Proc. Fla. State Hort. Soc. 116:151-158. 2003.

EVALUATION OF VARIOUS CHEMICAL TREATMENTS FOR POTENTIAL AS METHYL BROMIDE REPLACEMENTS FOR DISINFESTATION OF SOILBORNE PESTS IN POLYETHYLENE-MULCHED TOMATO

JAMES P. GILREATH[1], JOHN P. JONES,
TIMOTHY N. MOTIS, AND BIELINSKI M. SANTOS
University of Florida, IFAS
Gulf Coast Research and Education Center
5007 60th Street East
Bradenton, FL 34203

JOSEPH W. NOLING
University of Florida, IFAS
Citrus Research and Education Center
700 Experiment Station Road
Lake Alfred, FL 33850

ERIN N. ROSSKOPF
U.S. Horticultural Research Lab., USDA-ARS
2001 South Rock Road
Fort Pierce, FL 34945

Additional index words. Cyperus esculentus, Cyperus rotundus, Fusarium oxysporum, Lycopersicon esculentum, nematodes, soil fumigant

Abstract. **Florida tomato growers rely on methyl bromide (MBr) to eliminate soilborne pests including weeds, fungi, and nematodes. An experiment was conducted in fall 2001 in Bradenton and Immokalee as part of the USDA-IR4 Methyl Bromide Alternatives Program to evaluate the potential of various chemicals for replacement of MBr in polyethylene-mulched tomato (*Lycopersicon esculentum* Mill.). Treatment establishment began on 17 Aug. and 13 Dec. 2001 in Bradenton and Immokalee, respectively. In Bradenton, the nutsedge population (six plants per ft^{-2}) with non-treated soil on 6 Nov. 2001 was reduced similarly by 84% to 91% with MBr-chloropicrin (Pic), metam-Na (drip-applied), and pebulate + fosthiazate + Pic. Treatments that failed to control nutsedge were 1.) iodomethane/Pic, 2.) metam-Na (rototilled) with either Pic, 1,3-dichloropropene (1,3-D), or PlantPro 45, and 3.) pebulate + Pic + Na-tetrathiocarbonate (Enzone™). Root-knot (*Meloidogyne* sp.) nematode populations were not influenced by treatments; however, relative to those with no soil fumigation, populations of sting (*Belonolaimus* spp.) and stunt (*Tylenchorhynchus* sp.) nematodes were reduced by 84% to 100% with MBr-Pic, iodomethane alone or with Pic, 1,3-D-35% Pic + trifluralin + napropamide + Pic, metam-Na (drip-applied), metam-Na (rototilled) + 1,3-D, and pebulate + fosthiazate (preplant-incorporat-**

This research was supported by the Florida Agricultural Experiment Station, the USDA/IR-4 Program, and the Florida Tomato Committee, and approved for publication as Journal Series No. N-02400. Mention of a specific proprietary product does not constitute an endorsement by either the University of Florida or the authors.

[1]Corresponding author.

ed) + Pic. Tomato yield in Bradenton increased from 51 lb per 10 plants with non-treated soil to at least 84 lb per 10 plants with all treatments and was inversely correlated with Fusarium wilt (race 3, incited by *Fusarium oxysporum* f. sp. *lycopersici*) incidence. In Immokalee, weed and nematode populations were minimal; however, Fusarium crown rot (*Fusarium oxysporum* f. sp. *radicis-lycopersici*) infected 15% of the tomato plants in non-treated soil compared to incidences of 5% or less with metam-Na + PlantPro 20EC, pebulate + fosthiazate (drip-applied) + Pic, Na-azide at 100 lb/acre, and furfural allyl at 600 lb/acre. Tomato yield in Immokalee was not influenced by treatments, possibly due to low pest pressure. No treatment controlled all pests; however, for each pest, one or more treatments performed as well as Mbr.

Florida vegetable growers have relied on methyl bromide-chloropicrin (MBr-Pic) formulations since the 1970s for disinfestation of soilborne pests, including plant-parasitic nematodes, fungal and bacterial pathogens, and weeds (Overman and Martin, 1978). The ongoing phase-out of MBr as a soil fumigant has resulted in considerable research into chemical alternatives (Gilreath et al., 1994; Jones et al., 1995; Locascio et al., 1997; Nelson et al., 2002), most of which has focused on maximizing efficacy with commercially available (registered) pesticides including Pic, 1,3-dichloropropene (1,3-D), and compounds that generate methyl isothiocyanate (metam-Na and dazomet). These chemicals, used alone or in combination with other compounds, have shown promise. The combination of 1,3-D with Pic and pebulate (herbicide) has resulted in tomato yields comparable to that with MBr-Pic (Gilreath et al., 1994; Gilreath et al., 1997; Locascio et al., 1997; Nelson et al., 2002).

Use of some of the above-mentioned chemicals is limited by regulations because of environmental or toxicological issues, so MBr-alternatives proposed to date should not be considered long-term solutions to replace MBr. Compared to that with older chemicals, little evaluation has been done of newer chemicals for use in replacing MBr. Examples of recently- or non-registered compounds include fosthiazate, furfural, iodomethane, Messenger™ (EDEN Bioscience Corp., Little Rock, Ark.), Na-azide, Na-tetrathiocarbonate (Enzone™; Entek Corp., Elkridge, Md.), and PlantPro™ (Ajay North America, LLC, Powder Springs, Ga.). Of these, fosthiazate, iodomethane, Na-azide, Na-tetrathiocarbonate, and PlantPro™ are manufactured chemicals while furfural and Messenger™ are naturally-occurring compounds.

Fosthiazate is an experimental nematicide that, in field studies, has shown activity against root-knot (*Meloidogyne incognita* race 3) (Pullen and Fortnum, 1999) and root-lesion (*Pratylenchus penetrans*) (Sturz and Kimpinski, 1999) nematodes. Iodomethane, recently registered (Allan 2002), has been used in mixtures with high amounts of Pic to reduce the cost of this product. It has been theorized that nutsedge (*Cyperus* spp.) activity with iodomethane may be reduced when applied with high amounts of Pic because Pic does not typically control nutsedge (Locascio et al., 1997; Motis and Gilreath, 2002). Sodium- and K-azide are salts of hydrazoic acid (HN_3) formulated as granules or liquids, which, when added to soils with pH < 7.0, release the active ingredient (HN_3) that then reacts with water to form NH_4+ (Parochetti & Warren, 1970). Activity against nematodes and weeds with 15 liquid formulations of K-azide varied as much as 50% to 60% (Rodriguez-Kabana, 2000), indicating the importance of testing formulations and application methods of these materials. Enzone™ is formulated as a liquid solution suitable for chemigation. When applied to soil, Enzone™ breaks down to carbon disulfide gas, the active ingredient. PlantPro™ is an iodine-based chemical that reduced damage to tomato roots by root-knot nematodes in field-grown tomato in Florida (Kokalis-Burelle and Fuentes, 2000). Enzone™ and PlantPro™ are compounds with very low crop phytotoxicity.

Furfural alone or with allyl isothiocyanate is derived from 2-furfuraldehyde present in sugarcane and similar plants. These products were formulated to control nematodes, but herbicidal activity was observed in a greenhouse study with furfural + allyl isothiocyanate applied at a.i. rates of 500-600 lb/acre (Rodriguez-Kabana, 2000). Furfural + allyl isothiocyanate has not provided adequate control of sting nematode and weeds in sandy soils of Florida (Gilreath et al., unpublished data), indicating that efficacy of this material may be influenced by environmental conditions. Messenger™ contains 3% Harpin_{Ea} (EDEN Bioscience), a plant protein causing the expression of many genes including those associated with defence mechanisms against diseases (Wei and Beer, 1996; Wei et al., 1992). As a wettable dry granule, Messenger™ may be applied as a foliar spray.

This research was undertaken to evaluate chemical combinations with compounds that have not been tested extensively under Florida field conditions. Trials were conducted at two sites so that efficacy of the various treatments could be evaluated under varying conditions and with a wide diversity of soilborne pests. Success with the newer chemicals could result in long-term benefits to the Florida vegetable industry because they have little environmental impact and thus would likely be registered for use by the Environmental Protection Agency.

Materials and Methods

Two experiments were conducted in fall 2001 with one at the Gulf Coast Research and Education Center (GCREC) in Bradenton, Fla. on an EauGallie fine sand soil and the other on a sand (top soil comprised of 95% sand, 4% clay, and 1% silt) at McClure Farms near Immokalee, Fla. Treatments (Table 1) were arranged in a randomized complete block design with four (Bradenton) or five (Immokalee) replications. The first 16 treatments (Table 1) were evaluated in both locations with the exception of trifluralin + 1,3-dichloropropene (1,3-D) with 35% chloropicrin (Pic) + Messenger™, which was tested only in Bradenton. The remaining nine treatments were tested in Immokalee alone. Treatments were assigned to plots that were 50 (Bradenton) or 100 (Immokalee) ft long. Beds spaced 5 ft apart on centers that were 28 inches wide and 8 inches high.

Treatment establishment began 17 Aug. and 13 Dec. 2001 in Bradenton and Immokalee, respectively. Methods used and timing of applications are summarized in Table 1. Metam-Na rates reported refer to the amount of product; multiply by 0.42 to obtain the amount of active ingredient. With all treatments, a prebed was formed, pressed, and covered with polyethylene film. In-bed materials were shank-injected into a finished bed with a standard pressurized fumigation rig, utilizing nitrogen gas as the propellant, on a bedder equipped with three chisels per bed spaced 12 inches apart and a flow meter calibrated to deliver the specified quantity of fumigant about 2 inches below the bottom of the finished bed. Drip tape (T-Tape®, T-Systems International,

Table 1. List of treatments and application methods used in Bradenton and/or Immokalee.

Fumigant	Rate (amt. per acre)	Method	Timing	Bradenton	Immokalee
1. Nontreated	N/A	N/A	N/A	22 Aug.	13 Dec.
2. Methyl bromide/Pic 67/33	350 lb	In bed, 3 chisels	At bedding	17 Aug.	21 Dec.
3. Iodomethane/Pic	150 lb/110 lb	In bed, 3 chisels	At bedding	17 Aug.	21 Dec.
4. Iodomethane	150 lb	In bed, 3 chisels	At bedding	17 Aug.	21 Dec.
5. 1,3-D-35% Pic	26 gal	Broadcast, yetter	Prebed	21 Aug.	13 Dec.
Trifluralin	0.5 lb	Broadcast, disk in	Prebed	21 Aug.	21 Dec.
Napropamide	2 lb	Broadcast, disk in	Prebed	21 Aug.	21 Dec.
Pic	125 lb	In bed, 3 chisels	At bedding	21 Aug.	21 Dec.
6. Metam-Na[z]	75 gal	Drip, 3 tubes	Post bed	22 Aug.	14 Dec.
7. Metam Na	75 gal	Spray and rototill	Prebed	17 Aug.	14 Dec.
Pic	150 lb	Broadcast	Prebed	17 Aug.	14 Dec.
8. Metam Na	75 gal	Spray and rototill	Prebed	17 Aug.	14 Dec.
1,3-D	18 gal	Broadcast	Prebed	17 Aug.	14 Dec.
9. Metam Na[y]	37.5 gal	Spray on bed top	Post bed, pre-cover	22 Aug.	20 Dec.
PlantPro 45	41 lb	Drip, 2 tubes	Post bed	12 Sept.	
10. Metam Na[y]	37.5 gal	Spray on bed top	Post bed, pre-cover	22 Aug.	20 Dec.
PlantPro 45	55 lb	Drip, 2 tubes	Post bed	13 Sept.	
11. Metam Na[y]	37.5 gal	Spray on bed top	Post bed, pre-cover	22 Aug.	20 Dec.
PlantPro20EC	55 lb	Drip, 2 tubes	Post bed	4 Sept.	
12. Pebulate	4 lb	Broadcast ppi	Prebed	21 Aug.	14 Dec.
Fosthiazate	4.5 lb	Prebed ppi	Prebed	21 Aug.	14 Dec.
Pic	200 lb	In bed, 3 chisels	At bedding	21 Aug.	14 Dec.
13. Pebulate	4 lb	Broadcast ppi	Prebed	21 Aug.	14 Dec.
Fosthiazate	4.5 lb	Drip, 2 tubes	Preplant	24 Sept.	20 Dec.
Pic	200 lb	In bed, 3 chisels	Post bed	21 Aug.	14 Dec.
14. Dazomet[x]	400 lb	Drop spread	Post bed, 1 month preplant	17 Aug.	19 Dec.
1,3-D-35% Pic	35 gal	In bed, 3 chisels	Post bed, pre-cover	19 Aug.	21 Dec.
15. Pebulate	4 lb	Broadcast ppi	Prebed	21 Aug.	14 Dec.
Pic	50 lb	In bed, 3 chisels	Post bed, pre-cover	21 Aug.	14 Dec.
Na-tetrathiocarbonate	150 gal	In bed, 3 chisels	Post bed, pre-cover	21 Sept.	
Na-tetrathiocarbonate	700 ppm	Drip, 2 tubes	14 d after 1st application	11 Oct.	20 Dec.
Na-tetrathiocarbonate	700 ppm	Drip, 2 tubes	28 d after 1st application		
Na-tetrathiocarbonate	700 ppm	Drip, 2 tubes	42 d after 1st application		
16. Trifluralin	0.5 lb	Broadcast ppi	Prebed	21 Aug.	—
1,3-D-35% Pic	26 gal	Broadcast, yetter	Prebed		
Messenger™	9oz	Foliar spray	7 d preplant	20 Sept.	
Messenger™	9 oz	Foliar spray	14 d intervals until harvest		
17. Na-azide[w]	50 lb	Drip, 2 tubes	14 d preplant	—	17 Dec.
18. Na-azide[w]	100 lb	Drip, 2 tubes	14 d preplant	—	17 Dec.
19. Na-azide[w]	150 lb	Drip, 2 tubes	14 d preplant	—	18 Dec.
20. Na-azide[w]	200 lb	Drip, 2 tubes	14 d preplant	—	18 Dec.
21. Trifluralin	0.5 lb	Broadcast, disk in	Prebed	—	13 Dec.
Napropamide	2 lb	Broadcast, disk in	Prebed		13 Dec.
1,3-D- 35% Pic	26 gal	Yetter prebedder	Prebed		13 Dec.
Pic	125 lb	In bed, 3 chisels	Same day as prebed		14 Dec.
22. Trifluralin	0.5 lb	Broadcast, disk in	Prebed	—	13 Dec.
Napropamide	2 lb	Broadcast, disk in	Prebed		13 Dec.
1,3-D-Pic (Inline)[w]	26 gal	Drip, 2 tubes	Postbed		13 Dec.
23. Pic	125 lb	In-bed, 3 chisels	In bed	—	19 Dec.
Metam-K	60 gal	Drip, 2 tubes	In bed		19 Dec.
24. Furfural[w]	400 lb	Drip, 2 tubes	In bed	—	19 Dec.
25. Furfural[w]	600 lb	Drip, 2 tubes	In bed	—	19 Dec.

[z]Plots received 1 to 1.5 acre-inches H_2O 5 days prior to treatment and were irrigated 1 d before application. Treatment delivered with 1 to 1.5 acre-inches H_2O to wet the soil 18 inches deep.
[y]Metam-Na was surface sprayed on the finished bed top in 1000 gal H_2O using flood jets and then incorporated 6 to 8 inches deep with a rototiller. Plant Pro chemicals were applied in 1 acre-inch H_2O followed by an additional 0.5 acre-inch H_2O to flush the drip tubes.
[x]Half of the dazomet granules (200 lb·acre^{-1}) dropped on the flat (unfinished bed) and incorporated with a rotovator. The remainder (200 lb·acre^{-1}) of dazomet was dropped onto the finished bed. Post applications of 0.25 acre-inch H_2O via microsprinklers were made immediately after, 8 h later, the following morning, and the following afternoon after dazomet.
[w]Sodium azide, furfural with allyl isothiocyante, and 1,3-D-35% Pic as Inline applied in 1 acre-inch H_2O.

Inc., San Diego, Calif.; 0.029 $L \cdot s^{-1}$, 31 cm emitter spacing), applied under and simultaneously with polyethylene film (white on black), was buried 2 inches below the surface of finished beds with the appropriate number of tubes per bed. Drip tubes were spaced 10 inches apart, with 4 inches between the edge of the bed and the tube nearest the bed-shoulder, when three tubes were used in a bed. Polyethylene film was applied immediately after in-bed applications with in-bed or a combination of broadcast and in-bed applications, prior to drip applications, and after rototilling metam-Na.

Tomato ('Florida 47') seedlings were planted 28 Sept. 2001 and 21 Jan. 2002 in Bradenton and Immokalee, respectively. The late planting date in Immokalee was due to freezing weather. Tomatoes were grown using seepage in Immokalee and drip irrigation in Bradenton with standard cultural practices, including staking. Tomato plants were sprayed as needed with fungicides and insecticides.

Data recorded at various times during the season included tomato plant vigor, weed and nematode populations, and fungal disease incidence. Tomato plant vigor was evaluated using a percentage visual assessment scale where 100% represented optimum plant vigor and 0% indicated the plants were dead. Weeds were counted on a per-plot basis. Soil samples for nematode analysis were collected from the rhizosphere of tomato plants shortly before the first tomato fruit harvest. Nematodes were separated from 100 mL of soil using a standard sieving and centrifugation procedure (Jenkins, 1964). Tomato plants with symptoms of Fusarium wilt (race 3, incited by *Fusarium oxysporum* f. sp. *lycopersici*) or Fusarium crown rot (*Fusarium oxysporum* f. sp. *radicis-lycopersici*) were counted.

Mature green and colored tomatoes were harvested three times until the number of immature fruit were insufficient to warrant additional harvests. Fruit harvesting began on 31 Dec. 2001 at 13 weeks after planting (WAP) in Bradenton and on 17 Apr. 2002 (12 WAP) in Immokalee. Final fruit harvest occurred on 5 Feb. 2002 (18 WAP) in Bradenton and on 8 May (15 WAP) in Immokalee. Fruit were separated into marketable and cull categories, then marketable fruit were sorted by size into the standard extra-large (5 × 6), large (6 × 6), and medium (6 × 7) size grades and weighed.

Data were subjected to ANOVA using SAS (SAS Institute, 2000). Data were analyzed by location because some of the treatments were not tested in both locations. Nutsedge and nematode population data within each treatment replication were transformed [log10 (observation + 1)] or assigned a rank via PROC RANK (Eskridge, 1995), respectively, to stabilize variability of the data. Resulting log-transformed or rank means were then analyzed via PROC GLM. Treatment means were separated using Duncan's multiple range test.

Results and Discussion

Tomato plant vigor at 4 WAP in Bradenton, with nontreated soil, was low at 60% using a scale where 100% indicated plants with optimum vigor (Table 2). Plant vigor in Bradenton increased above 60% with all treatments, except metam-Na (rototilled) + Plant Pro 45 (41 lb/acre) and pebulate + Pic + Enzone™. The use of MBr resulted in a tomato plant vigor rating of 88%, and similar plant vigor ratings were obtained with iodomethane alone or with Pic, metam-Na

Table 2. Effect of fumigant treatments on tomato plant vigor at about 1 month after planting.

		Early-season vigor (%)[z]	
Fumigant[y]	Rate (amt. per acre)	Bradenton	Immokalee
Nontreated	N/A	60 e	80 b
MBr-Pic	350 lb	88 a	92 ab
Iodomethane/Pic	150/110 lb	82 ab	95 a
Iodomethane	150 lb	82 ab	80 b
1,3-D-35% Pic/Trifl./Napro./Pic	26 gal/0.5 lb/2 lb/125 lb	82 ab	90 ab
Metam-Na	75 gal	88 a	96 a
Metam Na/Pic	75 gal/150 lb	86 a	92 ab
Metam Na/1,3-D	75 gal/18 gal	85 a	88 ab
Metam-Na/PlantPro 45	37.5 gal/41 lb	70 c-e	87 ab
Metam-Na/PlantPro 45	37.5 gal/55 lb	72 b-d	85 b
Metam-Na/PlantPro 20EC	37.5 gal/55 lb	78 a-c	80 b
Pebulate/fosthiazate-ppi/Pic	4/4.5/200 lb	88 a	90 ab
Pebulate/fosthiazate-drip/Pic	4/4.5/200 lb	88 a	93 a
Dazomet/1,3-D-35% Pic	200 lb/35 gal	82 ab	87 ab
Pebulate/Pic/Na-tetrathiocarbonate	4 lb/50 lb/150 gal	66 de	85 b
Trifl./1,3-D-35% Pic/Messenger™	0.5 lb/26 gal/9 oz	85 a	—
Na-azide	50 lb	—	89 ab
Na-azide	100 lb	—	87 ab
Na-azide	150 lb	—	78 bc
Na-azide	200 lb	—	70 c
Trifl./Napro./1,3-D-35% Pic/Pic	0.5 lb/2 lb/26 gal/125 lb	—	90 ab
Trifl./Napro./1,3-D-35% Pic	0.5 lb/2 lb/26 gal	—	94 a
Pic/Metam-K	125 lb/60 gal	—	95 a
Furfural allyl isothiocyanate	400 lb	—	90 ab
Furfural allyl isothiocyanate	600 lb	—	90 ab

[z]Means within columns were separated by Duncan's multiple range test ($P \leq 0.05$).
[y]Herbicides used were trifuluralin (Trifl.) and napropamide (Napro.). A formulation of 67-33% methyl bromide (MBr)-chloropicrin (Pic) was used. See Table 1 for treatment details.

(drip-applied), metam-Na (rototilled with Pic, 1,3-D, or Plant Pro 20EC), pebulate + fosthiazate (preplant-incorporated and drip-applied) + Pic, dazomet + 1,3-D with 35% Pic, and trifluralin + 1,3-D with 35% Pic + Messenger™. Chemicals resulting in tomato plants with less vigor than that with MBr-Pic were metam-Na + Plant Pro 45 (with either 41 or 55 lb/acre Plant Pro) and pebulate + Pic + Enzone™.

Tomato plant vigor at about 4 WAP in Immokalee ranged from 80% with non-treated soil to 96% with drip-applied metam-Na (Table 2). Treatments in Immokalee that improved plant vigor above that obtained with non-treated soil were iodomethane + Pic, drip-applied metam-Na, pebulate + drip-applied fosthiazate + Pic, trifluralin + napropamide + 1,3-D with 35% Pic, and Pic + metam-K. The remaining treatments failed to improve tomato plant vigor above that with non-treated soil. Tomato plant vigor declined from 89% to 70% with an increase in the rate of Na-azide from 50 to 200 lb/acre, and vigor with 200 lb/acre Na-azide was less than that with the 50 and 100 lb/acre rates of Na-azide.

Nutsedge pressure by 6 WAP in Bradenton was high at six shoots per ft^{-2} on 6 Nov. 2001 with non-treated soil (Table 3), and this population was similar to that with iodomethane + Pic, metam Na (rototilled) with either Pic, 1,3-D, or PlantPro 45, and pebulate + Pic + Enzone™. The remaining treatments controlled nutsedge with greater control (89%) provided by pebulate + preplant-incorporated fosthiazate than that of 82% with 1,3-D with 35% Pic + trifluralin + napropamide + Pic, 73% with metam-Na + Plant Pro 20EC, and 76% with dazomet + 1,3-D-35% Pic. The 84% nutsedge control provided by MBr-Pic was similar to that with pebulate + preplant-incorporated fosthiazate. Nutsedge pressure in Immokalee was low at not more than three shoots per 40-ft row, and populations were similar with all treatments.

Fusarium wilt, by 15 WAP, infected 73% of the tomato plants grown in Bradenton with no soil fumigant, and incidence was reduced with all soil treatments (Table 4). Treatments that provided 100% control of Fusarium wilt were MBr-Pic, metam-Na + Pic, metam-Na + 1,3-D, pebulate + fosthiazate (preplant-incorporated or drip-applied) + Pic, and dazomet + 1,3-D with 35% Pic; the 0% incidence with these treatments was similar to that obtained with iodomethane + Pic, 1,3-D with 35% Pic + trifluralin + napropamide + Pic, drip-applied metam-Na, metam-Na + Plant Pro 45 at 55 lb/acre, pebulate + Pic + Enzone™, and trifluralin + 1,3-D with 35% Pic + Messenger™. Control of Fusarium wilt in Bradenton was intermediate with iodomethane alone, metam-Na + Plant Pro at 41 $lb \cdot acre^{-1}$, and metam-Na + Plant Pro 20EC.

Fusarium crown rot was present at Immokalee with observed symptoms at 16 WAP on 15% of the tomato plants grown in non-treated soil (Table 4), and incidence declined to 4% to 5% with metam-Na + Plant Pro 20EC, pebulate + drip-applied fosthiazate, Na-azide at 100 $lb \cdot acre^{-1}$, and furfural at 600 lb/acre. Remaining treatments failed to control Fusarium crown rot.

Nematode populations were not normally distributed, even when the data were log-transformed. Therefore, these data were analyzed using a nonparametric method as discussed above. Actual observed means, Duncan's letters, and rank means are shown in Table 5. Rank instead of observed means were subjected to Duncan's mean separation test, so

Table 3. Effect of fumigant treatments on purple nutsedge (*Cyperus rotundus*) populations at first tomato harvest at each location.

Fumigant[y]	Rate (amt. per acre)	Nutsedge (no. per 40-ft row)[z] Bradenton	Immokalee
Nontreated	N/A	555 a	0.1
MBr-Pic	350 lb	87 b-d	0.5
Iodomethane/Pic	150/110 lb	514 ab	1.2
Iodomethane	150 lb	98 b-d	1.1
1,3-D-35% Pic/Trifl./Napro./Pic	26 gal/0.5 lb/2 lb/125 lb	121 bc	0.2
Metam-Na	75 gal	49 cd	1.2
Metam Na/Pic	75 gal/150 lb	324 ab	0.7
Metam Na/1,3-D	75 gal/18 gal	366 ab	0.8
Metam-Na/PlantPro 45	37.5 gal/41 lb	237 ab	0.2
Metam-Na/PlantPro 45	37.5 gal/55 lb	381 ab	1.1
Metam-Na/PlantPro 20EC	37.5 gal/55 lb	148 bc	1
Pebulate/fosthiazate-ppi/Pic	4/4.5/200 lb	63 d	0.3
Pebulate/fosthiazate-drip/Pic	4/4.5/200 lb	54 cd	0.5
Dazomet/1,3-D-35% Pic	200 lb/35 gal	132 bc	0.5
Pebulate/Pic/Na-tetrathiocarbonate	4 lb/50 lb/150 gal	233 ab	0.8
Trifl./1,3-D-35% Pic/Messenger™	0.5 lb/26 gal/9 oz	90 b-d	—
Na-azide	50 lb	—	1.4
Na-azide	100 lb	—	0.9
Na-azide	150 lb	—	1.2
Na-azide	200 lb	—	3
Trifl./Napro./1,3-D-35% Pic/Pic	0.5 lb/2 lb/26 gal/125 lb	—	2.6
Trifl./Napro./1,3-D-35% Pic	0.5 lb/2 lb/26 gal	—	1
Pic/Metam-K	125 lb/60 gal	—	0.6
Furfural allyl isothiocyanate	400 lb	—	0.9
Furfural allyl isothiocyanate	600 lb	—	0.9

[z]Means within columns were separated by Duncan's multiple range test ($P \leq 0.05$).
[y]Herbicides used were trifuluralin (Trifl.) and napropamide (Napro.). A formulation of 67-33% methyl bromide (MBr)-chloropicrin (Pic) was used. See Table 1 for treatment details.

Table 4. Effect of fumigant treatments on percentage of tomato plants infected, by the end of the season, with Fusarium wilt in Bradenton and Fusarium crown rot in Immokalee.

Fumigant[y]	Rate (amt. per acre)	Incidence of Fusarium (%)[z]	
		Bradenton	Immokalee
Nontreated	N/A	73 a	15 a-d
MBr-Pic	350 lb	0 e	15 a-d
Iodomethane/Pic	150/110 lb	1 e	8 c-e
Iodomethane	150 lb	21 cd	20 a
1,3-D-35% Pic/Trifl./Napro./Pic	26 gal/0.5 lb/2 lb/125 lb	3 e	8 c-e
Metam-Na	75 gal	1 e	9 c-e
Metam Na/Pic	75 gal/150 lb	0 e	7 de
Metam Na/1,3-D	75 gal/18 gal	0 e	8 c-e
Metam-Na/PlantPro 45	37.5 gal/41 lb	30 c	8 c-e
Metam-Na/PlantPro 45	37.5 gal/55 lb	13 c-e	8 c-e
Metam-Na/PlantPro 20EC	37.5 gal/55 lb	49 b	5 e
Pebulate/fosthiazate-ppi/Pic	4/4.5/200 lb	0 e	10 b-e
Pebulate/fosthiazate-drip/Pic	4/4.5/200 lb	0 e	4 e
Dazomet/1,3-D-35% Pic	200 lb/35 gal	0 e	8 c-e
Pebulate/Pic/Na-tetrathiocarbonate	4 lb/50 lb/150gal	19 c-e	18 ab
Trifl./1,3-D-35% Pic/Messenger™	0.5 lb/26 gal/9 oz	5 de	—
Na-azide	50 lb	—	8 c-e
Na-azide	100 lb	—	4 e
Na-azide	150 lb	—	17 a-c
Na-azide	200 lb	—	10 c-e
Trifl./Napro./1,3-D-35% Pic/Pic	0.5 lb/2 lb/26 gal/125 lb	—	6 de
Trifl./Napro./1,3-D-35% Pic	0.5 lb/2 lb/26 gal	—	7 de
Pic/Metam-K	125 lb/60 gal	—	6 de
Furfural allyl isothiocyanate	400 lb	—	6 de
Furfural allyl isothiocyanate	600 lb	—	5 e

[z]Means within columns were separated by Duncan's multiple range test ($P \leq 0.05$).
[y]Herbicides used were trifuluralin (Trifl.) and napropamide (Napro.). A formulation of 67-33% methyl bromide (MBr)-chloropicrin (Pic) was used. See Table 1 for treatment details.

the letters were consistent with rank but not necessarily with observed means.

Nematode species present at 10 WAP in Bradenton included root-knot (*Meloidogyne* spp.), sting (*Belonolaimus* spp.), and stunt (*Tylenchorhynchus* spp). Root-knot nematodes in Bradenton were few and were not influenced by treatments (Table 5). All treatments, except those of metam-Na + PlantPro 45 (55 lb/acre) and metam-Na + PlantPro 20EC, reduced the sting nematode population by at least 85% in comparison to that with non-treated soil. Stunt nematode populations were highest and similar with non-fumigated, iodomethane alone, metam-Na (rototilled) + PlantPro™ (all three formulations), pebulate + fosthiazate (drip-applied), dazomet + 1,3-D-35% Pic, pebulate + Pic + Enzone™, and trifluralin + 1,3-D-35% Pic + Messenger™; whereas remaining treatments, including MBr-Pic, reduced the stunt nematode population to a similar extent. Nematode data from Immokalee were not shown because populations were very low.

The presence of root-knot and other nematodes at the end of the season (Table 5), regardless of soil treatment, indicated a lack of total nematode control with the various treatments at application time. After evaluating the efficacy of 1,3-D against root-knot nematodes in tomato and cucumber, Giannakou et al. (2002) concluded that the failure to control all nematodes near the time of application led to a nematode population increase by the end of the cropping season.

Marketable tomato fruit yields in Bradenton were lower with non-treated than treated (all chemicals) soil (Table 6). Tomato fruit weight increased from 51 lb per 10 plants with non-treated soil to 117 lb per 10 plants with MBr-Pic. Yields comparable to that with MBr-Pic were obtained with iodomethane + Pic, iodomethane alone, 1,3-D-35% Pic + trifluralin + napropamide + Pic, metam-Na (all methods, except with PlantPro™ at 41 lb/acre), pebulate + fosthiazate (preplant-incorporated or drip-applied) + Pic, dazomet + 1,3-D-35% Pic, pebulate + Pic + Enzone™, and trifluralin + 1,3-D-35% Pic + Messenger™. Metam-Na applied through three drip tubes resulted in the highest numerical fruit weight of 128 lb per 10 plants. Adding PlantPro 45 with metam-Na resulted in 31% greater yield when applied at 55 than 41 lb/acre, and combining metam-Na with 55 lb/acre PlantPro™ resulted in tomato yield comparable to that with drip-applied metam-Na. Marketable fruit weight in Bradenton was inversely correlated with Fusarium wilt incidence (Pearson coefficient = -0.73; P = <0.0001). Tomato production in Immokalee did not differ between treatments, possibly because of low pest pressure.

The fact that Pic with iodomethane increased nutsedge populations (Table 3) but decreased Fusarium (wilt and crown rot) incidence (Table 4), in comparison to iodomethane alone, suggests that the value of combining iodomethane with Pic depends on which pests are predominant in a field. The improved disease control with iodomethane + Pic over iodomethane alone was consistent with results obtained in 1996 from Immokalee where Pic controlled diseases in tomato (Gilreath and Jones, 1996).

Metam-Na applied through three drip tubes in a bed resulted in similar pest control and tomato yield as MBr-Pic. In agreement with these results, Locascio and Dickson (2002) found that metam-Na applied though three drip tubes per-

Table 5. Effect of fumigant treatments on populations of root knot (*Meloidogyne* spp.), sting (*Belonolaimus* spp.), and stunt (*Tylenchorhynchus* spp) nematodes in the rhizosphere of tomato plants in Bradenton on 7 Dec. 2001.

		Incidence of Fusarium (%)[z]		
Fumigant[y]	Rate (amt. per acre)	Root Knot	Sting	Stunt
Nontreated	N/A	0	20 a (16)	52 a (14)
MBr-Pic	350 lb	1	0 c (6)	8 bc (6)
Iodomethane/Pic	150/110 lb	0	<1 bc (8)	4 bc (6)
Iodomethane	150 lb	<1	2 bc (9)	5 a-c (8)
1,3-D-35% Pic/Trifl./Napro./Pic	26 gal/0.5 lb/2 lb/125 lb	0	0 c (6)	6 bc (5)
Metam-Na	75 gal	0	0 c (6)	4 bc (5)
Metam Na/Pic	75 gal/150 lb	0	1 bc (8)	15 bc (6)
Metam Na/1,3-D	75 gal/18 gal	0	0 c (6)	2 c (4)
Metam-Na/PlantPro 45	37.5 gal/41 lb	1	1 bc (8)	15 a-c (10)
Metam-Na/PlantPro 45	37.5 gal/55 lb	2	4 ab (12)	21 ab (12)
Metam-Na/PlantPro 20EC	37.5 gal/55 lb	<1	5 ab (12)	40 a (14)
Pebulate/fosthiazate-ppi/Pic	4/4.5/200 lb	0	0 c (6)	8 bc (6)
Pebulate/fosthiazate-drip/Pic	4/4.5/200 lb	0	0 c (6)	12 a-c (10)
Dazomet/1,3-D-35% Pic	200 lb/35 gal	0	0 c (6)	22 ab (11)
Pebulate/Pic/Na-tetrathiocarbonate	4 lb/50 lb/150 gal	<1	3 bc (10)	39 ab (12)
Trifl./1,3-D-35% Pic/Messenger™	0.5 lb/26 gal/9 oz	0	0 c (6)	10 a-c (8)

[z]Prior to mean separation via Duncan's multiple range test (P ≤ 0.05), each data point within a treatment replication was assigned a rank, and these ranks were subjected to ANOVA. Rank means (shown in parentheses) for each treatment were obtained by averaging the ranks across treatment replications.
[y]Herbicides used were trifuluralin (Trifl.) and napropamide (Napro.). A formulation of 67-33% methyl bromide (MBr)-chloropicrin (Pic) was used. See Table 1 for treatment details.

formed similarly as MBr-Pic in reducing nutsedge populations and galling by root-knot nematodes in field-grown tomato. Their results and those of the present study were also similar in that nutsedge populations were lower with drip- than broadcast-applied metam-Na.

The lack of consistent nutsedge (Table 3) and nematode (Table 5) control with metam-Na + PlantPro™ (all rates/formulations) indicated that activity against these pests with a reduced rate (38 instead of 75 gal/acre) of metam-Na was not enhanced by the addition of PlantPro™. The observation that

Table 6. Effect of fumigant treatments on seasonal total tomato yield.

		Marketable yield (lb per 10 plants)[z]	
Fumigant[y]	Rate (amt. per acre)	Bradenton	Immokalee
Nontreated	N/A	51 e	108
MBr-Pic	350 lb	117 a-c	128
Iodomethane/Pic	150/110 lb	121 ab	112
Iodomethane	150 lb	97 b-d	99
1,3-D-35% Pic/Trifl./Napro./Pic	26 gal/0.5 lb/2 lb/125 lb	101 a-d	112
Metam-Na	75 gal	128 a	97
Metam Na/Pic	75 gal/150 lb	117 a-c	121
Metam Na/1,3-D	75 gal/18 gal	112 a-c	95
Metam-Na/PlantPro 45	37.5 gal/41 lb	84 d	123
Metam-Na/PlantPro 45	37.5 gal/55 lb	110 a-c	112
Metam-Na/PlantPro 20EC	37.5 gal/55 lb	97 b-d	123
Pebulate/Fosth-ppi/Pic	4/4.5/200 lb	110 a-c	119
Pebulate/Fosth-drip/Pic	4/4.5/200 lb	115 a-c	97
Dazomet/1,3-D-35% Pic	200 lb/35 gal	108 a-c	112
Pebulate/Pic/Enzone™	4 lb/50 lb/150 gal	95 cd	119
Trifl./1,3-D-35% Pic/Messenger™	0.5 lb/26 gal/9 oz	104 a-d	—
Na-azide	50 lb	—	117
Na-azide	100 lb	—	117
Na-azide	150 lb	—	117
Na-azide	200 lb	—	121
Trifl./Napro./1,3-D-35% Pic/Pic	0.5 lb/2 lb/26 gal/125 lb	—	110
Trifl./Napro./1,3-D-35% Pic	0.5 lb/2 lb/26 gal	—	126
Pic/Metam-K	125 lb/60 gal	—	112
Furfural allyl isothiocyanate	400 lb	—	115
Furfural allyl isothiocyanate	600 lb	—	106

[z]Means within columns were separated by Duncan's multiple range test (P ≤ 0.05).
[y]Herbicides used were trifuluralin (Trifl.) and napropamide (Napro.). A formulation of 67-33% methyl bromide (MBr)-chloropicrin (Pic) was used. See Table 1 for treatment details.

PlantPro 45 at 55 lb·acre^{-1} controlled Fusarium wilt similarly as MBr-Pic (Table 4) was consistent with the finding that PlantPro 45 had activity against Fusarium wilt of basil (*Ocimum basilicum*) (Adams et al., 2003).

Results with fosthiazate with pebulate and Pic indicated that nematicidal activity was most consistent with preplant-incorporated fosthiazate, as this treatment controlled both sting and stunt nematodes. With the lack of a significant nematode population in Immokalee, it could not be determined if pebulate + preplant-incorporated fosthiazate + Pic provided adequate nematode control in more than one location. Previous research in Immokalee suggested that fosthiazate performed erratically as a nematicide (Gilreath and Jones 1996).

Inferences regarding the efficacy of Enzone™ and Messenger™ were difficult to make because these compounds were mixed with other chemicals. For example, the 93% reduction of Fusarium wilt incidence with trifluralin + 1,3-D-35% Pic + Messenger™ (Table 4) suggested that Messenger™ and/or Pic controlled Fusarium wilt, but it was not possible to determine the contribution to disease control of individual chemicals in the mixture. Results with pebulate + Pic + Enzone™ indicated that Enzone™ may have had activity against Fusarium wilt (Table 4) and sting nematodes (Table 5) but not against the other pests present. Enzone™ failed to control nematodes in a previous study (Gilreath and Jones, 1996).

With the lack of pest pressure in Immokalee, it was not possible to evaluate the effectiveness of Na-azide, metam-K, and furfural over a broad spectrum of pests. The apparent rate response of early-season crop vigor (Table 2) to Na-azide rate in Immokalee indicated that Na-azide was injurious to tomato plants at the higher rates; however, the lack of treatment effects on fruit production in Immokalee (Table 6) suggested that injured tomato plants had recovered by the end of the season. The low incidence of Fusarium crown rot with both metam-Na + Pic and metam-K + pic (Table 4) suggested that disease control was not influenced by the accompanying salt of metam. The fact that furfural at 600 lb/acre controlled Fusarium crown rot suggests that this material may control soilborne diseases even though it was formulated to control nematodes.

Overall, with respect to older chemicals already registered for commercial use, results of this research confirmed results of previous research as discussed above. Results with newer chemicals, used alone or in mixtures, indicated that some may have a place in controlling specific pests. No single MBr alternative treatment or treatment combination, with the possible exception of metam-Na applied through three drip tubes, provided broad-spectrum pest control; however, for each pest, one or more treatments performed as well as MBr.

Acknowledgments

The authors wish to thank McClure Farms for field space and production of the tomato crop in Immokalee and Taylor and Fulton for provision of the tomato transplants for this and related trials conducted at Bradenton. We also wish to thank Dr. Jack Norton with the USDA/IR-4 Program for his assistance and support and the various manufacturers who supplied products and other forms of support for these experiments.

Literature Cited

Adams, P. D., N. Kokalis-Burelle, and W. H. Basinger. 2003. Efficacy of Plant-Pro 45 as a seed and soil treatment for managing Fusarium wilt of basil. HortTechnology 13:77-80.

Allan, M. A. 2002. MIDAS™ (TM-425), 2002 development and regulatory update, p. 76. In 2002 Annu. Intl. Res. Conf. Methyl Bromide Alternatives Emissions Reductions. Orlando, Fla., 6-8, Nov. 2002. Methyl Bromide Alternatives Outreach. Fresno, CA. http://www.mbao.org/.

Eskridge, K. M. 1995. Statistical analysis of disease reaction data using nonparametric models. HortScience 30:478-481.

Giannakou, I. O., A. Sidiropoulos, and D. Prophetou-Athanasiadou. 2002. Chemical alternatives to methyl bromide for the control of root-knot nematodes in greenhouses. Pest Mgt. Sci. 58:290-296.

Gilreath, J. P. and J. P. Jones. 1996. Possible soil fumigant alternatives for methyl bromide in mulched tomato production. Methyl Bromide Alternatives Newsletter 2:4-5.

Gilreath, J. P., J. P. Jones, and A. J. Overman. 1994. Soil-borne pest control in mulched tomato with alternatives to methyl bromide. Proc. Fla. State Hort. Soc. 107:156-159.

Gilreath, J. P., J. W. Noling, P. R. Gilreath, and J. P. Jones. 1997. Field validation of 1,3-dichloropropene + chloropicrin and pebulate as an alternative to methyl bromide in tomato. Proc. Fla. State Hort. Soc. 110:273-276.

Jenkins, W. R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Dis. Reptr. 48:692.

Jones, J. P., J. P. Gilreath, A. J. Overman, and J. W. Noling. 1995. Control of soil-borne diseases of mulched tomato by fumigation. Proc. Fla. State Hort. Soc. 108:201-203.

Kokalis-Burelle, N. and P. Fuentes-Borquez. 2000. Efficacy of PLANTPRO45™ as an alternative to methyl bromide for control of root-knot nematode on tomato. J. Nematol. 32:Abstract.

Locascio, S. J. and D. W. Dickson. 2002. Alternative fumigants applied with standard and virtually impermeable mulches for tomato. Proc. Fla. State Hort. Soc. 115:192-194.

Locascio, S. J., J. P. Gilreath, D. W. Dickson, T. A. Kucharek, J. P. Jones, and J. W. Noling. 1997. Fumigant alternatives to methyl bromide for polyethylene mulched tomato. HortScience 32:1208-1211.

Motis, T. N. and J. P. Gilreath. 2002. Stimulation of nutsedge emergence with chloropicrin, p. 7. In 2002 Annu. Intl. Res. Conf. Methyl Bromide Alternatives Emissions Reductions. Orlando, Fla., 6-8, Nov. 2002. Methyl Bromide Alternatives Outreach. Fresno, CA. http://www.mbao.org/.

Nelson, S. D., S. J. Locascio, L. H. Allen, D. W. Dickson, and D. J. Mitchell. 2002. Soil flooding and fumigant alternatives to methyl bromide in tomato and eggplant production. HortScience 37:1057-1060.

Overman, A. J. and F. G. Martin. 1978. A survey of soil and crop management practices in the Florida tomato industry. Proc. Fla. State Hort Soc. 91:294-297.

Parochetti, J. V. and G. F. Warren. 1970. Behavior of potassium azide in the soil. Weed Sci. 18:555-560.

Pullen, M. P. and B. A. Fortnum. 1999. Fosthiazate controls *Meloidogyne arenaria* and *M-incognita* in flue-cured tobacco. J. Nematol. 31:694- 699.

Rodriguez-Kabana, R. 2000. Nematicidal and herbicidal properties of furfural-based biofumigants, p. 20. In 2002 Annu. Intl. Res. Conf. Methyl Bromide Alternatives Emissions Reductions. Orlando, Fla., 6-8, Nov. 2002. Methyl Bromide Alternatives Outreach. Fresno, CA. http://www.mbao.org/.

[SAS] Statistical Analysis Systems Institute. 2000. SAS User's Guide. Version 8. Cary, NC: Statistical Analysis Systems Institute.

Sturz, A. V. and J. Kimpinski. 1999. Effects of fosthiazate and aldicarb on populations of plant-growth-promoting bacteria, root-lesion nematodes and bacteria feeding nematodes in the root zone of potatoes. Plant Pathol. 48:26-32.

Wei, Z. and S. V. Beer. 1996. Harpin from *Erwinia amylovora* induces plant resistance. Acta Hort. 411:221-224.

Wei, Z., R. L. Laby, C. H. Zumoff, D. W. Nauer, S. Y. He, A. Collmer, and S. V. Beer. 1992. Harpin, elicitor of the hypersensitive response produced by the plant pathogen *Erwinia amylovora*. Science 257:85-88.