Alternatives to Methyl Bromide: A Florida Perspective

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Introduction

The first use of methyl bromide as a soil fumigant occurred in France in the 1930s (6). Since its discovery and implementation, methyl bromide has been consistently effective for control of nematodes, fungi, insects, and weeds and has been used on more than 100 crops worldwide. Methyl bromide’s high vapor pressure allows for rapid and thorough distribution through the soil, enhancing its effectiveness as a fumigant. The high vapor pressure also facilitates a relatively short plant-back interval and gives growers a great degree of flexibility. For nearly four decades, methyl bromide has been the fumigant most heavily relied upon for preplant soil treatment for the production of vegetables and ornamentals. The world’s largest consumer of methyl bromide is the United States, where the majority of use (83%) is for preplant soil fumigation (103). Other uses include post-harvest treatment of stored commodities (11%) and structural fumigation (6%). In 1997, 36% of preplant methyl bromide use took place in Florida crop production systems, with strawberry, pepper, and tomato accounting for 9, 23, and 62%, respectively, of the soil fumigation uses in the state (75). Methyl bromide is considered essential for the production of eggplant, pepper, strawberry, watermelon, and tomato in many locations (36,37,107). The nursery industry accounts for nine percent of the U.S. preplant consumption of methyl bromide for the production of potted plants, cut flowers, ornamental nursery plants, fruit and tree nursery plants, sod, bulbs, and strawberry and vegetable transplants (102). Within the floriculture industry, there are few statistics on methyl bromide use by individual crops, although certain segments such as the field production of chrysanthemum, caladium, and gladiola rely heavily on its use as a soil fumigant (52).

Based on its ability to deplete ozone in the atmosphere, methyl bromide has been classified as a Class 1 stratospheric ozone depletor (108). The Vienna Convention on the Protection of the Ozone Layer, signed in 1985, established the legal framework for addressing anthropogenic sources of ozone depleting substances. From this, the Montreal Protocol was established in 1987, in which the parties established guidelines for the reduction of ozone depleting substances. An amendment to the protocol in 1992 identified methyl bromide as a substance of concern and established a phase-out program in developed countries of 25, 50, 75, and 100% reductions from the 1991 domestic production level in 1999, 2001, 2003, and 2005, respectively. Developing countries were given a modified schedule in which a 20% reduction from 1995-1998 would be followed by a 100% reduction by 2015 (3). Initially, in 1994 under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) determined that this fumigant must be phased out by 2001. Quarantine and preshipment uses of methyl bromide are not subject to the Montreal Protocol’s 2005 phase-out.

Status of Methyl Bromide Critical Use Exemptions (CUE)

In 1997, the Parties to the Montreal Protocol recognized a justifiable need for transitional access to methyl bromide, and adopted a formal decision to allow limited critical use exemptions (CUE). Exemptions were to be granted only when the following criteria were met:
1. Failure to provide access to methyl bromide would result in a significant market disruption;

2. There were no technically and economically feasible alternatives available to an applicant that were acceptable from environmental and human health standpoints;

3. The applicant had taken all feasible steps to minimize their use of methyl bromide and the associated emissions; and

4. Appropriate efforts were being made to evaluate, commercialize, and register alternatives to methyl bromide for use by the applicant.

The exemption application process is extremely rigorous. Detailed information is required from each applicant, including comprehensive information on the impact of alternatives on crop yields and profit margins, and a description of efforts undertaken to develop, register, and apply new alternatives. In order to assist growers in the application process, in March 2001, the EPA began meeting with stakeholders to inform them of their understanding of requirements under the Montreal Protocol for attaining a CUE.

In 2002 and 2003, the U.S. nominated 16 crops/uses for a CUE for methyl bromide use in 2005 and 2006. These were commodity storage, cucurbits, eggplant, food processing, forest tree seedling nursery, ginger, nursery seed bed trays, orchard nursery, orchard replant, ornamental nursery, pepper, strawberry, strawberry nursery, sweet potato, tomato, and turf grass. For 2005, the Parties authorized 35% of the U.S. 1991 baseline for a critical use exemption.

For 2006 the Parties authorized 29% of the 1991 baseline, with 10% to be assessed at a one-day extraordinary meeting of the Parties in July 2005. This nomination covers exemptions for 17 crops or uses, including tomatoes, strawberries, peppers, cucurbits, orchard replant, forest nurseries, turf, and post-harvest uses.

For 2007 the U.S. is requesting 29 percent of 1991 baseline amounts to cover 15 agricultural sectors including tomatoes, strawberries, peppers, cucurbits, orchard replants, turf, forest nurseries, and post-harvest uses. This request will be considered by the Parties at their 17th Meeting at the end of 2005. See the Authors’ List of Related Links for additional information on specific commodity sectors and copies of all U.S. nominations.

**National management strategy (NMS).** In March 2004, at the Extraordinary Meeting of the Parties in Montreal, conditions for granting and reporting CUE were determined. In addition, they also requested that each Party making a nomination after 2005 submit a National Management Strategy (NMS) for phase-out of critical uses to the Ozone Secretariat before February 1, 2006. The NMS is to address:

1. Avoidance of any increase in methyl bromide consumption except for unforeseen circumstances;

2. Encouragement of the use of alternatives through expedited procedures, to develop, register and deploy technically and economically feasible alternatives;

3. Provision of information for each use for which a nomination is planned on the potential market penetration of newly deployed alternatives, to bring forward the time when methyl bromide consumption for such uses can be reduced or eliminated;

4. Promotion of the implementation of measures which ensure that any emissions of methyl bromide are minimized; and

5. Demonstration of how the NMS will be implemented to promote the phase-out of methyl bromide as technically and economically feasible alternatives are available, describing the progress of each Party with respect to research programs and adoption of alternatives.
**Allocation rule.** In late December 2004, the EPA finalized a rule to create the CUE. A framework for granting "critical use allowances" to producers and importers of methyl bromide has been designed to allow production and importation of up to 30% of 1991 methyl bromide baseline for use in 2005. An additional 5% of the 1991 baseline can be used from "critical stock allowances" which allow holders to sell methyl bromide to critical users from stocks that were manufactured or imported before January 1, 2005. Users of methyl bromide (excluding those for QPS applications) must meet specified criteria and their application must be designated as a critical use in order to be able to purchase methyl bromide from their supplier. Users must certify, under penalty of law, that they are approved critical users. For instance, in Florida, limiting conditions which qualify a use as critical include the presence of karst topography (land above caves or underground channels) or a reasonable expectation of moderate to high infestation of nutesedg (*Cyperus rotundus* or *C. esculentus*).

**Methyl Bromide-Dependent Crops: Florida Tomato and Pepper Production.** Florida’s cash receipts for bell peppers (*Capsicum annuum*) ranked first and tomato (*Lycopersicon esculentum*) receipts second in the country based on 2002 data. These crops account for 3.2 and 7.4% of Florida’s total agricultural receipts respectively. Based on 2004 receipts, Florida peppers from 7,487 ha and tomatoes from 17,159 ha have an annual value exceeding $725 million (30).

Commercial vegetable production takes place throughout Florida in climates ranging from humid sub-tropical to tropical (100) (Fig. 1). Average annual rainfall ranges from approximately 40 to 65 inches/year. Soils are sandy, have minimal organic matter, and are relatively low in fertility. Conventional growers use a "raised-bed, plastic-mulch" production system that was developed in the 1960s (37,53,87) and has served a pivotal role in the economic success of southeastern U.S. tomato and pepper production (7,36). This system is dependent upon the use of a polyethylene-mulch-covered raised bed, on which plants are staked and tied as they grow (84). Growers use either drip or seepage irrigation, which is composed of a system of irrigation ditches in which water levels are raised and lowered to control soil moisture levels in the field. Beds are fumigated with a mixture of methyl bromide and chloropicrin. Fumigants are shank injected using chisels spaced 30 cm apart as the soil is pulled up to form the beds (Fig. 2). The beds are then covered immediately with polyethylene plastic, which functions as mulch. Estimates of methyl bromide consumption in 2002 indicate use in bell pepper at 1101 metric tons and 2207 metric tons in tomato (Fig. 3).
Important pests in Florida tomato and pepper production. A plethora of pests impacts the production of Florida tomatoes and peppers. Major soilborne pests of tomato and pepper include root-knot nematode (*Meloidogyne* spp.) (Fig. 4), a number of fungal plant pathogens which vary according to the production area, and multiple weeds. On tomato, Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *lycopersici* and Fusarium crown rot (*Fusarium lycopersici* f. sp. *radiscis-lycopersici*) are found throughout Florida (14,96). Verticillium wilt and Corky brown root rot (*Pyrenochaeta lycopersici*) are pathogen problems that are unique to the Dade County tomato production area, but are of considerable concern (67).
Some pathogen problems are common to both tomatoes and peppers. Damping-off, caused by *Pythium* spp. and *Rhizoctonia* spp., is a significant problem in both crops, particularly during the early stages of growth. Recently, *Pythium* spp. have been associated with disease symptoms in mature plants and identified as a production limitation (12). Southern blight (*Athelia rolfsii*, sclerotial stage *Sclerotium rolfsii*) and white mold (*Sclerotinia sclerotiorum*) can also occur in both crops. White mold is a more serious problem in tomato than in pepper, although it occurs in both crops. Phytophthora blight, caused by *Phytophthora capsici* is often the most devastating disease impacting pepper (Fig. 5). It occurs sporadically throughout Florida and can impact the primary pepper crop as well as the secondary cucurbit crop (89).

Weeds are also extremely important in tomato and pepper and represent some of the most difficult pests to control. Nutsedges are consistently problematic throughout Florida (Fig. 6). Pigweeds (*Amaranthus* spp.), nightshades (*Solanum* spp.), ragweed (*Ambrosia artemisifolia*), and eclipta (*Eclipta prostrata*) are also common problems. The weed pests in these crops represent a two-fold problem in many cases. In addition to causing significant crop losses due to direct and indirect competition with crop plants, several of these weeds serve as hosts to a number of pathogens that affect the crops in which they are found. Solanaceous weeds harbor several pathogens, including viruses (Fig. 7), that are important in the production of solanaceous crops (1,16,65).
Solanaceous weeds and pigweeds are also able to support the reproduction of root-knot nematodes (Fig. 8) (81). In addition, nightshade is reported as a host to *P. capsici* (98), and galled nutsedge tubers may be found in fields with heavy root-knot nematode infestations. *Pythium* species are commonly isolated from roots of pigweeds, goose grass, and ragweed (E. N. Rosskopf, unpublished). Other weeds that are commonly found in production fields include purslane (*Portulaca oleracea*), which is a host to *P. capsici* (R. French-Monar [University of Florida]) and numerous grasses that support pathogen and nematode populations.

**Methyl Bromide-Dependent Crops: Florida Strawberry Production.** Florida currently ranks second to California in strawberry (*Fragaria ananassa*) production in the U.S., with 15% of the total crop, and 100% of the domestically-grown winter crop (31). The majority of Florida’s strawberry acreage is located in a concentrated region within a 40-km radius of Plant City, FL, on approximately 2,760 ha (29). The average farm is comprised of approximately 16 ha and most farms are located in, or very near residential areas, which can limit the pest control options available. In Florida, strawberries are grown as an annual crop using raised beds, with two rows of plants per bed (60). Strawberry production practices begin with land preparation in mid-July to mid-August. Soil fumigant is applied and beds are formed in mid-August to mid-September. Bed fumigation with methyl bromide in combination with
chloropicrin is applied approximately 2 weeks prior to transplanting. A single application at an average rate of 159 to 204 kg/ha is injected into the soil during construction of the raised beds (75). The bed is then immediately covered with plastic mulch. Transplants are primarily bare root and produced in northern-latitude nurseries. One drip irrigation line is typically placed in each bed with overhead irrigation used to help establish bare root transplants (23).

**Important pests in Florida strawberry production.** The most damaging pests in Florida strawberry production include sting nematode (*Belonolaimus longicaudatus*) and nutsedge. Surveys suggest that plant-parasitic nematodes have potential to be a major problem in at least 40% of Florida’s strawberry acreage (J. W. Noling [University of Florida]). Sting nematode can be extremely damaging to seedlings and transplants, which often undergo a progressive decline and eventually die (Figs. 9 and 10). Older plants with extensively developed root systems can also be severely affected by sting nematodes, making them much more susceptible to drought and injury from salt accumulation (22). Currently, there are no sting nematode-resistant or tolerant strawberry varieties and no post-plant nematode control options available.

The most important weeds in Florida strawberry production are nutsedges, Carolina geranium (*Geranium carolinianum*), cut-leaf evening primrose (*Onoethera laciniata*), and black medic (*Medicago spp.*) (104). Nutsedges are capable of penetrating plastic mulch, and all weeds remain a season-long problem in row middles and transplant holes. In addition, their survival through the first crop greatly impacts the following summer vegetable crop (Fig. 11). The strawberry production season in Florida lasts six to seven months, during which the density and composition of weed species change. This makes season-long control with herbicides difficult and requires a combination of control measures (97). Unlike in California, hand weeding is an option in Florida, but is not cost effective.
The most important soilborne pathogens in Florida strawberry production are Phytophthora crown rot (Phytophthora citricola and P. cactorum), and anthracnose (Colletotrichum spp.). Alternative chemical control options for these pathogens include preplant treatment with chloropicrin and season-long use of fungicides (100).

**Methyl Bromide-Dependent Crops: Florida Floriculture Production.** Floriculture is a highly diverse industry encompassing a wide range of ornamental plants. The portion of this industry that uses fumigation as a means to control soilborne diseases is limited to in-ground production of cut flowers, cut greens, and ornamental bulbs and tubers. Florida ranks first in the U.S. in production of cut greens with an estimated value of $83.4 million, and second in production of cut flowers with an estimated value of $21.9 million for 2003 (101). Caladium tubers (Caladium x hortulatum) produced in Florida have an estimated value of $15 million and represent 95% of world production. Caladiums are produced in central Florida in a region containing muck soil with high organic matter content (Fig. 12) (43).

The majority of caladiums are produced on open ground, on slightly raised beds without plastic mulch, and with or without shade or cover. Broadcast application of methyl bromide (Fig. 13) is typically applied at a depth of approximately 15 cm with shanks under a solid tarp of high density polyethylene (Fig. 14). Two formulations of methyl bromide:chloropicrin (98:2 or 90:10) are most commonly applied at 504 kg/ha. It is estimated that 1416 ha are treated annually in Florida for caladium production, using a total of 622,328 kg of methyl bromide (104).
Many floriculture growers in Florida use land that is near the Atlantic or gulf coasts because the mild climate is beneficial for growing a wide variety of specialized flowering plants. These coastal areas are typically urbanized and special considerations for pest management must be made by growers in order to coexist in populated regions. The majority of cut flower farms are directly adjacent to housing developments (Fig. 15), limiting the use of alternative fumigants because of restrictions near dwellings and potable water sources.

**Important pests in Florida floriculture production.** The diversity of floriculture crops dependent upon methyl bromide soil fumigation results in a large number of pests that have the potential to limit crop production in the absence of the fumigant. Common diseases and pests include Fusarium wilt, Pythium root rot, Sclerotinia stem rot, and various nematodes and weeds (Fig. 16 and Table 1) (94,104). Each crop, and sometimes each cultivar, may have different sensitivity to a pesticide. Weed problems in ornamental production are highly variable, and few herbicides are registered for use in these crops. In addition to providing control for diverse weed populations, methyl bromide has been used to transition from one cultivar to the next. Volunteers of the previous crop are considered weeds and reduce the value of the current crop.
Table 1. Key pests of major ornamental crops currently controlled with methyl bromide (modified from reference 104).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Pests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antirrhinum</td>
<td>Nematodes: Belanolaimus longicaudatus, Criconomella spp., Dolichodorus heterocephalus, Meloidogyne spp. Pythium root rot (Pythium irregulare)</td>
</tr>
<tr>
<td>Caladium</td>
<td>Nematode: Meloidogyne spp. Chalky rot (Fusarium sp.), Pythium root rot (Pythium sp.)</td>
</tr>
<tr>
<td>Calla lily</td>
<td>Erwinia soft rot (Erwinia carotovora) Pythium root rot (Pythium spp.)</td>
</tr>
<tr>
<td>Celosia</td>
<td>Pythium root rot (Pythium spp.), Fusarium wilt Nematodes: Meloidogyne spp.</td>
</tr>
<tr>
<td>Delphinium</td>
<td>Sclerotinia stem rot (Sclerotinia spp.)</td>
</tr>
<tr>
<td>Dianthus</td>
<td>Fusarium wilt (Fusarium oxysporum fsp. dianthii)</td>
</tr>
<tr>
<td>Eustoma</td>
<td>Nematodes: Meloidogyne spp. Fusarium wilt, root rot, and stem rot (Fusarium oxysporum, F. solani, F. avenaseaum)</td>
</tr>
<tr>
<td>Freesia</td>
<td>Fusarium wilt (Fusarium sp.)</td>
</tr>
<tr>
<td>Gladiolus</td>
<td>Fusarium wilt (Fusarium oxysporum fsp. gladioli), Stromatinia neck rot (Stromatinia gladioli)</td>
</tr>
<tr>
<td>Helianthus</td>
<td>Downy mildew (Plasmopara halstedii)</td>
</tr>
<tr>
<td>Hypericum</td>
<td>Nematodes: Meloidogyne spp. Pythium root rot (Pythium spp.)</td>
</tr>
<tr>
<td>Iris</td>
<td>Fusarium wilt (Fusarium oxysporum fsp. iridis)</td>
</tr>
<tr>
<td>Larkspur</td>
<td>Sclerotinia stem rot (Sclerotinia sclerotiorum)</td>
</tr>
<tr>
<td>Liatris spicata</td>
<td>Sclerotinia stem rot (Sclerotinia sclerotiorum)</td>
</tr>
<tr>
<td>Lilium</td>
<td>Pythium root rot (Pythium spp.)</td>
</tr>
<tr>
<td>Matthiola</td>
<td>Sclerotinia stem rot (Sclerotinia sclerotiorum), Xanthomonas leaf spot (Xanthomonas campestris pv. campestris)</td>
</tr>
<tr>
<td>Ranunculus</td>
<td>Pythium root rot (Pythium spp.), Xanthomonas leaf spot (Xanthomonas campestris)</td>
</tr>
<tr>
<td>Bulb, tuber, corm crops</td>
<td>Bulbs, tubers, corms from previous season</td>
</tr>
<tr>
<td>All</td>
<td>Weeds: Numerous species, including: nutsedge (Cyperus spp.), little mallow (Malva parviflora), sow thistle (Sonchus spp.)</td>
</tr>
</tbody>
</table>
Chemical Alternatives to Methyl Bromide

Currently-registered materials. Attempts to identify methyl bromide alternatives for vegetable, strawberry, and floriculture production has led to the re-examination of existing soil fumigants such as 1,3-D, methyl isothiocyanate (MITC) generators and chloropicrin (42,62). These compounds represent what is currently available, and they have been evaluated extensively. MITC-generating materials include metam sodium and metam potassium (Vapam and K-Pam, AMVAC Chemical Corp., Newport Beach, CA), as well as dazomet (Basamid). Metam sodium, introduced in 1954, is considered a Category 3 pesticide. The placement of the material must be directed to control specifically targeted pests, and combinations with other available materials are effective (18,95,105). Researchers in Florida have investigated metam sodium (300 liter/ha) and dazomet (440 kg/ha) applied to the bed surface and immediately incorporated, as well as metam sodium applied through irrigation. These treatments were not successful in controlling the targeted pests, including nutsedge (61), although treatments utilizing a combination that included pebulate (Tillam) did provide nutsedge control. In subsequent studies that focused on application methods, the optimal application for metam sodium involved a pre-bed spray (935 liter/ha) with incorporation to 15 to 20 cm prior to final bed preparation combined with pebulate at 4.5 kg/ha. This treatment resulted in Fusarium crown rot and nutsedge control that were equivalent to methyl bromide (66). In a more recent study by Gilreath and Santos (48), the combination of metam sodium (320 kg/ha) combined with pebulate (4.5 kg/ha) provided control of nutsedge that was equivalent to methyl bromide:chloropicrin (98:2, at 400 kg/ha) throughout the season. While this combination was effective in suppressing weeds and some soilborne plant pathogens, yields rarely reached those achieved when methyl bromide was used. In addition, the dependence on pebulate for nutsedge control significantly limits the usefulness of these materials due to the lapse in registration of the herbicide in 2002 (85).

Chloropicrin, a Class 1 pesticide, is considered primarily a fungicide. Chloropicrin has some nematicidal activity (47), although it is not as effective as other materials, such as 1,3-dichloropropene (1,3-D). However, its contribution for pathogen control is significant, and the majority of studies include chloropicrin as a component in a multi-tactic approach. Where fungal plant pathogens are the primary problem, it may be the only material needed. However, in most Florida production scenarios, the pest problems are more complex. Chloropicrin is an important component in the successful use of 1,3-D, expanding the spectrum of pests controlled, and may also be used to enhance herbicide efficacy for the control of nutsedge (73).

1,3-D was introduced by Dow in 1956. Formulations now include Telone II (100% 1,3-D), Telone C-17 (73% 1,3-D and 17% chloropicrin) and Telone C-35 (65% 1,3-D and 35% chloropicrin). In 2001, Telone EC and InLine were registered as drip application formulations of Telone II and Telone C-35, respectively. Initial studies to identify a chemically-based alternative using mixtures of 1,3-D and chloropicrin employed existing application procedures (19). In replicated field trials, the methyl bromide alternatives lacked broad-spectrum weed control, and the procedure was subsequently modified to include an herbicide application (46,61). At the time, workers present in the field during application of 1,3-D were required to wear personal protective equipment (PPE) including gloves, coveralls, and full-face respirators. These requirements were impractical and potentially dangerous for workers during the summer application period in Florida. Research efforts then focused on separating fumigant application from plastic laying operations by broadcast applying 1,3-D 10 days in advance of plastic laying using straight shank, forward swept, or parishes arranged in staggered rows (45,79). Deep disking prior to fumigation was recommended to achieve deep placement and uniform diffusion of the fumigant through soil. However, using this approach, concerns emerged regarding fumigant emissions from treated soil and average yield losses in large-scale field trials were 21.8% compared to adjacent methyl bromide treated plots (79).
A deep-placement coulter system (Avenger, Yetter Manufacturing Co., Colchester, IL) was modified to permit injection of 1,3-D into undisturbed soil (Fig. 17) (11). The intact crust layer at the soil surface served as a barrier to reduce fumigant emission from the soil. Sealing devices incorporated in the design further minimized movement of the fumigant up through airspace created by the coulter. Elimination of deep disking prior to fumigation reduced application costs, saved time, and expanded the application window. Additional field trials expanded the herbicide application program to account for regional diversity in weed communities and included an application of chloropicrin during bed formation. Application rates and procedures currently recommended to growers are included in Table 2. Twenty-one large-scale field trials have been conducted on 12 tomato and pepper farms in Florida since 2000. Disease control was equivalent to methyl bromide (within 5% of adjacent methyl bromide-fumigated areas) in 19 trials, inferior in one and superior in one. Soilborne diseases present in the trials were Fusarium wilt and crown rot of tomato and Phytophthora blight of pepper. Repeated applications in the same field over several years did not lead to an increase in soilborne pests. Yields ranged from 11.5% less to 18% more than in adjacent methyl bromide plots depending upon crop and year. After re-registration in 1999, label changes were implemented that modified the worker protection requirements for 1,3-D based materials, making them practical for use in Florida. Full-face respirators are no longer required, which significantly reduces the potential for heat stress of field workers during application. In addition, the buffer zones required were reduced from 91.4 m to 30.5 m.

Table 2. Broadcast-based chemical program for fresh market tomato and pepper.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Chemical</th>
<th>Rate per ha</th>
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<tbody>
<tr>
<td>1. Cultivate and seal soil surface</td>
<td>--</td>
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</tr>
<tr>
<td>2. Broadcast fumigant using deep placement coulter system</td>
<td>1,3-D:Pic&lt;sup&gt;x&lt;/sup&gt; (65:35)</td>
<td>187-221 liters</td>
</tr>
<tr>
<td>3. Wait 10 days</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4. Broadcast herbicides using directed spray, incorporate with cultivator, seal soil surface</td>
<td>napropamide trifluralin</td>
<td>2.2 kg 0.6 kg</td>
</tr>
<tr>
<td>5. Shank inject additional fumigant during preparation of the plastic-mulched beds</td>
<td>Pic</td>
<td>156 kg&lt;sup&gt;y&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>x</sup> 1,3-D = 1,3-dichloropropene and Pic = chloropicrin.
<sup>y</sup> Actual amount used by grower will be less because only planting beds are treated with the fumigant.
Currently, the best available alternative to methyl bromide for pepper production in Florida is a combination of Telone C-35 (1,3-D + 35% chloropicrin) at 187 to 221 liter/ha broadcast 3 to 5 weeks before planting, followed by chloropicrin at 78 to 116 kg/ha shanked into the bed. This is coupled with an herbicide tank mix of clomazone at 1.1 kg/ha or napropamide at 2.24 kg/ha, and s-metolachlor at 1.1 kg/ha over the bed top at plastic laying (11,80). The approach for tomato is much the same (50,80), except for tomatoes grown in Dade County, where Telone-based products cannot be used due to karst topography. In Dade County, the best available alternative is metam sodium (701.5 liter/ha) or metam potassium (561.2 liter/ha) with 160 kg/ha chloropicrin. Additional applications of halosulfuron can be used as a post-emergent directed spray where nutsedge is a problem (104). Vegetable trials focused on enhancing efficacy with Telone-based products, herbicides, and the effects of alternatives on the second crop in a double-crop situation are on-going (47; W. M. Stall [University of Florida]).

The best available alternative for strawberry also consists of Telone C-35 (1,3-D + 35% chloropicrin), applied in-bed at 331 liter/ha, 3 to 5 weeks before transplanting. Fumigant application is supplemented by an herbicide tank mix of oxyfluorfen 0.56 kg/ha plus napropamide 4.5 kg/ha. A minimum 30-day interval is required for oxyfluorfen before transplanting. No post-emergent nutsedge material is available at this time for Florida strawberry production (80,104). Although this has been identified as the best available alternative, strawberry growers are still concerned about the increased vegetative growth that is associated with high concentrations of chloropicrin (80).

There has been limited research on the efficacy of alternatives to methyl bromide for floricultural crops in the United States. Although much of the technology developed for vegetable production can be transferred to ornamentals, evaluation of their performance on specific crops must be completed before informed recommendations can be made. The majority of research on alternatives to methyl bromide for floriculture has been conducted in California. Many floriculture products are required to be free of nematodes and diseases by regulatory agencies. Currently, methyl bromide is the only chemical capable of providing a level of control that allows growers to ship products under these guidelines.

In California, research has been conducted on several floricultural crops including calla lily (Zantedeschia sp.), Freesia x hybrida, Liatrus spicata, Ranunculus asiaticus, snapdragon (Antirrhinum majus), Delphinium sp., and Gladiolus sp. (24,25,26,27,28,38,39,40,41,92). In Florida, the limited research that has been conducted includes work on snapdragons (Antirrhinum majus), cockscomb (Celosia argentea), and caladium (17,43,44,52,70,71,72). Telone and metam sodium-based treatments have shown promise in these trials, but additional testing is required to establish a multi-tactic alternative program.

Unregistered materials. A great deal of research has been conducted evaluating methyl iodide, also known as iodomethane (MI), as a drop-in replacement for methyl bromide. This material was originally developed by researchers in California, where the bulk of initial testing was performed (21). It is an attractive replacement due to its soil mobility and broad-spectrum of activity. It is not associated with ozone depletion and rapidly breaks down when exposed to UV light. Registration of methyl iodide is being sought by Arysta LifeScience North America (San Francisco, CA) under the trade name of Midas. In California, it has been tested in carrot, peach, cut-flower, and strawberry production (94). In south Florida, it has been tested alone and in combination with chloropicrin for control of Phytophthora capsici, root-knot nematodes, and yellow nutsedge. Pathogen control and yields of bell pepper were equivalent to methyl bromide when MI was combined with chloropicrin (420 kg/ha and 84 kg/ha MI and chloropicrin) (67,68). In microplot trials, Noling and Gilreath (78) evaluated methyl iodide at 28-336 kg/ha for control of root-knot nematodes and yellow nutsedge in tomato. Nutsedge germination and mid-season root-knot nematode counts were reduced by all application rates of methyl iodide. Nematode counts and root gall ratings at final harvest were not different from the untreated check, which would not allow for a double crop to be planted. Although roots were galled, tomato yields were higher than the untreated check.
with all rates over 56 kg/ha. Additional studies have been conducted to compare rates for nutsedge and nematode control (20, 49). Gilreath and Santos (49) found that the best control of nutsedge was achieved with 392 kg/ha of the 50/50 (MI:chloropicrin) formulation.

Propargyl bromide was patented as a soil fumigant by Dow Chemical Co. in 1957. Due to its high volatility, it was taken off of the market after a brief period during which it was used in combination with methyl bromide and chloropicrin. In 1999, a more stable formulation was developed that utilized toluene as a carrier. Albemarle Chemical Company was originally identified as a potential registrant (99). Phytotoxicity resulting from the toluene-formulated product lead to a second formulation. In Florida, trials evaluating application rates of propargyl bromide ranging from 45 to 224 kg/ha, rates between 45 to 112 kg/ha were as effective in controlling all tested pests, including root-knot nematodes, *Fusarium oxysporum* f. sp. *lycopersici* race 3, *Phytophthora capsici* (Figs. 18 and 19), and yellow nutsedge (82, 83). Although the results of all trials conducted with propargyl bromide have been positive, there is no registrant currently identified for this fumigant.

**Effect of propargyl bromide on survival of**

*Fusarium oxysporum* f. sp. *lycopersici* **Race 3**

![Graph showing the effect of propargyl bromide on survival of *Fusarium oxysporum* f. sp. *lycopersici* race 3](image)

Fig. 18. Impact of increasing rate of propargyl bromide on survival of *Fusarium oxysporum* inoculum buried at multiple depths.
Dimethyl disulfide (DMDS) is currently under development by Cerexagri (King of Prussia, PA), a subsidiary of ATOFINA Chemicals Inc. (Philadelphia, PA). DMDS has been identified as one of the volatile compounds produced when soil is amended with cabbage and solarized, which leads to a reduction in fungal plant pathogens and nematodes (34). This material has zero ODP and is reported to have a complex mode of action affecting mitochondrial function and causing inhibition of cytochrome oxidase in pathogens (4,8). Good control of several soilborne fungal pathogens and pathogenic nematodes was achieved in trials in France, Italy, and California (32). Recent work with DMDS in cut flowers has produced some encouraging results. Two trials were conducted with growers in Florida, where DMDS was shank applied at 785 kg/ha. At one site, DMDS provided weed control that was equivalent to methyl bromide. Weed pressure at a second site was very low, and no differences were detected among any treatments. DMDS provided Pythium root rot control that was comparable to methyl bromide (Fig. 20), and controlled root-knot nematode juveniles in soil at a level comparable to methyl bromide (Fig. 21). Most importantly, although the DMDS did reduce vegetative growth of cockscomb, marketable yields were equivalent to methyl bromide (Fig. 22) (17).
Fig. 20. Severity of Pythium root rot in celosia with DMDS (*scale 0 to 4: 0 = healthy, 1 = 1 to 25% root necrosis, 2 = 26 to 50% root necrosis, 3 = 51 to 75% root necrosis, 4 = 76 to 100% root necrosis). Bars with the same letter are not significantly different according to LSD (0.05).

Fig. 21. Root-knot nematode control in celosia with DMDS. Mean nematode counts from 100-cc composite soil samples collected from each plot. Bars with the same letter are not significantly different according to LSD (0.05).
Sodium azide has also been investigated as an alternative to methyl bromide. This material has been reported to have a wide range of activity, including control of nematodes, fungi, and weeds in a variety of crops (90, 91). The current formulation of sodium azide, SEP-100, is being registered with the EPA by American Pacific Corporation (Las Vegas, NV). Maximum use rate is 112 kg ai/ha.

Propylene oxide also falls into the near-registration category. This product, which has been used for more than 40 years as a stored-product treatment, is currently under development for soil applications by Aberco, Inc. (Seabrook, MD) under the trade name PROPOZONE. It consists of 100% propylene oxide and is shanked or drip-applied at rates ranging from 374 to 935 liter/ha. Gilreath et al. (51) found that rates of 748 to 935 liter/ha were required to control nutsedge, but that lower rates were effective in controlling nematodes and fungal plant pathogens. This material is not as effective in cooler climates, but would be an option in Florida. The active ingredient converts to propylene glycol, which is a common food additive.

Many of the materials previously discussed are in the registration process and provide broad-spectrum activity. There also are new chemistries currently being investigated for efficacy. A select group of numbered compounds have been screened using laboratory and greenhouse bioassays for their effects on fungi, weeds, and nematodes. Each compound screened falls under all of the three following categories: (i) reduced risk, (ii) biodegradable, and (iii) non-ozone depleting. One compound, referred to as AJMC-330 (Ajay North America, LLC, Powder Springs, GA), has broad-spectrum activity against multiple fungal plant pathogens (Fig. 23), nutsedge, and root-knot nematodes (5, 93). Initial field trials with this material have been conducted in Florida tomato and cut-flowers and California strawberries. Florida trials identified rates and methods resulting in effective nutsedge control (E. N. Rosskopf, unpublished). In California, AJMC-330 (224 kg/ha) combined with chloropicrin (224 kg/ha) resulted in strawberry yields that are 102% of the methyl bromide control (Fig. 24) (H. Ajwa [University of California]).

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**Fig. 22.** Cut flower yield. Stems represents the total number of flowers (stems) in each meter of row. Marketable stems represents the number of these flowers (stems) that are saleable according to the grower’s standard. Bars with the same letter are not significantly different according to LSD (0.05).
Virtually Impermeable Films and Under-bed Fumigation

To ensure that alternative fumigants are used in an effective, economical, and environmentally sound manner, soil disinfestation programs must be developed to improve the spectrum of pest control while minimizing negative impacts to the environment. Application rates can be reduced without compromising efficacy by extending the exposure time of pest propagules to the fumigant (74). This can be accomplished by maintaining the fumigant in the soil for an extended period of time. Agricultural films made from polyethylene plastic are highly permeable to soil fumigants and have marginal impact on fumigant retention in soil (35,88,106,109). Virtually impermeable films (VIF) contain additional polymers that are impermeable to soil fumigants.

To permit the fumigation of existing raised, plastic-mulched beds in the absence of drip irrigation systems, a novel apparatus referred to as an "under-bed fumigator" (patent pending) was invented to inject fumigants into the soil (10). Fumigation under raised beds that were covered with VIF dramatically improved the retention of 1,3-D and chloropicrin in the soil (Fig. 25). The application potential of a soil disinfestation program that combined the under-bed fumigator with VIF (Fig. 26) was validated in six large-scale trials conducted on commercial tomato and pepper farms (Table 3). Application costs were $806 per hectare higher than the methyl bromide industry standard (Table 4). The cost of methyl bromide would have to increase to $10.11/kg or the price of VIF reduced from $211 per roll to $122 to make the costs equivalent. However, intangible costs such as PPE requirements and liability for workers present in
the field at the time of methyl bromide application are eliminated in the under-
bed fumigation program. The under-bed fumigator mitigates regulatory hurdles
associated with worker exposure and the use of personal protective equipment
by separating the fumigant application from land preparation activities. It also
allows growers to make more efficient use of their production fields by creating
opportunities to disinfest soil in fields that do not have access to fumigant
injection through drip irrigation systems (Fig. 27).

![Fig. 25. Retention of the fumigant 1,3-dichloropropene resulting from the use
of virtually impermeable film (VIF).](image)

![Fig. 26. Application of 1,3-dichloropropene after the beds are prepared using the
Under-bed Fumigator, which limits worker exposure to the fumigant.](image)

![Fig. 27. Detail of the Under-bed Fumigation system. Note "right-angled" shank
under the wheels that delivers the fumigant under the covered raised bed.](image)
Table 3. Commercial field demonstration/validation trials for soil disinfestation program based upon application of Telone 3-35 into established raised, plastic-mulched beds using the 'Under-bed Fumigator’ and virtually impermeable films.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Crop</th>
<th>Size (ha)</th>
<th>Disease</th>
<th>Weeds</th>
<th>Nematodes</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>2003</td>
<td>pepper</td>
<td>0.4</td>
<td>superior*</td>
<td>inferior*</td>
<td>equivalent</td>
<td>+3%</td>
</tr>
<tr>
<td>13</td>
<td>2003</td>
<td>tomato</td>
<td>1.0</td>
<td>superior</td>
<td>equivalent</td>
<td>equivalent</td>
<td>+8%</td>
</tr>
<tr>
<td>13</td>
<td>2004</td>
<td>tomato</td>
<td>2.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>2004</td>
<td>tomato</td>
<td>2.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>2004</td>
<td>tomato</td>
<td>0.2</td>
<td>equivalent</td>
<td>equivalent</td>
<td>equivalent</td>
<td>+7.5%</td>
</tr>
<tr>
<td>16</td>
<td>2005</td>
<td>tomato</td>
<td>2.5</td>
<td>equivalent</td>
<td>equivalent</td>
<td>equivalent</td>
<td>+3.3%</td>
</tr>
</tbody>
</table>

Total area treated 9.0 hectares
Total area treated 22.5 acres

* Levels 5% or more below adjacent methyl bromide fumigated area
x Levels 5% or more above adjacent methyl bromide fumigated area.
Y Levels within 5% of adjacent methyl bromide:chloropicrin fumigated area.
Z Not determined due to damage from 2 hurricanes.
Table 4. Projected application costs\(^x\) for alternative soil disinfestation programs for Florida fresh market tomato and pepper production.

<table>
<thead>
<tr>
<th>Chemical and plastic</th>
<th>Cost per unit</th>
<th>Application rate per ha</th>
<th>Cost per ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Broadcast</td>
<td>Bed application(^y)</td>
</tr>
<tr>
<td>MeBr:Pic (67:33)</td>
<td>$6.62/kg</td>
<td>392 kg</td>
<td>196 kg</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>$190 per roll (1829 meters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$690.00(^2)</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>$1,866.00</td>
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<table>
<thead>
<tr>
<th>Chemical</th>
<th>Cost per unit</th>
<th>Application rate per ha</th>
<th>Cost per ha</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Broadcast</td>
<td>Bed application(^y)</td>
</tr>
<tr>
<td>napropamide</td>
<td>$23.37/kg</td>
<td>2.24 kg</td>
<td>--</td>
</tr>
<tr>
<td>trifluralin</td>
<td>$7.40/liter</td>
<td>1.17 l</td>
<td>--</td>
</tr>
<tr>
<td>Chloropicrin</td>
<td>$4.96/kg</td>
<td>157 kg</td>
<td>78.50 kg</td>
</tr>
<tr>
<td>Telone C-35</td>
<td>$4.62/liter</td>
<td>206 l</td>
<td>--</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>$190 per roll (1829 meters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$690.00</td>
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<tr>
<td><strong>TOTAL</strong></td>
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<td>$2,092.13</td>
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<th>Cost per ha</th>
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<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>napropamide</td>
<td>$23.37/kg</td>
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</tr>
<tr>
<td>trifluralin</td>
<td>$7.40/liter</td>
<td>1.17 l</td>
<td>--</td>
</tr>
<tr>
<td>oxyflorfen</td>
<td>$23.77/liter</td>
<td>2.38 l</td>
<td>1.19 l</td>
</tr>
<tr>
<td>Chloropicrin</td>
<td>$4.96/kg</td>
<td>157 kg</td>
<td>78.50 kg</td>
</tr>
<tr>
<td>Telone C-35</td>
<td>$4.62/liter</td>
<td>206 l</td>
<td>--</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>$190 per roll (1829 meters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$690.00</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>$2,120.47</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Product</th>
<th>Cost per unit</th>
<th>Application rate per acre</th>
<th>Cost per ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtually impermeable film</td>
<td>$211 per roll (731 m)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Telone C-35</td>
<td>$4.62/liter</td>
<td>327 liter</td>
<td>164 liter</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>$2,672.25</td>
</tr>
</tbody>
</table>

\(^x\) September 2005 price estimates.  
\(^y\) bed application = 50% of area treated.  
\(^2\) 1.5 m row centers = 6,638 linear m of row per ha.

**Non-Chemical Alternatives**

Soil solarization for fresh market tomato and pepper in Florida. In Florida, soil solarization was initially conducted by covering entire fields (broadcast solarization) with clear or photo-selective polyethylene plastic (13,69,86). Subsequently solarization was adapted by using clear plastic to solarize raised beds (strip solarization), and then painting the plastic white so it could be used as a horticultural mulch (14). Solarization on raised beds achieved...
higher soil temperatures than broadcast applications, thus improving efficacy and eliminating border effects (14). Strip solarization also was found to be effective and economically feasible when compared to soil fumigation with methyl bromide:chloropicrin (14,15).

From 1995 to 1999, 18 large-scale solarization trials (Fig. 28) were conducted in Florida on commercial tomato and pepper farms. A total of 34.8 ha were treated. Some of the trials included combinations of 1,3-D, chloropicrin and solarization. Compared to adjacent areas fumigated with methyl bromide:chloropicrin, levels of pest control were more erratic. Disease control was superior in two trials and inferior in two. Weed and nematode control were inferior in four and five trials, respectively. Compared to adjacent methyl bromide fumigated areas, the average yield was 5% less under soil solarization. The field trials identified variability in the spectrum of pests controlled that was not evident in small-plot trials and identified the relationship between pest damage and marketable yields. Technical problems not evident in smaller research plots were also identified including the need to bury drip-irrigation tubing in the soil to prevent melting, and problems with painting clear plastic with white latex paint (14,15). Following the large-scale trials, soil solarization was used by a commercial pepper farm to transition from conventional to a biorational farm management system (107).

Biological agents

Plant growth-promoting rhizobacteria (PGPR) are beneficial soil bacteria that colonize plant roots and increase plant growth or protect against disease (54). The introduction of PGPR into peat-based growing mixes for vegetable production is an alternative to seed treatment for small-seeded, transplanted crops (33,76). This approach also enables application of larger quantities of beneficial organisms to the root zone of developing plants before transplanting into the field. In order to integrate the application of PGPR into production systems, root colonization under agricultural field conditions was determined and dose-response data for establishment of populations in the rhizosphere were developed (57). A formulation of *Bacillus subtilis* (strain GB03) and *B. amyloliquefaciens* (strain IN937a) was studied following application to pepper transplants (57). Both isolates established stable populations throughout the root system that persisted through the fall growing season in Florida. Additional post-plant applications of the organisms did not increase their colonization in the rhizosphere compared to treatments receiving bacteria only in the potting medium at seeding. Application of PGPR to transplant plugs at seeding has resulted in increased plant vigor (Fig. 29), reduction in root diseases (Fig. 30), and increased yield in a variety of crops (55,56,59).
The PGPR technology has excellent potential for use in the production of strawberry transplant plugs and in combination with alternative fumigants (56). The ability to improve early yield and reduce transplant shock and water requirements for bare-root transplant establishment may prove advantageous to Florida strawberry producers in the post methyl bromide era. Another beneficial effect of PGPR is the significant increase in transplant growth during greenhouse production, resulting in a shorter production period for standard sized transplants and a reduction in the amount of chemical fertilizers necessary to produce acceptable transplants (58). Because typical disease control levels observed with PGPR treatments are less than those achieved with chemicals, it is most practical to use these organisms as components in integrated management systems that include reduced rates of chemicals, practices to reduce fumigant emissions, and optimum cultural control practices that limit development of pest populations.

**Conclusions**

There are a substantial number of alternative approaches that have not been covered within the scope of this review. For additional information on research conducted on chemical and non-chemical methyl bromide replacements, particularly in California, Ajwa (2), Duniway (21), and Martin (63) provide excellent overviews. While an emphasis is currently being placed on the short-term chemical replacements for methyl bromide due to the urgency driven by the Montreal Protocol, there is a need to be visionary in the development of more sustainable production systems for methyl bromide-dependent crops.
An integrated approach that includes biologically-based pest management tactics, such as PGPRs, soil solarization, and biological control agents combined with crop rotations and cover crops will be a necessity in the future. This approach could become increasingly important as many agricultural chemicals undergo intense scrutiny with regard to human toxicity and environmental impact during the re-registration process (77). It is uncertain if soil fumigants currently available to growers as methyl bromide alternatives will remain available or have additional restrictions associated with their use following re-registration (102). It is acknowledged that non-fumigant approaches to crop production for all crops have not been perfected in terms of realizing the broad-spectrum pest control and high yields that have been achieved with methyl bromide. However, it is critical that research in these areas continues to move forward so that the next phase-out does not result in the end of vegetable or ornamental production in the United States.

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Literature Cited


Author's List of Related Links

CEU final ruling
www.epa.gov/ozone/mbr/CueFRfactsheet.html
Fact Sheet: Final Rule to Create a Critical Use Exemption to the Phase-Out of Methyl Bromide and Exempt Certain Quatities for Critical Uses in 2005 Action from the U.S. Environmental Protection Agency

Specific commodity sectors and copies of all U.S. Nominations
www.epa.gov/ozone/mbr/2007_nomination.html
Fact Sheet: U.S. Nomination for Methyl Bromide Critical Use Exemptions from the 2007 Phaseout of Methyl Bromide
www.epa.gov/Ozone/title66/phaseout/68fr237.pdf
Protection of Stratospheric Ozone: Process for Exempting Quarantine and Preshipment Applications of Methyl Bromide; Final Rule from the Environmental Protection Agency.

Process for exempting quarantine and preshipment applications
www.epa.gov/ozone/mbr/CueFRfactsheet.html
Final Rule to Create a Critical Use Exemption to the Phase-Out of Methyl Bromide and Exempt Certain Quatities for Critical Uses in 2005

Comments from stakeholders regarding the allocation of methyl bromide for critical use in Florida
www.ffva.com/publications/harvester/nov04_mb.htm
Methyl Bromide Critical Use Exemptions -- Today's Concern is Allocation: What About Existing Stocks? from the Florida Fruit & Vegetable Association

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Montreal Protocol
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Methyl Bromide Critical Use Exemptions -- Today's Concern is Allocation: What About Existing Stocks? from the Florida Fruit & Vegetable Association
www.epa.gov/ozone/mbr/2007_nomination.html
U.S. Nomination for Methyl Bromide Critical Use Exemptions from the 2007 Phaseout of Methyl Bromide from the EPA
www.epa.gov/ozone/mbr/index.html
The Phaseout of Methyl Bromide from the EPA