Received: 10 December 2010 Revised: 17 May 2011 Accepted article published: 30 May 2011

(wileyonlinelibrary.com) DOI 10.1002/ps.2249

Effects of surface treatments and application shanks on nematode, pathogen and weed control with 1,3-dichloropropene

Amit J Jhala,[a] Suduan Gao,[b] James S Gerik,[b] Ruijun Qin[b] and Bradley D Hanson[a*]

Abstract

BACKGROUND: Preplant fumigation with methyl bromide (MeBr) has been used for control of soilborne pests in high-value annual, perennial and nursery crops, but is being phased out. In 2007 and 2008, research trials were conducted to evaluate the effects of surface treatments and two application shanks on pest control with 1,3-dicloropropene (1,3-D) in perennial crop nurseries.

RESULTS: All 1,3-D treatments controlled nematodes similarly to MeBr. Application of 1,3-D with virtually impermeable film (VIF) reduced *Fusarium oxysporum* compared with unfumigated plots, but was not as effective as MeBr. Applications of 1,3-D with VIF or 1,3-D followed by metam sodium reduced *Pythium* spp., but 1,3-D followed by intermittent water seals was comparable with the untreated plots. When sealed with high-density polyethylene (HDPE) film or VIF, 1,3-D generally was as effective as MeBr for reducing weed density and total weed biomass, but weed control was reduced by intermittent water seals and in unsealed plots subsequently re-treated with additional 1,3-D or metam sodium.

CONCLUSION: Applications of 1,3-D sealed with HDPE or VIF film or with intermittent water seals can control nematodes similarly to MeBr. However, additional management practices may be needed for effective pathogen and weed control if plastic film is not used.

Keywords: 1,3-dichloropropene; methyl bromide; nursery stock; soil fumigation; surface sealing

1 INTRODUCTION

The fumigant methyl bromide (MeBr; CH_3Br) has been widely used for several decades for preplant control of nematodes, pathogens and weeds in horticultural crops, and also for commodity and post-harvest quarantine treatments. However, MeBr was listed as an ozone-depleting substance and officially phased out as of January 2005 under the US Clean Air Act and the Montreal Protocol.[1] Owing to the commercial importance of this pesticide, there have been a considerable number of studies conducted to find technically feasible, economically viable and environmentally sound alternatives to MeBr for broad-spectrum pest control in high-value annual, perennial and nursery cropping systems.

California produces more than 50% of all fruits, vegetables and nuts and accounts for about 22% of the total agricultural pesticides used in the United States.[2] Open-field nursery production of tree, vine and ornamental plants in California is subjected to strict certification procedures for production of nematode-free nursery stock.[3] MeBr is currently used in tree nurseries under the Critical Use Exemption (CUE) and Quarantine/Preshipment (QPS) criteria allowed under the provisions of the Montreal Protocol.[1] Because these uses are under increasing international scrutiny, effective alternatives are needed in order to avoid severe economic impacts on the California nursery industry.[4,5] Without effective treatments, the impacts of soilborne diseases and nematodes could increase nursery stock losses to unpredictable levels and reduce the productivity of thousands of hectares of fruit orchards and vineyards planted with infested nursery stock.[5,6] Economic losses as a result of MeBr withdrawal could be in excess of $US 1.5 billion annually in the United States if suitable alternatives are not found.[7]

Several fumigants, including 1,3-dichloropropene (1,3-D), chloropicrin, metam sodium and other methyl isothiocyanate (MITC) generators, carbon disulfide, propylene oxide, methyl iodide and propargyl bromide have been tested in various cropping systems.[8–12] However 1,3-D is the only one of these alternatives that is currently widely used as a nematacide in California because of registration or efficacy limitations.[13] In 1990, concerns about the health effects of 1,3-D air emissions resulted in suspension of registration in California; however, with modified equipment and soil condition requirements, use of 1,3-D was re-established

---

* Correspondence to: Bradley D Hanson, Department of Plant Sciences, University of California Davis, Mail Stop 4, One Shields Ave, Davis, CA 95616, USA. E-mail: bhanson@ucdavis.edu

a Department of Plant Sciences, University of California Davis, Davis, CA, USA

b United States Department of Agriculture, Agricultural Research Service, San Joaquin Valley Agricultural Sciences Center, Parlier, CA, USA

in 1995.[14] Currently, 1,3-D is a registered treatment for certified nursery stock production in nurseries with sandy soils, but not in nurseries with fine-textured soil.[3]

Most of the currently available MeBr alternatives, including 1,3-D, are volatile organic compounds (VOCs), and minimizing their emissions is required to reduce air quality concerns.[15] In response to evolving regulations, research has been conducted to evaluate fumigant application and emission reduction strategies.[16,17] Surface sealing with high-density polyethylene (HDPE) film is used after fumigation to reduce the rate of fumigant diffusion from soil to the atmosphere.[18] A recent study comparing soil surface sealing methods to reduce soil fumigant emission loss demonstrated that virtually impermeable film (VIF) was the most promising technique in reducing 1,3-D emission.[19] Applying intermittent water seals after 1,3-D application also has been shown to reduce emissions by 30–50%.[20] Gao *et al.*[21] reported that application of water treatments with or without manure incorporation reduced 1,3-D and chloropicrin peak emission rates by 80% and cumulative emissions by approximately 50%.

In orchards and vineyards where the primary pests are nematodes and pathogens at tree root depth, 1,3-D is usually applied by shank injection into the soil, and the surface soil is compacted with a disk and roller to prevent rapid emission. However, to provide more effective pest control in surface soils with 1,3-D, nursery certification requires sealing with HDPE film or a sequential application of additional 1,3-D or metam sodium several weeks after the initial 1,3-D application. In perennial nurseries, 1,3-D is normally applied with a conventional Telone rig which injects fumigants about 45 cm deep with shanks spaced 51 cm apart. Deep fumigant injection may significantly reduce emissions from treated soil and their potential exposure risks to workers.[20] The Buessing shank[22] is one example of an experimental deep injection shank that splits the fumigant at 40 and 66 cm and may reduce total emissions and benefit nematode control deeper in the soil owing to better fumigant distribution.

Although considerable research has been conducted on reducing 1,3-D emissions, relatively little information is available on the interaction of surface seals and application techniques on pest control efficacy with 1,3-D. The objective of this research was to determine the effects of several emission-reducing surface seal treatments on nematode, pathogen and weed control with 1,3-D applied with either a Buessing shank rig or a conventional Telone rig.

2 MATERIALS AND METHODS

2.1 Field trials

Field trials were conducted in 2007 and 2008 to determine the effects of surface seals and shank treatments on pest control with 1,3-D (Telone®II; 97.5% 1,3-D and 2.5% inert ingredient; Dow AgroSciences, Indianapolis, IN). In 2007, the experiment was conducted at the University of California, Kearney Agricultural Center (KAC), located near Parlier, CA. At this site, soil texture was a Hanford fine sandy loam (coarse loamy, mixed, superactive, non-acid, thermic Typic Zerorthents) with pH 7.2 and 0.65% organic matter with 70% sand, 24% silt and 6% clay. In 2008, the experiment was repeated at the United States Department of Agriculture – Agriculture Research Service (USDA-ARS), San Joaquin Valley Agricultural Sciences Center (SJVASC), near Parlier, CA. Soil texture at this site was also a Hanford fine sandy loam with pH 7.6 and 0.32% organic matter with 73% sand, 21% silt and 6% clay.

The experimental sites were prepared following removal of established plum (*Prunus domestica* L.) and peach (*Prunus persica* L.) orchards, respectively in 2007 and 2008. To ensure adequate soil moisture to meet label[23] requirements, the sites were irrigated approximately 2 weeks prior to fumigation. The KAC site was prepared by deep tillage to a depth of 1.5 m in one direction, with shanks spaced 60 cm apart. The SJVASC site was tilled to a depth of 1 m, with shanks spaced 60 cm apart in two operations perpendicular to one another. Both sites were repeatedly disked and rolled to pulverize soil clods and prepare the soil to seedbed conditions prior to fumigation. The average soil water content in the top 100 cm of soil prior to fumigation was 9.1 ± 0.9% (v/v) or about 35% of field capacity at KAC in 2007, and 9.5 ± 0.8% (v/v) or about 36.5% of field capacity at SJVASC in 2008.

The experiments were arranged in a split-plot design with five (2007) or four (2008) surface treatments as main plots and two shank systems as subplots. Each treatment combination was replicated 3 times. An untreated control (bare soil without fumigation) and a standard MeBr treatment (MeBr/chloropicrin 98 : 2 at 392 kg ha^{-1} sealed with HDPE) were included for comparison (Table 1). MeBr was applied with a Noble plow rig set up to inject fumigants at a 25 cm depth through nozzles spaced 30 cm apart while simultaneously installing 0.025 mm thick HDPE film. The 1,3-D treatments (373 kg ha^{-1}) were applied by a commercial applicator (TriCal Inc., Hollister, CA) and consisted of a split-plot arrangement of application shanks and surface treatments. The standard Telone rig had shanks spaced 51 cm apart and an injection depth of 45 cm, and the Buessing shank rig had shanks spaced 60 cm apart and split the fumigant injection at 40 and 66 cm depths. The Buessing shank also had wings above each injection nozzle to scrape soil into the shank trace and minimize rapid upward movement of the fumigant. Surface treatments included three soil seals [HDPE and VIF (Bromostop®; Industria Plastica Monregalese, Mondovi, Italy) plastic film and intermittent water seals] and two supplemental fumigation treatments designed to disinfest the surface soils. For the surface soil treatments, 168 kg ha^{-1} of 1,3-D was applied 21 days after the initial treatment using a standard Telone rig; however, this treatment was only included in the 2007 experiment. Metam sodium (Vapam HL®; Amvac Chemical Corporation, Los Angeles, CA) was applied at 179 kg ha^{-1} in 7 cm irrigation water through sprinklers 14 to 30 days after the initial 1,3-D treatment in both experiments.

Fumigants and surface seal treatments were applied on 2 October 2007 at KAC and on 24 September 2008 at SJVASC. Average soil temperature in the upper 50 cm during fumigation was 21 °C at KAC in 2007 and 26 °C at SJVASC in 2008. Following 1,3-D application, a disk and ring roller was used to level and compact the surface soils before surface seals were applied over the 1,3-D-fumigated plots. HDPE and VIF film was installed after the tillage operation using a Noble plow rig. Intermittent water seals were applied 3 h (12 mm), 12 h (5 mm), 24 h (4 mm) and 48 h (4 mm) after fumigation using sprinkler systems installed after the post-fumigation tillage operation. All plastic films were removed 2–3 weeks after fumigation at both sites.

2.2 Data collection

The effects of the application techniques and surface treatments on pest control with 1,3-D were determined by evaluating nematode and soilborne pathogen survival and by monitoring weed emergence and productivity in each plot. To evaluate nematode survival, two sets of muslin bags containing 100 g of

Table 1. List of treatments used in the field trials conducted at KAC in 2007 and at SJVASC in 2008 to evaluate effects of surface seals and application rigs on nematode, pathogen and weed control with 1,3-D[a,b]

Treatment number	Fumigation[b]	Rate (kg AI ha^{-1})	Surface seal/soil treatments[c]	Shank system
1	Untreated	–	–	–
2	MeBr	392	HDPE film	Noble plow
3	1,3-D	373	HDPE film	Standard
4	1,3-D	373	HDPE film	Buessing
5	1,3-D *fb* metam sodium	373 *fb* 179	Bare soil	Standard
6	1,3-D *fb* metam sodium	373 *fb* 179	Bare soil	Buessing
7	1,3-D	373	Intermittent water seals	Standard
8	1,3-D	373	Intermittent water seals	Buessing
9	1,3-D	373	VIF	Standard
10	1,3-D	373	VIF	Buessing
11	1,3-D *fb* 1,3-D	373 *fb* 168	Bare soil	Standard
12	1,3-D *fb* 1,3-D	373 *fb* 168	Bare soil	Buessing

[a] Treatments 11 and 12 were included in the 2007 experiment only.
[b] 1,3-D, 1,3-dichloropropene; *fb*, followed by; HDPE, high-density polyethylene; KAC, Kearney Agricultural Center; MeBr, methyl bromide; SJVASC, San Joaquin Valley Agricultural Sciences Center; VIF, virtually impermeable film.
[c] HDPE, VIF and intermittent water seals were surface seal treatments, while sequential applications of metam sodium or 1,3-D were surface soil treatments.

soil infested with citrus (*Tylenchulus semipenetrans* Cobb) and free living non-parasitic nematodes were buried at 15, 30, 60 and 90 cm below the soil surface in each plot prior to fumigation. Soil used in the bioassay was collected from a commercial citrus orchard and contained 3848 and 4086 nematodes per 100 g of soil in 2007 and 2008 respectively. Nematode bags were recovered 1 month after fumigation and processed using the sieving/Baermann funnel protocol, and surviving nematodes were counted.[24]

The treatment effects on representative soil fungal pathogens were evaluated in the 2007 experiment. At least ten soil cores were collected 2 weeks after fumigation from the upper 25 cm of soil near the middle of each subplot and homogenized, and a subsample was assayed for two common fungal pathogens (*Fusarium oxysporum* and *Pythium* spp.) using dilution plating techniques on selective media. *Pythium* spp. samples were plated on P_5ARP medium for 48 h,[25] and *Fusarium oxysporum* Schlecht. samples were plated on Komada medium for 6 days.[26]

Weed density and species composition were determined on 17 January 2008 at KAC and on 9 December 2008 at SJVASC. Weeds were counted in one subsample per plot in the KAC experiment and in two subsamples per plot in the SJVASC experiment, and data were standardized to a 1 m^2 area. In March 2008 at KAC and in January 2009 at SJVASC, all weed species from a random 1 m^2 area in each plot were cut at the soil surface and dried for 72 h at 60 °C, and total weed biomass was recorded.

2.3 Statistical analysis

Although the 1,3-D treatments were arranged in a 2×5 or 2×4 combination of application shanks and surface treatments, initial analysis of variance indicated no effect of shank system or interactions among shank and surface treatments. Therefore, data from the application rig subplots were pooled over surface treatments and reanalyzed with seven treatments in 2007 and six treatments in 2008 (SAS v.9.1; SAS Institute, Cary, NC). Except for weed biomass, all data were transformed [ln $(x + 1)$] prior to analysis; however, the actual values are presented for comparison. Fisher's protected least significant difference (LSD) procedure was performed to compare the treatment means at $\alpha = 0.05$.

3 RESULTS AND DISCUSSION

Citrus and non-parasitic nematode control at all depths (15, 30, 60 and 90 cm) was effective with all fumigation treatments compared with untreated plots at KAC in 2007 and at SJVASC in 2008 (data not shown). In fact, none of the 1,3-D- or MeBr-treated plots had any surviving citrus nematodes, and only minor, non-significant differences in non-parasitic nematode survival.

Soilborne pathogen evaluations conducted at KAC in 2007 indicated that MeBr completely controlled *Fusarium* and *Pythium* spp. propagules in the soil compared with untreated plots (116 and 184 propagules g^{-1} soil respectively) (Table 2). Only 1,3-D sealed with VIF reduced *Fusarium* spp. compared with the untreated control. *Pythium* spp. was controlled by 1,3-D sealed with VIF and 1,3-D followed by metam sodium (<2 propagules g^{-1} soil) ($P < 0.0001$). Intermittent water seals reduced control of *Pythium* spp. (45 propagules g^{-1} soil) compared with all other treatments.

Weed species at KAC (2007) and SJVASC (2008) were different, so weed density and biomass data were analyzed separately for each location. Because of relatively low populations of individual species, weed data were combined and analyzed as total broadleaf and total grass weed density. Primary broadleaf weeds present at KAC in 2007 were common chickweed (*Stellaria media* L.), henbit (*Lamium amplexicaule* L.), redstem filaree (*Erodium cicutarium* L.), panicle willowherb (*Epilobium brachycarpum* C. Presl), shepherd's purse [*Capsella bursa-pastoris* (L.) Medic.], cudweed (*Gamochaeta luteo-album* L.), horseweed (*Conyza canadensis* L.) and coast fiddleneck (*Amsinckia intermedia* Fisch. & Mey). When 1,3-D was sealed with VIF, broadleaf weed density was reduced to 16 weeds m^{-2}, which was comparable with MeBr (Table 3). These results are similar to a previous report which indicated that 1,3-D or 1,3-D plus chloropicrin sealed with HDPE or VIF resulted in weed seed viability and hand weeding time comparable with MeBr under nursery conditions.[27] Intermittent water seals after 1,3-D application resulted in a broadleaf weed density similar to the untreated control at KAC in 2007 (Table 3). Because most weeds germinate near the soil surface, techniques such as intermittent water seals

Table 2. Effects of 1,3-D with surface seal/soil treatments on *Fusarium* and *Pythium* spp. propagules at KAC in 2007[a]

Treatment[a]	*Fusarium* propagules[b,c] (number g^{-1} soil)	*Pythium* propagules[b,c] (number g^{-1} soil)
Untreated	115.7a	183.9a
MeBr	0.0c	0.0c
1,3-D (HDPE)	65.0a	5.4b
1,3-D *fb* metam sodium	22.5ab	0.3c
1,3-D (water seals)	37.5ab	44.6a
1,3-D (VIF)	9.7b	1.2bc
1,3-D *fb* 1,3-D	24.8ab	5.9b

[a] 1,3-D, 1,3-dichloropropene; *fb,* followed by; HDPE, high-density polyethylene film; KAC, Kearney Agricultural Center; MeBr, methyl bromide; VIF, virtually impermeable film.
[b] The data were log transformed [ln $(x + 1)$] for homogeneous variance prior to analysis; however, data presented here are the means of actual values for comparison.
[c] Least-squares means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P < 0.05$.

Table 3. Effects of 1,3-D with surface treatments on broadleaf and grass weed density and biomass at KAC in 2007[a]

Treatment[a]	Broadleaf[b,c] (weeds m^{-2})	Grass[b,c] (weeds m^{-2})	Total weed biomass[c] (g m^{-2})
Untreated	241.3a	28.7a	152.5a
MeBr	7.2c	0.0c	11.8b
1,3-D (HDPE)	21.4b	0.1c	62.5b
1,3-D *fb* metam sodium	24.5b	0.1c	62.4b
1,3-D (water seals)	121.7a	5.1b	164.6a
1,3-D (VIF)	16.1bc	0.1c	44.2b
1,3-D *fb* 1,3-D	54.1b	3.4b	117.1b

[a] 1,3-D, 1,3-dichloropropene; *fb,* followed by; HDPE, high-density polyethylene; KAC, Kearney Agricultural Center; MeBr, methyl bromide; VIF, virtually impermeable film.
[b] The data were log transformed [ln $(x + 1)$] for homogeneous variance prior to analysis; however, data presented here are the means of actual values for comparison.
[c] Least-squares means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P < 0.05$.

that limit fumigant movement into surface soils can adversely affect weed control. The other surface treatments (HDPE, 1,3-D followed by 1,3-D or metam sodium) had intermediate densities of broadleaf weeds (21–54 weeds m^{-2}) compared with untreated plots (241 weeds m^{-2}) (Table 3). Primary grass weeds present at KAC in 2007 were annual bluegrass (*Poa annua* L.) and volunteer wheat (*Triticum aestivum* L.). Compared with untreated plots, all treatments reduced grass weed density (Table 3); however, greatest reductions were observed in plots treated with MeBr, 1,3-D sealed with HDPE or VIF and 1,3-D followed by metam sodium (<0.2 weeds m^{-2}). In the absence of fumigation and surface seal treatments, weed biomass was as high as 153 g m^{-2}, which was comparable with 1,3-D followed by intermittent water seals (165 g m^{-2}) (Table 3). All other treatments reduced total weed biomass by 23–98% compared with the unfumigated control (Table 3).

Table 4. Effects of 1,3-D with surface treatments on broadleaf and grass weed density and total weed biomass at SJVASC in 2008[a]

Treatment[a]	Broadleaf[b,c] (weeds m^{-2})	Grass[b,c] (weeds m^{-2})	Total weed biomass[b] (g m^{-2})
Untreated	313.2 a	50.9 a	244.7 a
MeBr	16.9 c	0.6 c	22.5 b
1,3-D (HDPE)	15.3 c	0.1 c	24.8 b
1,3-D *fb* metam sodium	129.3 b	13.0 b	146.5 a
1,3-D (water seals)	222.6 ab	22.6 ab	160.0 a
1,3-D (VIF)	19.3 c	0.0 c	15.6 b

[a] 1,3-D, 1,3-dichloropropene; *fb,* followed by; HDPE, high-density polyethylene; MeBr, methyl bromide; SJVASC, San Joaquin Valley Agricultural Sciences Center; VIF, virtually impermeable film.
[b] The data were log transformed [ln $(x + 1)$] for homogeneous variance prior to analysis; however, data presented here are the means of actual values for comparison.
[c] Least-squares means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P < 0.05$.

Major broadleaf weed species at SJVASC in 2008 were redstem filaree, little mallow (*Malva parviflora* L.), common lambsquarters (*Chenopodium album* L.), common chickweed, swinecress [*Coronopus squamatus* (Forsskaol) Asch.], horseweed, white clover (*Trifolium repens* L.) and shepherd's purse. In addition, yellow nutsedge (*Cyperus esculentus* L.) populations were also noticed at this site. The applications of 1,3-D sealed with HDPE or VIF were as effective as MeBr for reducing broadleaf weed density at this location (Table 4). Yellow nutsedge was controlled only by MeBr and 1,3-D sealed with VIF (data not shown). MeBr and 1,3-D sealed with HDPE or VIF were effective for controlling grass weeds (<1 weed m^{-2}), primarily annual bluegrass at SJVASC in 2008 (Table 4). Compared with the untreated plots, 1,3-D followed by intermittent water seals did not reduce grass weed density. Lowest weed biomass in the 2008 experiment was recorded in plots treated with MeBr or with 1,3-D sealed with VIF or HDPE (Table 4). Weed biomass in plots treated with 1,3-D with intermittent water seals and 1,3-D followed by metam sodium was similar to the untreated control plots.

It was clear in this study that surface seal treatments including HDPE and VIF can be an effective strategy to use with 1,3-D to reduce weed density and biomass. However, this treatment combination will likely not control all weeds in every situation. For example, nursery field experiments with 1,3-D and other fumigants suggested that weed species with hard seed coats, such as field bindweed (*Convolvulus arvensis* L.), California burclover (*Medicago polymorpha* L.) and little mallow, may not be adequately controlled by any of the fumigants and will likely require additional weed control measures.[28] A previous study also reported that 1,3-D alone was not effective for controlling *Cyperus* spp.[29] In a study to evaluate weed control in tree nurseries in California, pre-emergence application of oryzalin, isoxaben and dithiopyr provided improved weed control compared with fumigation and tillage alone.[30] However, relatively few pre- and post-emergence herbicides are registered in tree nurseries, and additional research and demonstration trials are needed to facilitate the approval and adoption of new herbicide tools for tree nursery growers. Thus, in the absence of MeBr, integrated weed control in high-value nursery crops will likely require greater reliance on a combination of crop rotation, hand weeding, sanitation, mulching, soil solarization, preplant fumigation and herbicides.

4 SUMMARY AND CONCLUSIONS

In this study, deep-split application using the Buessing shank did not improve pest control with 1,3-D compared with the conventional injection shank. However, in less than ideal conditions, such as fine textured soils or in fields with soil moisture gradients or compacted layers, split injection may prove beneficial. Surface treatments had a significant impact on pest control, although this varied among pests. For example, surface treatments had little impact on nematode and *Fusarium* spp. control, but strongly affected weed and *Pythium* spp. control. Intermittent water seals and a sequential application of 1,3-D with no seal resulted in poor weed and *Pythium* spp. control, whereas plastic films, especially VIF, greatly increased pest control near the soil surface. However, additional work is required to confirm these results on other soilborne pathogens and under more conventional cropping practices. Similarly, although 1,3-D provided nematode control comparable with MeBr in these experiments, these data were not from a resident nematode population, and no host crop was grown after the treatments, which limits the interpretation of the nematode results.

Use of high-barrier films such as VIF or emerging multilayer films such as totally impermeable film (TIF) may overcome some of the regulatory and efficacy issues limiting adoption of MeBr alternative fumigants in California cropping systems.[19] However, because costs vary considerably among surface treatments, additional research is needed to evaluate the economic impacts of available surface treatment alternatives for various cropping systems. Finally, high fumigant retention under the improved plastic films has raised questions about the dangers of emission surges following tarp removal and the possibility of maintaining pest control efficacy at reduced 1,3-D rates; further research is under way to address these concerns.

ACKNOWLEDGEMENTS

Funding for this project was provided by the USDA-ARS Pacific area-wide pest management program for integrated methyl bromide alternatives. The authors thank TriCal Inc. and Dow AgroSciences for providing in-kind support. The technical support of Stella Zambrzuski, Nancy Goodell, Jim Gartung, Patty Munger, Curtis Koga, Ashley Torres and other USDA-ARS Water Management Research Unit staff is appreciated.

REFERENCES

1 *Critical Use Exemption Information*. [Online]. United States Environmental Protection Agency (2010). Available: http://www.epa.gov/ozone/mbr/cueinfo.html [1 December 2010].

2 Pease WS, Liebman J, Lundy D and Albright D, Pesticide use in California: strategies for reducing environmental health impacts. California Policy Seminar Brief Vol. 8, University of California, Berkeley, CA (1996).

3 *Approved Treatment and Handling Procedures to Ensure against Nematode Pest Infestation of Nursery Stock*. [Online]. Nursery Inspection Procedures Manual, Item 7, California Department of Food and Agriculture (2010). Available: http://www.cdfa.ca.gov/phpps/PE/Nursery/pdfs/NIPM_7.pdf [15 November 2010].

4 Schneider SM, Rosskopf EN, Leesch JG, Chellemi DO, Bull CT and Mazzola M, United States Department of Agriculture – Agricultural Research Service research on alternatives to methyl bromide: preplant and post-harvest. *Pest Manag Sci* **59**:814–826 (2003).

5 Zasada IA, Walters TW and Hanson BD, Challenges in producing nematode and pathogen free fruit and nut nursery crops in the United States. *Outlooks Pest Manag* **21**:246–250 (2010).

6 Zasada IA, Halbrendt JM, Kokalis-Burelle N, LaMondia J, McKerney MV and Noling JW, Managing nematodes without methyl bromide. *Annu Rev Phytopathol* **48**:15.1–15.18 (2010).

7 The biologic and economic assessment of methyl bromide. National Agriculture Pest Impact Assessment Program, United States Department of Agriculture, Washington, DC (1993).

8 Fennimore SA, Haar MJ and Ajwa HA, Weed control in strawberry provided by shank- and drip-applied methyl bromide alternative fumigants. *HortSci* **38**:55–61 (2003).

9 Gilreath JP, Motis TN and Santos BM, *Cyperus* spp. control with reduced methyl bromide plus chloropicrin rates under virtually impermeable films in pepper. *Crop Prot* **24**:285–287 (2005).

10 Santos BM, Gilreath JP, Motis TN, Noling JW, Jones JP and Norton JA, Comparing methyl bromide alternatives for soilborne disease, nematode and weed management in fresh market tomato. *Crop Prot* **25**:690–695 (2005).

11 Schneider SM, Ajwa HA, Trout TJ and Gao S, Nematode control from shank- and drip-applied fumigant alternatives to methyl bromide. *Hort Sci* **43**:1826–1832 (2008).

12 Schneider SM and Hanson BD, Effects of fumigant alternatives to methyl bromide on pest control in open field nursery production of perennial fruit and nut plants. *Hort Technol* **19**:331–339 (2009).

13 Basile M, Senesi N and Lamberti F, A study of some factors affecting volatilization losses of 1,3-dichloropropene (1,3-D) from soil. *Agric Ecosyst Environ* **17**:269–179 (1986).

14 *California Management Plan: 1,3-Dichloropropene*. [Online]. California Department of Pesticide Regulation (2002). Available: http://www.cdpr.ca.gov/docs/emon/methbrom/telone/mgmtplan.pdf [23 March 2011].

15 *Reducing VOC Emissions from Field Fumigants*. [Online]. California Department of Pesticide Regulation (2010). Available: http://www.cdpr.ca.gov/docs/emon/vocs/vocproj/reg_fumigant.htm [15 October 2010].

16 Yates SR, Gan J, Papiernik SK, Dungan R and Wang D, Reducing fumigant emission after soil application. *Phytopathology* **92**:1344–1348 (2002).

17 Gao S and Trout TJ, Surface seals reduce 1,3-dichloropropene and chloropicrin emissions in field tests. *J Environ Qual* **36**:110–119 (2007).

18 Wang D, Yates SR, Ernst FF, Gan J and Jury WA, Reducing methyl bromide emission with a high barrier plastic film and reduced dosage. *Environ Sci Technol* **31**:3686–3691 (1997).

19 Gao S, Hanson BD, Qin R, Wang D and Yates S, Comparisons of surface sealing methods to reduce soil fumigant emission loss (2011). *J Environ Qual* **40**:(in press).[online]. DOI:10.2134/jeq2009.0422 (2010). [12 November 2010].

20 Yates SR, Knuteson J, Ernst FF, Zheng W and Wang Q. The effect of sequential surface irrigations on field-scale emissions of 1,3-dichloropropene. *Environ Sci Technol* **42**:8753–8758 (2008).

21 Gao S, Qin R, Hanson BD, Tharayil N, Trout TJ, Wang D, *et al*, Effects of manure and water applications on 1,3-dichloropropene and chloropicrin emission in a field trial. *J Agric Food Chem* **57**:5428–5434 (2009).

22 McKenry MV, Buessing D and Williams K, New chisel shanks enable improved fumigation of finer-textured soils. *Proc Annu Int Res Conf on Methyl Bromide Alternatives and Emissions Reduction, 31 October–3 November 2003, San Diego, CA*, pp. 36-1–36-3 (2003).

23 *Specimen Label. Telone II, Soil Fumigant*. [Online]. Dow AgroSciences, Indianapolis, IN (2010). Available: http://www.cdms.net/ldat/ld6GB001.pdf [15 October 2010].

24 Barker KR, Nematode extraction and bioassays, in *An Advanced Treatise on Meloidogyne. Vol. II. Methodology*, ed. by Barker KN, Carter CC and Sasser JN. North Carolina State University Graphics, Raleigh, NC, pp. 19–35 (1985).

25 Martin FN, The genus *Pythium*, in *Methods for Research on Soil Borne Phytopathogenic Fungi*, ed. by Singleton LL, Mihail JD and Rush CM. American Phytopathological Society, St Paul, MN, pp. 39–49 (1992).

26 Komada H, Development of a selective medium for quantitative isolation of *Fusarium oxysporum* from natural soil. *Rev Plant Prot Res* **8**:114–125 (1975).
27 Shrestha A, Browne GT, Lampinen BD, Schneider SM, Simon L and Trout TJ, Perennial crop nurseries treated with methyl bromide and alternative fumigants: effects on weed seed viability, weed densities, and time required for hand weeding. *Weed Technol* **22**:267–274 (2008).
28 Hanson BD, Gerik JS and Schneider SM, Effects of reduced-rate methyl bromide applications under conventional and virtually impermeable plastic film in perennial crop field nurseries. *Pest Manag Sci* **66**:892–899 (2010).
29 Gilreath JP, Santos BM, Gilreath PR, Jones JP and Noling JW, Efficacy of 1,3-dichloropropene plus choloropicrin application methods in combination with pebulate and napropamide in tomato. *Crop Prot* **23**:1187–1191 (2004).
30 Hanson BD and Schneider SA, Evaluation of weed control and crop safety with herbicides in open field tree nurseries. *Weed Technol* **22**:493–498 (2008).