful pre- and post-plant applications of soil solarization or other film mulching techniques for management of soilborne pests and pathogens in orchards. For example, solarization is known to control *Verticillium* wilt in pistachios (Ashworth and Gaona 1982) and olive trees (Tjamos et al. 1991, Katan and DeVay 1991), almonds and apricots (Stapleton, et al. 1993) and white root rot in apple trees (Freeman et al. 1990, Sztejnberg et al. 1987). Solarization is also effective against certain nematode species and non-specific replant diseases in other crops, such as almonds, peaches, and walnuts (Abu-Gharbieh et al. 1991, Stapleton et al. 1989, Jenson and Buszard 1988, Stapleton and DeVay 1984, 1983). Although solarization is an effective treatment method for a wide variety of orchard crops, crop response to solarization varies. For example, apricots are very responsive to soil solarization in that they are only susceptible to *Verticillium* wilt during the first 4 to 6 years of growth, therefore only one solarization treatment is required. Other orchard trees (i.e., certain cultivars of olive and pistachio); however, are susceptible to *Verticillium* wilt both in the first few years of growth and as mature trees and therefore must be treated repeatedly (Stapleton et al. 1993).

Although solarization can be a viable alternative to methyl bromide in orchards, there are limitations to it use. While solarization is just as effective as methyl bromide in the upper layers of the soil, the combined high heat levels and duration are often not adequate to penetrate into deeper soil levels (Stapleton 1995, DeVay 1995). This may impact overall yields when this is the only pest control tool utilized. Recent research; however, suggests that soil solarization, in combination with other alternatives to methyl bromide (e.g., Telone® or Vapam®) offers an "additive" effect that actually increases the efficacy of both chemical alternatives and solarization compared to their stand-alone uses. Although solarization is most effective in warm, arid climates; clear, thicker, and at even double layers of plastic (not currently feasible) can be used to achieve lethal levels of heat in more temperate regions (Katan and DeVay 1991). Although solarization has been successfully used in mature orchards, excessive shading by mature tree canopies may limit the effectiveness of this treatment under certain conditions (Stapleton et al. 1993, Stapleton et al. 1989).

Reducing Chemical Usage and Costs

Solarization can be a cost-effective technique and when the additional benefits of increased growth response, water conservation, and enhanced nutrient availability are considered, the economics are further improved (Stapleton 1994, Katan and DeVay 1991). Furthermore, solarization can be (and sometimes must be) combined with other chemical, physical, and biological methods (e.g., fertilizers, soil amendments, integrated pest management strategies, limited pesticide use, and biological control agents) for enhanced management of soilborne pests and pathogens (DeVay 1996, Katan and DeVay 1991).

The cost of solarization varies depending on the thickness of the plastic, areas of soil coverage (partial vs. complete coverage), irrigation methods, and the method of plastic application, connection, and removal (Pullman, 1984). For example, strip mulching can reduce solarization costs to two thirds the cost of full tarping (McKenry 1996). General cost estimates for solarization compared to methyl bromide fumigation are provided in Table 1 below. As mentioned above, chemical treatments can improve the control levels achieved with solarization. Therefore, representative chemical costs for Telone® or Vapam® have been included in the cost ranges presented in the table below. As shown, reduced chemical usage and cost savings can be achieved by using solarization for controlling soil-borne pests and pathogens. The direct costs of soil solarization can be one-half that of methyl bromide treatments (DeVay 1995; Stapleton 1995). Both this technique and the use of methyl bromide will require consideration of costs associated with the disposal or recycling of the plastic tarps.

Table 1. The Comparative Costs of Solarization and Methyl Bromide Fumigation

Cost Factor	Treatment #1: Solarization ($/acre)	Treatment #2: Methyl Bromide ($/acre)
Tarp	280-350	200-550
Labor (including tarp removal)	350	350
Chemical	0-405	500-550
Total	630-1,105	1,050-1,450

Sources: DeVay 1996, McKenry 1996, PolyWest 1996, Asgrow 1995, Lukes Agrisales 1995, Helena Chemical 1995.

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Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Integrated Pest Management and Soil Pest Control Technologies In California Vineyards

Integrated Pest Management (IPM) practices which do not utilize methyl bromide have begun to replace the use of this fumigant for the control of soilborne pests in a number of California vineyards. Currently, only about half of California's vineyard acreage are fumigated with methyl bromide as a preplant treatment. In fact, large-scale California grape producers, including Fetzer Vineyards, Savage Island Farms, Soghomonian Farms, Steven Pavich, and many other vineyards in the Lodi-Woodbridge region are succesfully using IPM practices to grow grapes profitably without methyl bromide. Furthermore, it is likely that the use of IPM practices will continue to expand as the research base increases, the market for environmentally friendly products increases, and on-farm demonstrations facilitate technology transfer.

Currently, field research, on-farm efficacy studies, and economic analyses of various alternatives are helping to accelerate the transition from methyl bromide soil fumigation to IPM practices. For example, the Lodi-Woodbridge Winegrape Commission (LWWC), working under grants from the California Energy Commission, the Kellogg Foundation, and California's Department of Environmental Protection, are studying the energy costs associated with conventional and sustainable farming systems, the implementation of IPM strategies region-wide, and the education and promotion of existing IPM techniques to growers in California (Lanchester 1996). Further, scientists at the Kearney Agricultural Station are studying metam sodium to improve its efficacy for nematode control (Peacock 1995, Westerdahl 1995). These and other research and implementation efforts will help to reduce the use of methyl bromide in California's vineyards.

Benefits of IPM

- ✔ IPM reduces grower's vulnerability to regulatory actions on pesticides and on pest resistance to chemical controls
- ✔ Growers already practicing IPM can serve as mentors and provide site demonstrations to other farmers
- ✔ The research base for IPM techniques is increasing for products derived from environmentally friendly production practices is increasing
- ✔ The less chemical pesticides used, the fewer residues in soil and crops

Overview of Methyl Bromide Use in California Vineyards

Approximately 10,000 California farms produced 89 percent of the 11 billion pounds of grapes harvested in the U.S. in 1992 (U.S. Department of Commerce 1994). While the number of acres devoted to grape production in California has declined slightly over the past decade, production has nearly doubled (CAS 1993), and in 1992 the California grape crop was valued at $1.7 billion (Liebman and Daar 1995).

Although grape vines are perennial crops and typically remain in production for many years, vines grown for commercial production are periodically replanted to maintain high productivity and uniform fruit quality. In conventional grape production, soil pest control technologies are used primarily to prepare soils for replanting (NRC 1989, Peacock 1995). Three to five years after the new rootstock is planted, grape vines begin to reach their productive potential; on average, vines remain in peak production for approximately 20-25 years although some produce for up to 40 years (NRC 1989, CAN, et al. undated, Peacock 1995).

Grape production is the third largest use of methyl bromide for soil fumigation in California (Liebman and Daar 1995). In 1992, approximately 5,600 acres of vineyard land, or 45 percent of the area planted with wine, raisin or table grape crops, were fumigated with approximately 900 metric tons of methyl bromide (Liebman and Daar 1995, EPA 1994). California vineyards account for about 4 percent of the total U.S. methyl bromide consumption, 10 percent of all California soil fumigant application, and 1.3 percent of world wide use (EPA 1994).

Methyl bromide (combined with chloropicrin) is applied prior to planting vineyards in order to control a variety of soilborne pathogens, nematodes, insects, and weeds (SCEPA 1993, NRC 1989). Primary target pests are nematodes; however, phylloxera and oak root fungus are also a concern in many vineyards (Westerdahl 1995). Fumigation primarily occurs on soils that previously supported grape-vines, orchard trees, or native oaks and are scheduled to be replanted into vineyards. Because these soils may contain insects and pathogens harbored by the remains of the previous crop, fumigation is often performed to control soilborne pathogens prior to re-planting. Methyl bromide is usually distributed to depths of four feet by tractors through hollow tubes driven into the soil. Application rates are typically 300 to 500 pounds per acre. Although tarps are often used to maintain fumigant concentrations, sometimes the use of tarps is omitted to reduce costs by up to $600 per acre. In some instances, fumigation is not practiced prior to replanting, especially if pests are absent or are present in low numbers (e.g., in some coastal areas or in parts of the San Joaquin Valley) (Liebman and Daar 1995).

In addition to its impact on stratospheric ozone, there are several reasons to find alternatives to methyl bromide use in vineyards. First, material and application costs for methyl bromide can range anywhere from $600-$1,500 per acre. Second, methyl bromide, as well as other chemical fumigants, are restricted use pesticides that can not be applied near urban areas, on unsuitable terrain, or in areas where soils are damp. Third, grower aversion to methyl bromide and availability of alternatives has tended to decrease use over the past few years (Liebman 1994, DPR 1994a, DPR 1994b). For example, methyl bromide applications are often ineffective in controlling vineyard soil pests due to an inability to penetrate deep into soils which are heavy, coarse, or poorly prepared. Lastly, growers are concerned that methyl bromide fumigation will stunt plant growth by destroying beneficial mycorrhizal fungi (Liebman and Daar 1995).

IPM as a Replacement for Methyl Bromide

Research indicates that grapes can be produced in the absence of methyl bromide without jeopardizing quality or profitability (Liebman 1994). A majority of the grape industry in California has turned to integrated pest management (IPM) practices as a long-term approach for managing pests. IPM techniques rely on combining biological, cultural, and chemical tools in a way that minimizes economic, health, and environmental risks (Lanchester 1996). Pesticides are used only when needed and the least toxic formulations and lowest dosages required for effective pest suppression are encouraged (Liebman and Daar 1995).

Growers practicing IPM rely on a variety of pest control methods, including the use of chemical alternatives, resistant rootstocks, crop rotations, cover crops, biological controls (e.g., manures, compost or mineral adjustments). Other farmers produce grapes using organic farming practices. Some growers forgo preplant fumigation and rely instead on post-plant pesticides such as carbofuran (Furadan™), fenamiphos (Nemacur™), and sodium tetrathiocarbonate (Enzone™), or other chemical alternatives such as dazomet (Basamid™), 1,3-dichloropropene (Telone™) and metam sodium (Vapam™), which may be used in combination with non-chemical techniques to increase their effectiveness in controlling soil pests. The use of these methods vary, depending on the pest species present, soil type, topography, grape varieties grown, market conditions, land values and ownership, access to capital, regulatory restrictions, and personal philosophy. In general, these activities reduce the population size and impact of pests and improve the plant vigor and ability to tolerate pest damage (Liebman and Daar 1995). Examples of growers that have successfully used non-chemical and least toxic chemical IPM techniques to produce grapes profitably with out the use of methyl bromide include:

- Fetzer vineyards, in southern Mendocino county, produces organic grapes on 455 acres. After a four-year transitional period during which methyl bromide was not applied, the vineyard has achieved yields that are "competitive" and the prices received are "comparable" (CAN, et al. undated).

- Savage Island Farm produces table grapes in the San Joaquin Valley. New vines are planted 1 to 1.5 years after old vines are removed, reducing the fallow period with the use of deep-rooted cereal rye and vetch cover crops. Nematodes are not considered a serious problem because applications of raw green manure and compost help to suppress the populations (Liebman and Daar 1995).

- Soghomonian Farms, near Fresno, produces organic wine, table, and raisin grapes. Nematode damage is countered by adding manure to the soil and replanting damaged areas. Also, land is allowed to lie fallow for one year before re-planting (Liebman and Daar 1995).

- Steven Pavich plants both organic and conventional grape acreage in California and Arizona. He relies on field monitoring and application of preplant treatments only when necessary. Additionally, there is a program for soil building including cover cropping and applications of organic, mineral and beneficial microbe amendments (Liebman and Daar 1995).

The most promising alternatives include a variety of chemical and non-chemical alternative technologies including alternate fumigants, pasteurizing soil with hot water, soil solarization, resistant rootstocks, soil amendments, biological control, and disease suppressive cover crops (Liebman and Daar 1995):

Chemical Alternatives. The most promising chemical alternative technologies include fumigation with Telone™ (1,3-D) and metam sodium. These compounds have been shown to effectively manage a variety of the soil pests currently controlled with methyl bromide. Additional research will help to enable growers to implement application techniques with increased effectiveness in managing soil pests (Peacock 1995, Westerdahl 1995, University of California 1992).

Pasteurizing with Hot Water. This technique involves applying hot water into the soil at a depth of 12 inches and using a rotovator to distribute the heat through the top foot of soil. This procedure not only manages pests but also irrigates the fields. This has yet to be fully tested on the deep rooted pests found in vineyards.

Resistant Rootstocks. The use of grape rootstocks that show tolerance or resistance to pest species (Flaherty et al. 1992) and have acceptable vigor and viticultural properties can be used to help replace the use of methyl bromide. Resistant rootstocks are a promising alternative to methyl bromide (Peacock 1995) and there has been remarkable effort in California to develop grape rootstocks that are tolerant to nematode infestation in a variety of climates, soils, and pest pressures (University of California 1992, Peacock 1995).

Soil Management. Cultural controls and the addition of soil amendments (e.g., minerals, compost, manure, and green matter) that improve and strengthen root growth and help grape vines become established more quickly are also effective pest management techniques. Efforts to enhance natural biological controls in the absence of fumigation can also be an effective approach to managing soil pests (e.g., oak root rot is controlled by naturally occurring soilborne fungi in the *Trichoderma* genus in many California vineyards).

Cover Crops and Crop Rotation. Cover crops are used to reduce soil pathogens (mainly nematodes) and to provide organic matter that will lead to improved yields (Peacock 1995). Crop rotation can also be an effective method of suppressing damage caused by soilborne pests, but there are costs associated in terms of keeping land out of perennial crops for a period of time.

Solarization. Solarization is a method in which clear plastic is laid on the soil surface to trap solar radiation and heat the soil. Although the method is particularly effective in hot areas such as the Central Valley (Katan and DeVay 1991, Chellemi et al. 1994), to date, this technique has not been widely studied or utilized for grape production.

Costs of IPM Treatments

Development of cost estimates for IPM treatments is limited by the diversity of possible techniques to managing soil pests using an integrated approach. In general, an IPM approach could include using an alternative fumigant, increasing the use of soil amendments and cover crops, paying increased attention to soil conditions (i.e., pest populations), managing cultivation and irrigation schedules more effectively, and using rootstocks with resistance to soil pests. In addition, the selected approach and the resulting treatment cost will be affected by the local site conditions. Given these limitations, Table 1 presents a cost comparison of two methods that could be used to manage soilborne pests when establishing a vineyard. As shown, the up-front costs of the IPM treatment are estimated to be approximately $300 less than the methyl bromide treatment, suggesting that IPM would be an viable alternative to methyl bromide. In addition, future treatments, including periodic scouting, soil testing, spot nematicide treatments, additional soil amendments, and the use of cover crop may be used to maintain or increase the effectiveness of the IPM approach. Although not all of these activities may be required on an annual basis, they could increase future per acre treatment costs by about $50 to $200 annually.

Table 1. Comparison of Soil Treatment Costs for Establishing a Vineyard

Treatment	Estimated Cost ($/acre)	Cost Components	
Methyl Bromide	1,110 to $2,010	Fumigation with methyl bromide Soil Amendments Cover Crops, Cultivation, Mowing, and Herbicides	$600 - $1,500 $400 $110
IPM	$1,670	Fumigation with metam sodium Soil Amendments Cover Crops, Cultivation, Mowing, and Herbicides	$ 1,000 $ 500 $ 170

Sources: Howe 1994, Klonsky 1992a, Klonsky 1992b, McKenry 1995, Smith 1992, Verdegall 1994.

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Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Heat Treatments (Hot-water Immersion, High Temperature Forced Air, Vapor Heat) As Alternative Quarantine Control Technologies for Perishable Commodities

Hot-water immersion, high temperature forced air, and/or vapor heat are three heat treatment technologies that can be used for post-harvest insect control for perishable commodities such as fresh fruits (e.g., mangos, papaya, persimmon, citrus, bananas, carambola), fresh vegetables (e.g., peppers, eggplant, tomatoes, cucumber, and zucchini squash), bulbs, and cut flowers (Tsang et al. 1995, UNEP 1994, 1992, APHIS 1993, Hansen et al. 1992). Heat treatments for disinfestation of fruit have been used since 1929 when Baker and co-workers developed a vapor heat treatment against the Mediterranean fruit fly (Couey 1989). However, interest in heat treatments waned with the development of chemical fumigants, which could be applied cheaply and easily. Today, with the increasing cost of developing new chemicals and regulatory restrictions on existing ones, interest in heat disinfestation has been revived (Couey 1989).

Currently, methyl bromide is the most commonly used fumigant for controlling quarantine pests on perishable commodities; however, methyl bromide can only be used on certain commodities at specific temperatures and dosages because some commodities are highly sensitive to its use (e.g., certain tropical fruits imported from Hawaii) (Hara et al. 1994). The percentage of global consumption of methyl bromide used to treat perishable commodities is estimated to be 8 percent or 6,500 tonnes (UNEP 1994). Almost half of the methyl bromide used for commodity treatments are for disinfestation of exported fruits and nuts (e.g., papaya, mango, dried fruits, grapes, berries, nectarines, cherries, apples, walnuts, and pistachios). Methyl bromide fumigation is also the predominant treatment used for pests in vegetable shipments (e.g., cucumbers, squash, tomatoes) imported into many countries (UNEP 1994). Lastly, methyl bromide fumigation is widely used by many countries as a standard quarantine treatment for various arthropod-infested flowers and foliage. Across these uses, methyl bromide application rates vary depending on the temperature, exposure period, and commodity (Folwell 1996).

Benefits of Heat Treatment

- ✔ *Provides effective insecticidal and fungicidal action*
- ✔ *Easy to apply*
- ✔ *No environmental harm*
- ✔ *Absence of chemical residue on treated fruits and vegetables*

Heat treatment technologies are currently a relatively simple, non-chemical alternative to methyl bromide that can kill quarantine pests (insects and fungi) in perishable commodities, as well as control some postharvest diseases. Unlike methyl bromide, heat treatments do not pose significant health risks from chemical residues and, as a result, are more appealing to consumers than methyl bromide fumigation (Couey 1989). Furthermore, heat has been approved as a quarantine treatment by the U.S. Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS) against pests (mainly fruit flies) for several perishable commodities.

In most cases, heat treatments are performed by the country of origin before a product is exported. The temperature, duration, and application method is both cultivar and commodity specific and must be very precise to kill pests without damaging the commodity. Heat is unsuitable for highly perishable products such as asparagus, nectarines, avocados, or leafy vegetables as their shelf-life and marketability is reduced (UNEP 1994, Couey 1989). Fruit responses to heat varies depending on the condition of the fruit prior to treatment (Mitcham et al. 1994), the commodity concerned, the temperature and duration of treatment, as well as the mode of heat application (i.e., hot air vs. water). If not properly applied, heat treatments (as well as methyl bromide treatments) may result in commodity damage, which typically is manifested as browning fruit surfaces, uneven ripening, and breakdown of the fruit flesh. However, beneficial effects of heat treatment, include reduced susceptibility to chilling injury in avocados and persimmons (Lay-Yee 1994).

Heat Treatment Methods and Research

The majority of quarantine research on heat treatment methods for perishable commodities is conducted by the USDA, Agriculture Research Service (ARS) in Florida, Texas, Washington State and Hawaii. Many studies have shown that heat treatments do not affect market quality of the commodity and can meet the mandated USDA Probit 9 security level of quarantine pest control, which allows no more than 3.2 survivors out of 100,000 larvae (99.9968 percent mortality) at the 95% confidence level (Baker 1939, McGuire 1991), when the core of the fruit reaches a sufficiently high temperature. Heat treatment methods, as well as approved quarantine heat treatments and on-going research on potential quarantine heat-treatments for perishable commodities, are discussed below.

Hot-Water Immersion: Hot-water immersion consists of submerging the commodity in a hot-water bath at a specific temperature for a specified time based on the commodity being treated and the pests that may be present (APHIS 1993). For perishable food commodities, the mandated probit 9 level of fly control can be achieved by heating the core of the fruit to 43–46.7°C (109.4–116.1°F) with exposure times varying from 35 to 90 minutes (APHIS 1993, Gould 1988, Gould and Sharp 1992, Hallman 1989, Sharp 1986, 1990, Sharp and Picho-Martinez 1990, Sharp et al. 1988, 1989, 1989a, 1989b, Sharp and Spalding 1984, UNEP 1994). Variations are noted for different commodities, pest species, and life stages of insect pests. Hot-water is an effective heat transfer medium and, when properly circulated through the load of fruit, quickly establishes a uniform temperature profile (Couey 1989). Hot-water immersion also has the additional benefit of controlling postharvest microbial diseases such as anthracnose and stem end rot (Couey 1989, McGuire 1991). Immersion of non-food perishable commodities (such as cut flowers and bulbs) in hot water (43.3–49°C (109.9–120.2°F)) for 6 minutes to 1 hour is effective in destroying insect pests while maintaining product quality (Hara et al. 1994, UNEP 1994).

Hot-water immersion is currently used to successfully treat mangos infested with the Mediterranean fruit fly and several different *Anastrepha* species of fruit fly before importation into the United States from Mexico, the Caribbean, and Central and South America (APHIS 1993). Research performed by ARS on mangos, which are relatively resistant to heat damage, led to approval by USDA-APHIS of hot-water immersion quarantine treatments for mangos infested with fruit fly immatures (Sharp and Picho-Martinez 1990, Sharp and Spalding 1984, Sharp 1986, 1988, Sharp et al. 1988, 1989, 1989a, 1989b). Successful hot-water immersion quarantine treatments against fruit flies were also developed for papayas (Couey and Hayes 1986), guavas (Gould and Sharp 1992), and bananas (Armstrong 1982), however, these treatments are not currently approved by USDA-APHIS. Hot-water immersion treatment is not recommended for grapefruit, stone fruits (plums, nectarines and peaches), or carambolas (star fruit), because this treatment does not produce probit 9 security and/or produces unacceptable fruit damage in these specific commodities (Hallman 1989, 1991, Hallman and Sharp 1990a, Sharp 1985, 1990). Hot-water immersion of narcissus bulbs is also an APHIS-approved treatment for controlling the *Stenearsonemus laticeps* mite (UNEP 1994). A promising potential hot-water immersion treatment has also been developed for cut flowers and foliage (Hara et al. 1994).

High Temperature Forced Air: Recirculated air that has been heated and humidified can be forced over fruit surfaces to raise the temperature to a level that is lethal to target pest species. Heated air treatments of 40–50°C (104–122°F) (usually at four incrementally increased temperatures) for less than eight hours are becoming more common for fruit fly control in tropical commodities (Armstrong et al. 1989, Gaffney and Armstrong 1990, Mangan and Ingle 1992, UNEP 1994, Sharp 1989a, 1992, Sharp and Gould 1994, Sharp and Hallman 1992). Condensation on fruit surfaces or in the treatment chamber is prevented by keeping the dew-point temperature 2-3°C below the dry-bulb temperature throughout the duration of the test. This precise control of temperature and relative humidity is advantageous because it prevents condensation inside the treatment area and on the fruit surface thus preventing fruit desiccation and scalding (Gaffney and Armstrong 1990, Sharp et al. 1991).

Fruits shown to tolerate treatment with hot air are mango (Mangan and Ingle 1992, Miller et al. 1991, Sharp 1992, Sharp et al. 1991), grapefruit (McGuire 1991a, Sharp 1989a, Sharp and Gould 1994), navel orange (Sharp and McGuire 1996), carambola (Sharp and Hallman 1992), persimmon (Lay-Yee 1994), and papaya (Armstrong et al. 1989). Hot air is not recommended for avocado, lychee, and nectarine at treatment controlled temperatures needed to disinfest them of quarantine pests (Sharp 1994, Kerbel et al. 1987). USDA-APHIS has approved forced air treatments for grapefruit, papaya, and mango (APHIS 1993). Fruit flies of concern are Mexican fruit fly in grapefruit from Mexico; Mediterranean fruit fly, oriental fruit fly, and melon fruit fly in papaya from Hawaii; and Mexican fruit fly, West Indian fruit fly, and black fruit fly in mango from Mexico (APHIS 1993).

Vapor Heat: Vapor-heat quarantine treatment uses heated air saturated with water vapor to heat perishable food commodities to a specified temperature and holds that temperature for a specified period to ensure that all pests (such as tephritid fruit fly immatures) within the commodity are killed (APHIS 1993, Hallman 1990, Hallman et al. 1990). Typically, the pulp temperature of the commodity is raised by the saturated water vapor to 43.3–44.4°C (109.9–11.9°F) during a period of 6 or 8 hours and then held at the required temperature for another 6 or 8 hours (APHIS 1993). For several varieties of cut flowers and foliage, vapor heat treatments of 1-2 hours were greater than 99.7 percent effective in controlling pests (Hansen et al. 1992).

Vapor heat (greater than 90 percent relative humidity) is approved by USDA-APHIS for treatment of clementine, grapefruit, orange, and mangos imported from Mexican fruit fly infested areas and for bell peppers, eggplants, papayas, pineapples, tomatoes, zucchini, and squash imported from areas infested with Mediterranean, Oriental, and Melon fruit flies (APHIS 1993). Vapor heat was found to be effective as a potential quarantine treatment for carambola (Hallman 1990), grapefruit (Miller et al. 1991), codling meth in sweet cherries (Neven and Micham 1996), against the Caribbean fruit fly for tropical cut flowers as well as on foliage against aphids, soft and armored scales, mealybugs, and thrips (Hansen et al. 1992, UNEP 1994).

Costs

Hot-water immersion, high temperature forced air, and vapor heat are effective quarantine alternatives to methyl bromide fumigation for fruits and vegetables that are not susceptible to heat damage, particularly tropical and subtropical commodities, with proven efficacy against various pests and diseases. In general, methyl bromide treatment systems can range in cost from $21,000 to as much as $291,000, depending on the commodity and quantities being treated (Folwell 1996). A hot-water immersion system, on the other hand, can be easily assembled; and is durable, mobile, and inexpensive (Sharp 1989). While hot water immersion is inherently more efficient than vapor heat as a heat transfer medium and hot water treatment systems can be assembled for less than $8,000 (Sharp 1989, Hara et al. 1994), it can damage some fruits and vegetables. Hot water immersion is the only approved quarantine treatment for mangos. More than 75 commercial hot water treatment facilities are in place in Mexico, Haiti, Puerto Rico, South America, and Florida. The cost for each facility averages about $200,000. Additional facilities are planned or being constructed. APHIS/PPQ must certify each facility and ensure that inspectors are on site.

Alternatively, vapor heat and forced hot-air treatment systems are less damaging to commodities and more versatile than other treatment systems, however they are more expensive. For example, both vapor heat and hot-air treatment systems may initially require larger capital investments ranging from $20,000 to $200,000 for large commercial facilities (Williamson 1996, Sharp 1994, Hara et al. 1994).

A comparison of the capital and operating costs of these technologies is provided in Table 1. Capital costs for both vapor/forced air heat and methyl bromide treatments were calculated by dividing the costs to setup commercial treatment systems (see above) by the tonnes of fruit treated over the 20 year lifetime of the facilities at full capacity (i.e., capacities of 45,372 tonnes/yr. and 275,862 tonnes/yr. for forced air/vapor (for apples) and methyl bromide treatment systems respectively). It was also assumed that treatment systems were operational 250 days of the year and that three forced air/vapor, and one methyl bromide treatment could be completed each day. Operating costs included labor, energy, maintenance, insurance, and chemical costs in the case of methyl bromide.

As shown in Table 1, the capital costs for heat treatments are only slightly higher than that for methyl bromide on a per tonne commodity basis. Operating costs for heat treatments, on the other hand, are eight times higher than those for methyl bromide attributable primarily to longer treatment times and high energy costs. It is likely, however, that operating costs will decrease in the future as the number of commercial heat treatment facilities increases. Although the total costs for perishable commodity treatments with heat are seven times greater than that with methyl bromide on a per tonne commodity basis, the relative proportion of this cost is small when compared to the value of the commodity. Furthermore, other related costs (i.e., harvesting, packaging, storage, processing, and transportation costs to bring the commodity to market) further reduce the percent contribution of heat treatments, making it a relatively insignificant cost overall. As a result, heat treatment can be a viable alternative to methyl bromide for commodity treatment. In fact, Hawaii and many tropical countries have been using heat treatments as an alternative to commodity fumigation for decades (Williamson 1996).

Table 1. Capital and Operating Cost Comparison

Cost Factor	Treatment #1 Forced Air/Vapor Heat ($/tonne)	Treatment #2 Methyl bromide ($/tonne)
Capital Costs	4.41	1.33
Operating Costs	25.00	3.04
TOTAL	29.41	4.37

Sources: Folwell 1996, Williamson 1996, Sharp 1989, Hara et al. 1994, Sharp 1994.

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Stratospheric Ozone Protection
Case Study
Methyl Bromide Alternative

Heat Treatments to Control Pests on Imported Timber

Exotic or introduced timber pests can have damaging effects on forest ecosystems or timber production areas. North American forests are particularly vulnerable to pests such as fungi, nematodes, or insects introduced through importation of logs, lumber, or unmanufactured wood articles (USDA, 1994a). Because trees produced in temperate areas outside North America are affected by and can introduce a wide variety of pests and diseases that are non-indigenous to this continent, special care is required to ensure that imported wood and wood products are pest-free. The introduction of non-indigenous species could be detrimental to U.S. forest production, recreation, and urban forest resources (USDA, 1991a). Pests from tropical hardwoods, however, pose less of a threat, because tropical hardwood pest habitat requirements cannot generally be met within the temperate forests of the United States (Thomas 1996). These pests can bore into the roots, limbs, or trunk can interfere with a tree's reproductive capabilities, and can cause defoliation, wood damage, or a shift in tree species composition over time. Extensive tree death can have serious impacts on the ecosystem and cause changes in habitat and food supply. In addition, establishment of non-indigenous organisms has clearly been shown to reduce biodiversity (USDA 1994a).

There are several historical examples showing that importation of non-indigenous timber pest species has led to wide-spread blights within the United States. Notable cases this century have included: Chestnut blight (*Cryphonectria parasitica*, 1904-1955), Dutch elm disease (caused by the fungus *Ophiostoma ulmi*, mid-1920s), White pine blister rust (fungus *Cronartium ribicola*, early 1900s), Port Oxford cedar root rot (fungus *Phytophthora lateralis*, 1923), and the recent Gypsy moth (*Lymantria dispar*, 1870s) outbreaks. Each of these outbreaks has caused ecological damage such as shifts in species composition, changes in habitat, as well as tree defoliation, stress, and death (USDA, 1994a).

Benefits of Heat Treatment of Logs and Lumber

- ✓ *Reduces or eliminates insect and fungal pests*
- ✓ *Increases value of wood products*
- ✓ *Excellent penetration to wood core*
- ✓ *Saves time, labor, and resources.*
- ✓ *No chemical residues or environmental contamination*

Methyl Bromide May Not Effectively Control Pests on Imported Logs and Lumber

Currently, many U.S. timber importers rely on methyl bromide fumigation to control pests and pathogens such as *Lymantria dispar* (Asian gypsy moth), *Lachnellula willkommii* (Larch canker), and *Sirococcus strobilinus* (Conifer shoot blight) (USDA 1991a p.6). While methyl bromide is used to fumigate timber and wood products, it may not be the most effective treatment for controlling quarantine pests (e.g., bark beetles and borers, termites, and fungus) on imported logs and lumber (USDA 1994a p. 31 and 19, USDA 1991a p.5-6). Further, it is believed that methyl bromide does not penetrate well into logs, particularly logs with a high moisture content. Cross (1992) found that it is difficult to achieve useful insecticidal doses much beyond a depth of 100 millimeters in green materials using conventional tent fumigation techniques. Likewise, according to the USDA, "there is little scientifically derived efficacy data available to determine the most effective ways to employ methyl bromide fumigation to destroy plant pests associated with imported wood products" (USDA 1994a, p. 31). Additionally, recent test shipments of wood products imported into U.S. that were fumigated with methyl bromide have been found to be infested with fungal pests upon arrival (Forest Service, 1992 in USDA 1994a, p. 31 and Appendix B-81). Methyl bromide, therefore, when used to treat logs and lumber, does not completely eradicate the risk of quarantine pests entering new territory.

USDA Risk Assessments

In 1990, the Department of Agriculture Animal and Plant Health Inspection Service (APHIS) received its first request to import logs from the Soviet Union. At the time, the associated risks of importing timber, and the lack of APHIS regulations led to concern over the long-term impact of importing foreign timber. Three months later, APHIS turned down the request, and implemented a formal ban on all logs from the Soviet Union until further research could be conducted (USDA 1994a, USDA 1990a). As a result, between 1991 and 1993, the USDA Forest Service conducted three risk assessments on imported timber:

- Assessment of the Importation of Larch from Siberia and the Soviet Far East (1991) (USDA 1991b);
- Assessment of the Importation of *Pinus radiata* and Douglas Fir Logs from New Zealand (1992) (USDA 1992); and,
- Assessment of the Importation of *Pinus radiata, Nothofagus dombeyi,* and *Laurelia phillippiana* from Chile (1993) (USDA 1993).

APHIS used these assessments to develop its extensive mitigation measures for minimizing pest introductions in the U.S. during the importation of foreign logs and lumber. The proposed APHIS plan, which has been developed as a result of the Forest Service risk assessments, would allow importers to choose between several pest treatment strategies (APHIS would oversee decisions and evaluate all strategies on the basis of effectiveness). If a strategy cannot be shown to produce negligible risk, then APHIS has the power to deny entry.

Heat Treatments are Considered a Viable Method to Control Quarantine Pests

Based on USDA risk assessments, heat treatments of logs and lumber are considered to be more effective than methyl bromide for providing quarantine security and are considered to be an effective alternative to methyl bromide for the control of quarantine pests (USDA 1996). As a result, the use of heat-based sterilization to control biological pests offers great potential for the imported timber industry. Both moist heat (steam or hot water) and dry heat have been shown to effectively control fungi, insects, and nematodes associated with logs and lumber products (USDA 1991a) (Task Force on Pasteurization of Softwood Lumber 1991, Jones 1973, Baker 1969, Snyder and St. George 1924) (Dwinell 1990, USDA 1991; Ostaff and Cech 1978, Ostaff and Sheilds 1978, Parkin 1973, Department of Scientific and Industrial Research, Great Britian 1957, Snyder and St. George 1924, Snyder 1923).

To effectively eliminate pests, heat treatment requires that the internal temperature of the logs and lumber be raised to a specified temperature over a given period of time. Regulations require that all heat treatments be performed at a facility authorized by APHIS or by an inspector authorized by the national government of the country in which the facility is located (USDA 1994a). Core temperatures can be monitored by using thermocouples. Heat treatment techniques may include the use of steam, hot water, kilns (lumber only), microwave energy, or any other method that raises the temperature at the center of the log to at a minimum of 71°C (167°F) for at least 60 minutes.

Several treatment specifications are available for using steam or dry heat to treat logs and lumber. Typically, pressurized steam can be introduced to a chamber, and dry heating (with moisture added to minimize warping and spliting) can be accomplished using a commercial kiln. Because the killing efficacy of heat treatments depends on the time, temperature, and humidity (USDA 1991a p. 17), steam heat will kill pests more efficiently and rapidly than dry heat because the organisms under moist conditions are more susceptible to thermal killing due to the denaturation of proteins, particularly enzymes (USDA 1994a p. 3, USDA 1991, USDA 1990a). However, despite the effectiveness of steam heat treatments, kiln drying is the most commonly used heat treatment for lumber (Mathews 1996, Griffin 1996, Waggener 1996, Briggs 1996, Morrell 1996, Loromer 1996). The specifications for moisture-reduced heat treatment are the same as those for standard heat treatment, with the added component that moisture must be reduced to 20 percent or less. Penetration of dry heat proceeds at a much slower rate than steam heat, therefore kiln drying requires a much longer exposure time (USDA 1994a).

As is the case with methyl bromide, heat treatment has been found to be effective for killing insects and plant pathogens on and within the regulated article only at the time of treatment (i.e., with no residual protective effect), articles must be protected against subsequent reinfestation. A wide variety of methods, separate or in combination, may be used to control reinfestation, including storage in pest-free warehouses, storage in sealed containers, or the use of prophylactic pesticide sprays or dips (USDA 1994a). Kiln drying, stream heating, and hot water immersion can eliminate deep wood pests and can also make the regulated article less vulnerable to reinfestation.

Heat Treatment: Effects on Wood Quality

Both steam and dry heat can effectively penetrate logs and raise the internal temperatures to levels that effectively control pests without causing wood damage (USDA 1991a). In general, heat treatments do not have any significant deleterious effects on log quality because controlled heat treatments help to reduce wood damage caused by uneven drying (USDA, 1994). Temperatures up to 82.2 °C (180 °F) for periods up to one hour do not appreciably affect the properties of wood (USDA 1994a). Depending upon the type of wood and size, some surface damage may be noted. Potential damage to lumber caused by poor drying includes the following: surface checks, warping, uneven moisture content, and discoloration (USDA 1991c). Additional research is needed to determine more clearly the potential deleterious effects of heat treatment on logs and other wood articles (USDA 1994a).

Additionally, the value of wood is often increased by proper heat treatment. Whereas green wood products treated with methyl bromide do not incur any additional value, heat treatments cure the wood and impart value compared to unseasoned or untreated wood. For example, wood that has been milled and heat treated (i.e., kiln dried or steam treated) typically has 30-50 percent greater value than untreated wood (Rice 1996, McDonagh 1996). Because wood treated with methyl bromide must be dried and cured via heat treatment anyway and because heat treatments provide similar pest control benefits compared to methyl bromide, methyl bromide treatments may be superfluous. However, some users prefer to purchase "green wood", re-manufacture the material, then dry it.

Costs

A comparison of the costs of sterilizing logs and lumber with methyl bromide fumigation vs. heat treatment (i.e., kiln-drying and steam treatments) is provided in the Table 1. As shown, the net costs for both kiln-drying and steam treatments are negative because of the increased product value resulting from the heat treatment process. However, it must again be noted that some types of timber and wood products may be damaged by heat treatments, and thus would change the cost listed here. The costs for methyl bromide fumigation include labor, tarp, and chemical costs. The costs for heat treating and steam treating lumber include labor, energy, and equipment costs. The labor and energy costs for both kiln-drying and steam treatments, however, vary according to treatment time. Heat treatment can take up to 25 days, whereas steam treatment takes only 1-2 days. Furthermore, steam heating is less labor intensive than kiln drying. Kiln drying requires that "sticks" (or pieces of wood) be inserted between layers of wood to allow better distribution of heat and air flow during the treatment process, however, these sticks must be removed before shipping. However, many mills now have automatic stackers which markedly reduce labor costs. In steam drying, a lath (or a thin piece of residual wood) is used to separate the layers, and does not need to be removed before shipping. Another factor contributing to the cost discrepancy between kiln-dried vs. steam treated wood is Btu utilization. For dry heat sterilization, low heat (low Btu) is used initially, but then gradually increased until the maximum heat (high Btu) is obtained on the 25th to 26th day (for hardwoods -- conifers are normally dried for 3-5 days). For steam sterilization, however, the same amount of heat used in the final stage of kiln drying is used at the beginning of the process and is sustained by small bursts of heat throughout the short 1 or 2 day treatment process. Furthermore, the chamber vents are kept closed to aid in heat conservation. Therefore, steam sterilization takes both less time and utilizes less heat energy compared to that used in dry heat sterilization, ultimately reducing energy costs.

Table 1. Timber Treatment Cost Comparison

Cost Considerations	Methyl Bromide ($/1000 bd. ft.)	Heat Treatment ($/1000 bd. ft.)		Steam Treatment ($/1000 bd. ft.)	
		Softwood (e.g., Fir)	Hardwood (e.g., Oak/ Cherry)	Softwood (e.g.,Fir)	Hardwood (e.g., Oak/ Cherry)
Product Initial Cost/Value (Pre-Treatment)	500-850	500	850	500	850
Treatment Cost	1-3	85-155[a]	100-200[b]	35-60	41-77
Total Cost	501-853	585-655	950-1050	535-560	891-927
Value Added	N/A	30-50%		30-50%	
Product Value (Post Treatment)	500-853	655	1275	650	1275
Net Cost	1-3	5-(65)	(225-325)	(90-115)	(348-384)

N/A - not applicable.
( ) - indicates a negative net cost attributed to increased product value
[a] Cost refers to kiln treatment of softwood species indigenous to the western U.S. (e.g., Cedar, Douglas Fir).
[b] Treatment cost and value added refers to kiln treatment of hardwood species indigenous to the eastern U.S. (e.g., Oak, Cherry).

Sources: Rice 1996, USDA 1996, Mathews 1996, Milota 1996, McDonagh 1996, McGehee 1996, UNEP 1995.

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Stratospheric Ozone Protection Case Study

Methyl Bromide Alternative

The Use of Irradiation for Post-Harvest and Quarantine Commodity Control

In both domestic and international agricultural markets, expanding the use of irradiation can help to reduce the need for methyl bromide for the post-harvest control of insect pests. Currently, irradiation treatments have been approved for a variety of food use applications by the U.S. Food and Drug Administration (FDA). The United States Department of Agriculture (USDA)/Animal and Plant Health Inspection Service (APHIS)/Plant Protection and Quarantine Service (PPQ) has outlined policy positions regarding the development and use of irradiation treatments for quarantine pest control, and is actively seeking ways to incorporate additional irradiation uses into their plant protection program (USDA 1995, USDA 1996a, 1996b, 1996c). Furthermore, research has been conducted to determine optimal irradiation dosages for controlling pests and maintaining produce quality, a variety of irradiation technologies have been commercialized worldwide, and there is extensive data available on the capital, operating, and per unit treatment costs associated with irradiation projects. In addition, recent market studies have generally found that consumers are willing to buy irradiated produce (Morrison 1992). In fact, research conducted in Florida indicated that consumer acceptance for such commodities is high, and many actually prefer the methods to traditional chemical fumigation (Marcotte 1992).

Food irradiation is a process by which products are exposed to ionizing radiation to sterilize or kill insects and microbial pests by damaging their DNA. The FDA permits three types of ionizing radiation to be used on foods: gamma rays from radioactive cobalt-60, high energy electrons, and x-rays. Although all three have similar effects, gamma rays are most commonly used in food irradiation because of their ability to deeply penetrate pallet loads of food (Forsythe and Evangelou 1993, Morrison 1989). Gamma irradiation equipment irradiates packaged or bulk commodities by exposing the product to gamma energy from cobalt-60 in closed chambers, which range in size from single modular pallet irradiators to large research or contract irradiation facilities. Absorbed dose is measured as the quantity of radiation imparted per unit of mass of a specified material. The unit of absorbed dose is the gray (Gy) where 1 gray is equivalent to 1 joule per kilogram (ICGFI 1991, NAPPO 1996).

Benefits of Food Irradiation

- ✓ *Disinfests fruits, vegetables, and grains by sterilizing or killing insects and microbial pests.*
- ✓ *Insures the delivery of pest-free commodities to importing nations resulting in increased trade opportunities.*
- ✓ *Reduces the risk of infection and disease.*
- ✓ *Slows sprouting and ripening in some fresh fruits and vegetables resulting in an extended shelf life.*

Benefits of Irradiation

There are several benefits of expanding the use of irradiation treatments to control pests infesting perishable and non-perishable commodities in the United States. First, irradiation may be useful for preventing the movement of quarantine species possibly present in trade commodities into areas where such pests are not established (USDA 1996b). From an economic standpoint, irradiation, therefore, has the potential to increase trade opportunities between nations, especially from major fruit and vegetable producing countries with high infestation rates (ICGFI 1994).

Irradiation also can be used to reduce the risk of infection and disease caused by foodborne pathogens (Moy 1991). Although consumers have concerns associated with the safety of irradiation technology and its effects on food, research indicates that properly irradiated food does not pose a risk to consumers (Thorne 1983, OTA 1985). In fact, the potential for human health impacts from exposure to foodborne pathogens is believed to be substantially reduced through the use of irradiation (OTA 1985, Morrison et al. 1992).

In addition, by interfering with cell division, irradiation inhibits sprouting in tubers, bulbs, and root vegetables (potatoes, onions) and can delay ripening of some tropical fruits, resulting in an extended shelf life for many foods. In turn, longer shelf lives will enhance trade opportunities between nations by extending time constraints under which fresh produce must be delivered to more distant geographic markets or by allowing the use of slower and less expensive modes of transportation (Kader 1986, Moy 1991, OTA 1985).

Uses of Irradiation

Irradiation is used as a pest control tool in over 40 countries, including the United States, Russia, Great Britian and Brazil (Nordion 1995). The disinfestation of grain as it enters the Soviet Union at the Black Sea Port of Odessa, estimated at over 500,000 metric tons per year, is one of the largest documented commercial industrial applications (Giddings 1991). In the United States, the FDA approved low-doses irradiation for wheat, wheat flour, and potatoes in the early 1960s. In 1984 and 1985, the FDA approved irradiation of spices and pork, and in the following year, approved low-dose irradiation (up to 1 kGy) to control insects in foods and extend the shelf life of fresh fruits and vegetables (Kader 1986, Morrison 1989). Irradiation has also been used to sterilize food for U.S. hospital patients and astronauts (Morrison 1992). Further, irradiation disinfestation has been found to be effective for treatment of dried fruits, spices, nuts, cut flowers, lumber, and wood chips (ICGFI 1994, Marcotte 1992, Morrison 1989, OTA 1985). At doses below 1 kGy, irradiation is an effective treatment against various species of fruit flies, mango seed weevils, naval orange worms, potato tuber moths, codling moths, and other insect species of significance to quarantine situations (Kader 1986). For irradiation to be approved as a quarantine treatment in the United States, either as a single treatment, or as part of a combined approach (e.g., systems approach), USDA/APHIS/PPQ will require that the level of efficacy be scientifically demonstrated, and that efficacy be demonstrated under commercial settings (USDA 1996b).

Effective Dosages and Impact on Produce Quality

Because foods differ in their radiation dose requirements, densities, as well as specific packing configurations (Kunstadt et al. 1990), research has focused on insect mortality, morbidity, and sterilization, as well as the effects of ionizing radiation on fruit quality. The effects of irradiation depend on the dose absorbed. Low doses (up to 1 kGy) inhibit sprouting in tuber, bulb and root vegetables, inhibit the growth of asparagus and mushrooms, and delay physiological processes (ripening, etc.) in such fruits as banana, mango, and papaya. Medium doses (1 to 10 kGy) extend the shelf life of commodities, eliminate spoilage and pathogenic microorganisms, and improve the technical properties of food. Lastly, high doses (10 to 50 kGy) can be used for industrial sterilization and decontamination of certain additives or ingredients (Morrison 1992, ICGFI 1994, OTA 1985, Kader 1986).

In 1984, the International Consultive Group on Food Irradiation (ICGFI) convened in Washington, D.C., to develop a set of guidelines for the irradiation of fresh produce. The group established minimum doses that could provide effective treatments against most arthropod pests (ICGFI 1994). Doses used to disinfest foods and agricultural products are usually between 0.15 kGy (minimum dose for fruit fly sterilization and to prevent larval development) and 0.30 kGy (to control other species of insects and mites), but may go as high as 1 kGy (Forsythe and Evangelou 1993, Marcotte 1992). While research has proven irradiation to be effective at sterilizing pest insects, there is concern as to how quarantine inspectors would tell the difference between sterile and non-sterile insects that physically appear the same.

Unless already established, the correct dose required for a specific commodity infested with a specific pest must be determined through testing. Results of some of the studies that have investigated dose requirements include:

- Research on the mango seed weevil in the U.S. has shown that irradiation at doses of 0.30 kGy prevented adult emergence from infested fruit (ICGFI 1994).

- USDA researchers in Florida found that radiation doses as low as 0.30 kGy were effective in eliminating plum curculio (*Conotrachelus nenuphar*), and blueberry maggot (*Rhagoletis mendax*), without altering overall fruit quality (Hallman and Miller 1994).

- Researchers at Washington State University conducted a series of tests on 'Rainier' cherries and determined that irradiation levels as high as 0.30 kGy had no effect on composition, color, or taste. They also concluded that doses of 0.15 and 0.25 kGy were effective in controlling cherry fruit flies and codling moths, respectively (Drake et al. 1994).

- Studies done at the U.S. Horticultural Research Laboratory in Florida (USDA/ARS, Orlando) showed that irradiation doses up to 0.75 kGy were sufficient in controlling apple maggot (*Rhagoletis pomonella*), blueberry maggot (*Rhagoletis mendax*), and plum curculio (*Conotrachelus nenuphar*), without doing any damage to the fruit's composition or taste (Miller and McDonald 1994).

Factors influencing the response of fresh fruits and vegetables to irradiation include the type of commodity and cultivar, production area and season, maturity at harvest, initial quality, and post harvest handling procedures. Similarly, environmental conditions during irradiation (temperature and atmospheric composition), and dose rates are also influencing factors (ICGFI 1994, Kader 1986, OTA 1985, Morrison 1992). The relative tolerances of fresh fruits and vegetables to irradiation doses below 1 kGy are listed in Table 1 below.

Table 1. Relative Tolerance of Fresh Fruits and Vegetables to Irradiation below 1 kGy

Relative Tolerance	Commodities
High	Apple, cherry, date, guava, longan, muskmelon, nectarine, papaya, peach, rumbutan, raspberry, strawberry, tamarillo, tomato
Medium	Apricot, banana, cherimoya, fig, grapefruit, kumquat, loquat, lychee, orange, passion fruit, pear, pineapple, plum, tangelo, tangerine
Low	Avocado, cucumber, grape, green bean, lemon, lime, olive, pepper, sapodilla, soursop, summer squash, leafy vegetables, broccoli, cauliflower

Source: Kader 1986.

Costs

The actual cost of food irradiation is influenced by dose requirements, the food's tolerance of radiation, handling conditions (i.e., packaging and stacking requirements), construction costs, financing arrangements, and other variables particular to the situation (Forsythe and Evangel 1993, USDA 1989). Irradiation is a capital-intensive technology requiring a substantial initial investment, ranging from $1 million to $3 million (or possibly more for special applications). In the case of large research or contract irradiation facilities, major capital costs include a radiation source (cobalt-60), hardware (irradiator, totes and conveyors, control systems, and other auxiliary equipment), land (1 to 1.5 acres), radiation shield, and warehouse. Operating costs include salaries (for fixed and variable labor), utilities, maintenance, taxes/insurance, cobalt-60 replenishment, general utilities, and miscellaneous operating costs (Kunstadt et al., USDA 1989).

Based on a review of public information on the costs of treating a variety of food items with irradiation, Table 2 presents data on the per-unit costs for gamma irradiation and methyl bromide treatments for selected crops. Although irradiation is more expensive than fumigating with methyl bromide, the cost of irradiation may be offset by its many benefits, including reduced damage to fruits and vegetables and an extended shelf life. Furthermore, it is likely that irradiation costs will decrease in the future as the number of commercial irradiators and volumes of treated commodities increases. In addition, the relative proportion of the treatment cost is small when compared to the value of the commodity. Furthermore, other related costs (i.e., harvesting, packaging, storage, processing, and transportation costs to bring the commodity to market) further reduce the percent contribution of irradiation treatments, making it a relatively insignificant cost overall.

Table 2. Comparison of Estimated Post-Harvest Treatment Costs for Selected Crops.

Crop	Methyl Bromide (cents per pound)	Irradiation (cents per pound)
Strawberries	0.88 to 0.94	2.5 to 8.1
Papaya		0.9 to 4.2
Mango		N/A

N/A = Data not available.
Sources: Forsythe and Evalgelou 1993 and 1994, Morrison 1989.

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Stratospheric Ozone Protection Case Study

Methyl Bromide Alternative

Structural Fumigation Using Sulfuryl Fluoride: DowElanco's Vikane™ Gas Fumigant

Sulfuryl fluoride (SO_2F_2), also known as Vikane™ (99.8 percent by weight sulfuryl fluoride and 0.2 percent inerts), was developed by Dow Chemical in the late 1950s as a structural fumigant. Vikane™ (currently manufactured by DowElanco) possesses characteristics for the eradication of structure-infesting insects (Derrick et al. 1990). It is non-flammable, non-corrosive, and does not cause undesirable odors. It quickly penetrates structural materials, is effective against a variety of structural pests, and dissipates rapidly during aeration (Chambers and Millard 1995, Stewart 1957 and 1966, Kenaga 1957). This material is an established structural fumigant, and therefore is considered an alternative to methyl bromide. Since first marketed in the United States in 1961, it has been used to fumigate more than one million buildings, including museums, historic landmarks, rare book libraries, government archives, scientific and medical research laboratories, and food-handling facilities (DowElanco 1994). Compared to methyl bromide, sulfuryl fluoride penetrates structural materials more rapidly, and is effective against a wide variety of pests, and leaves less residue in materials after aeration. These characteristics make it a viable alternative to methyl bromide in structural fumigation (Derrick et al. 1990).

Benefits of Vikane™

- ✓ *Non-flammable, non-corrosive and does not cause undesirable odors.*
- ✓ *Easily dispersed into a structure and quickly penetrates structural materials*
- ✓ *Effective against a wide variety of pests*
- ✓ *Does not form residues on fumigated materials*
- ✓ *Dissipates rapidly during aeration*

Sulfuryl fluoride is an excellent broad-spectrum fumigant, due to its toxicity to target pests, good dispersion and penetrating qualities. It is commonly used to control a wide variety of household pests, including drywood and Formosan termites (Bess and Ota 1960, Stewart 1957), wood-boring beetles (powder post beetles, death watch beetles, and old house borers), fabric and museum pests (clothes moths and furniture and carpet beetles), cockroaches, bed bugs, snails (Richardson and Roth 1965), brown dog ticks, and rodents (rats and mice) infesting buildings, furnishings, construction materials, and vehicles (DowElanco 1996a, Kenaga 1957, Bess and Ota 1960, Roth 1973).

Fumigant Qualities Compared with Methyl Bromide

In many ways, Vikane™ can be a preferred structural fumigant over the use of methyl bromide. Unlike methyl bromide, sulfuryl fluoride does not react with sulfur-containing materials to form off- or skunk-odors (DowElanco 1996a). Vikane™ passes through nylon and polyethylene sheeting much more slowly than does methyl bromide, so that the gas is easily confined by the plastic tarps commonly used in structural fumigation. Furthermore, sulfuryl fluoride penetrates into and aerates from wood much faster than methyl bromide (DowElanco 1996a, Bond 1984, Grey 1960). Rapid penetration of substrates inhabited by the pests allows for variable (shorter) exposure times compared with standard exposure times for methyl bromide (DowElanco 1996a). Lastly, because sulfuryl fluoride is about 20 times less soluble in water than methyl bromide (i.e., 0.075 percent by weight at 77 °F (Meikle and Stewart 1962)), water can be used to form a barrier or bottom seal during the fumigation process (DowElanco 1996a).

Efficacy

Sulfuryl fluoride is highly toxic to all post-embryonic life stages of insects (UNEP 1994), eggs of most species are less susceptible (DowElanco 1996a; Bond 1984). The efficacy of sulfuryl fluoride depends on the concentration reaching the target pest and the duration of exposure. As a result, the dosage of sulfuryl fluoride required for a specific pest is calculated in "ounce-hours," ounces of Vikane™ multiplied by hours of exposure. In general, insect eggs require a higher ounce-hour dosage of sulfuryl fluoride compared to later life stages (i.e., a 10-fold increase in dosage for some insect species) (UNEP 1992, UNEP 1994). However, the ability to control egg stages of social insects (i.e., termites and ants) is not necessary because these newly hatched larvae cannot survive without adult care. Furthermore, the higher dosages required to control insect eggs can be obtained by increasing the exposure time, concentration of sulfuryl fluoride, or a combination of the two. Fumigators use a "fumiguide calculation system" to determine the amount of Vikane™ required for specific pest and fumigation conditions (DowElanco 1994 and 1996a).

Sulfuryl fluoride prevents insects from metabolizing the stored fats they need to maintain a sufficient source of energy for survival by disrupting the glycolysis cycle (Meikle et al. 1963). Mortality may be delayed for insects for several days following fumigation (Osbrink et al. 1987), therefore insects that have received a lethal exposure to sulfuryl fluoride may still be alive immediately following fumigation (no longer than 3 to 5 days for termites) (DowElanco 1994). Sulfuryl fluoride has also been demonstrated to reduce oxygen uptake in insect eggs (Outram 1970).

Usage

Vikane™, a restricted-use pesticide, is currently registered to control certain pests in the following infested sites: structures, fumigation chambers, construction materials and furnishings (including household effects), and all vehicles except aircraft and subsurface water vessels (Derrick et al. 1990, DowElanco 1996a). Vikane™ is odorless, colorless, non-flammable, non-reactive, and non-corrosive at temperatures normally encountered in structural and other fumigations. As a result, it can be used to fumigate photographic supplies, metals, paper, leather, rubbers, plastics, cloths, wallpapers, household furnishings, and a variety of other articles (Trinkley 1996, Derrick et al. 1990, Anonymous 1980). It has little or no effect on the germination of weed and crop seeds; however, it is injurious to green plants, vegetables, fruits, and tubers. Sulfuryl fluoride does not form toxic surface residues on household items, and thus dishes, cloths, and other items do not need to be removed or washed following fumigation with Vikane™ (DowElanco 1994). It is not registered for use where food and grain commodities are present because food residue tolerances have not been established. Guidelines for use of the fumigant specifically state that "under no conditions should Vikane™ be used on raw agricultural food commodities, foods, feeds, or medicinal products destined for human or animal consumption, or on living plants" (UNEP 1994, Bond 1984).

Application

To control termites, Vikane™ is applied to tarped or sealed structures for an exposure period of 2 to 72, commonly 20-24 hours (the duration depends on fumigant and labor cost considerations and time constraints), followed by a 6 to 8 hour aeration period (UNEP 1994). It is packaged in white cylinders as a liquid under pressure (99.8 percent Vikane™ with no other pesticides, solvents, or additives); however, it volatilizes rapidly upon release from the cylinder. Therefore, the gas is released under its own vapor pressure through tubing directly into the structure from pressurized cylinders. The released sulfuryl fluoride is dense (3.5 times heavier than air), and will extract heat from the air as it changes from a liquid to a gas. Fans are used not only to distribute Vikane™ throughout the fumigation area, but also to as heat exchangers to mix cool air near the fumigation introduction site with surrounding warmer air to prevent condensation of moisture from the air. Unlike methyl bromide, no auxiliary heat source is required (Stewart 1957).

As with methyl bromide, exposing sulfuryl fluoride to open flames can form acids which may react with metals, glass, ceramic tiles, or china near the heat source. Thus, prior to structural fumigation, all open flames and glowing heat filaments are turned off or disconnected (i.e., pilot lights, electric heater elements, or automatic switches) (DowElanco 1994, Derrick et al. 1990). Once the appropriate amount of Vikane™ is introduced, the fumigator closes the cylinder valve and removes the tubing from the cylinder. Concentrations of Vikane™ can be monitored during fumigation using a fumiscope. Because sulfuryl fluoride is odorless and does not irritate the eyes or skin, trace amounts of a warning agent (e.g. chloropicrin, which causes irritation to the eyes, tears, discomfort, and has a noticeable disagreeable pungent odor) are typically introduced into the structure prior to fumigation to act as a warning agent (DowElanco 1994 and 1996a).

Because of a multitude of structural, environmental, and fumigation variations, no two fumigations are alike. The required dosages of Vikane™ are influenced by the temperature at the site of the pest, the length of the exposure period, containment or the rate the fumigant is lost from the structure, and the susceptibility of the pest to be controlled. As a result, dosages vary, however a typical dry wood home fumigation uses 6-16 ounces (0.4 - 1.0 lbs.) per thousand cubic feet. A specially designed Fumiguide™ calculator, which takes into account varying fumigation conditions (e.g., wind speed, relative humidity, tarp condition, volume in cubic feet being treated, soil type around structure, target pest, fan capacity, and exposure duration), is used to determine the required fumigant dosage. Once the fumigation is complete, the fumigator will return to the structure to conduct the aeration procedure (DowElanco 1994 and 1996a).

Aeration, the final step in a fumigation, requires proper ventilation and clearance of Vikane™ and the warning agent from a structure. According to the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) and the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) for Vikane™, the fumigator must aerate the structure so that the concentration of sulfuryl fluoride is 5 ppm or less prior to reentry. Reentry must be approved by trained and state-licensed/certified professionals (DowElanco 1996a). Because sulfuryl fluoride has a very high vapor pressure (potential to escape from an area) and a low boiling point (it is a gas at -67°F), it will quickly diffuse from high concentrations within a structure to the outside air where it rapidly dissipates to non-detectible levels (Ultraviolet radiation and reactions with solid particles in the atmosphere catalyze the breakdown of Vikane™) (DowElanco 1994).

The relatively small amounts of sulfuryl fluoride released are calculated to have virtually no impact on the global atmosphere or environment. It is broken down mainly through hydrolysis to release fluoride and sulfide ions. Because it is fully oxidized it does not interact with or contribute to local ozone formation. Furthermore, the relative contribution of sulfuryl fluoride to acid rain is infinitely small compared to massive amounts of sulfur released to the atmosphere from industry. Lastly, sulfuryl fluoride contains no chlorine or bromine and therefore does not contribute to stratospheric ozone depletion (Chambers and Millard 1995, Baily 1992).

Toxicity

Sulfuryl fluoride is a toxic gas that can be handled safely by trained professional fumigators. This gas (as well as methyl bromide) is acutely toxic to humans, although the severity of toxicological effects is dependent on the exposure concentration and exposure duration. Short-term inhalation exposure to high concentrations may cause respiratory irritation followed by pulmonary edema (an accumulation of fluid in the lungs, which can cause death), nausea, abdominal pain, central nervous system depression, and numbness in the extremities. Chronic longer-term inhalation exposure to concentrations significantly above the threshold limit value (TLV) may result in fluorosis (i.e., fluoride binding to the teeth and bones) because sulfuryl fluoride is converted to fluoride ion in the body (DowElanco 1994). Mammalian toxicity by inhalation is about equal to that of methyl bromide (Bond 1984).

Market Trends

Currently, sulfuryl fluoride is used in approximately 85 percent of all structural fumigations, while methyl bromide is used for the remaining 15 percent (Sansone 1996). In California, fumigating dwellings with sulfuryl fluoride has reduced the use of methyl bromide by more than 80 percent. For example, about 2,300 tones of methyl bromide were used in 1990 compared with 430 tones in 1992 (UNEP 1994).

DowElanco supplies 100 percent of the Vikane™ structural fumigation market. The company is currently involved in efforts to increase the use of Vikane™ gas fumigant in two selected markets: 1) quarantine fumigation applications and 2) use in empty food processing facilities. Under current quarantine procedures (USDA-APHIS PPQ Treatment Manual and the AQIS Cargo Container Quarantine Aspects and Procedures Manual), treatment rates for are provided for fumigation of non-food cargo potentially infested with wood-infesting beetles. Efforts are currently underway to develop treatment schedules for additional target insect pests of non-food goods. An additional potential quarantine fumigation opportunity for Vikane™ is the development of treatment schedules to fumigate timber being imported into the United States, Europe, and Japan to control wood-destroying beetles and/or fungal pathogens.

Cost of Fumigating with Vikane™ vs. Methyl Bromide

A general picture of the kinds of fumigation costs associated with using Vikane and Methyl Bromide is provided in the table below. Vikane™ application rates, (and the associated fumigant costs) are derived from the DowElanco Fumiguide calculator system (DowElanco 1996a). This system uses a number of variables that can positively or negatively affect the ability to achieve a lethal concentration. These factors include: the target pest (insect); ground temperature at structure site; structure size; the duration of the fumigation; the foundation type of the structure (slab, crawl space, basement, etc.); and whether or not the fumigation will be monitored. A fumigation performed in warmer months, on larger structures, with a slab foundation or a basement, can be more cost efficient than a comparable fumigation using methyl bromide. As indicated by the figures in the tables below, monitoring sulfuryl fluoride levels to confirm lethal dose during the fumigation utilizes less chemical and is less expensive than fumigation without monitoring.

The following cost breakout examples are for a 35,000 cubic foot structure - a typical home (Table 1), and for a 250,000 cubic foot structure - a commercial structure (Table 2). Cost estimates are for non-monitored and monitored (in parenthesis) fumigations. Label rates for methyl bromide range from 1 to 3 lbs/1000 ft^3. The examples listed below use the 1 lb/1000 on a slab foundation and 2 lb/1000 for a structure with a crawl space. The conditions for these examples were: Tarp = good; Seal = Good; Wind = 4mph; Crawl space = sandy loam. The temperature was 75° F and a 24 hour exposure period. The dosages for these examples were calculated on the Fumiguide electronic calculator.

These examples are for fumigations to eliminate drywood termites. Fumigating for other insects (like powder post beetles or wood borers) would increase the amount of fumigant required for Vikane™. There are additional costs that are not considered in these examples. These costs include: 1) Extended aeration times for methyl bromide may require additional manpower and equipment costs for the fumigator. There will also be costs absorbed by the structure owner because the extended aeration period delayed re-occupancy . Methyl Bromide costs for homes would include four nights hotel room rental (1 during fumigation + 3 for aeration) compared to 2 nights (1 during fumigation + 1 aeration) for Vikane™. 2) There also may be potential replacement costs for material which may react with methyl bromide to cause odor problems in fumigated structures.

Table 1. Vikane™ vs. Methyl Bromide Costs for a Typical Home (35,000 ft³).

Cost Factors	Treatment #1 Vikane ($/1,000 ft²)		Treatment #2 Methyl Bromide ($/1,000 ft²)	
Expense	**Crawl Space (Monitored)**	**Slab Foundation (Monitored)**	**Crawl Space**	**Slab Foundation**
Price/Pound	$9.00	$9.00	$2.75	$2.75
Fumigant Costs	$312.30 ($234.90)	$118.80 ($89.10)	$192.50	$96.25
Clearing Equipment	$2.40 ($3.30)	$2.40 ($3.30)	$42.50	$42.50
Total Expenses	**$314.70 ($238.20)**	**$121.20 ($92.40)**	**$235.00**	**$138.75**

Table 2. Vikane™ vs. Methyl Bromide Costs for a Commercial Structure (250,000 ft³).

Cost Factors	Treatment #1 Vikane ($/1,000 ft²)		Treatment #2 Methyl Bromide ($/1,000 ft²)	
Expense	**Crawl Space (Monitored)**	**Slab Foundation (Monitored)**	**Crawl Space**	**Slab Foundation**
Price/Pound	$9.00	$9.00	$2.75	$2.75
Fumigant Costs	$1,371.60 ($1,028.70)	$747.80 ($561.60)	$1,375.00	$687.50
Clearing Equipment	$2.40 ($3.30)	$2.40 ($3.30)	$85.00	$85.00
Total Expenses	**$1,374.00 ($1,032.00)**	**$751.20 ($564.90)**	**$1,460.00**	**$772.50**

Source: DowElanco 1996b.

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