Evaluation of Methyl Iodide as a Soil Fumigant for Root-Knot Nematode Control in Carrot Production

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ABSTRACT

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Methyl iodide performance as a soil fumigant was compared with methyl bromide for *Meloidogyne incognita* control in carrot production. Both compounds were applied to tarped beds by hot-gas fumigation in growers' fields near Bakersfield, California. Methyl iodide was applied at 112, 168, 224, and 336 kg ha⁻¹ and methyl bromide at 112 and 224 kg ha⁻¹. Other chemical treatments included a non-fumigated control, metam sodium (373 liters ha⁻¹), applied through overhead irrigation, and 1,3-dichloropropene (1,3-D; 112 liters ha⁻¹) commercially shank applied. Soil was either extracted or bioassayed with tomato plants to determine *M. incognita* populations prior to application of fumigants, 2 weeks after fumigant application, and at carrot harvest. Carrots were rated for marketability based on size and nematode-induced damage. Methyl bromide, methyl iodide, and 1,3 D were effective at reducing *M. incognita* populations over the season at all rates tested. In both trials, plants in plots fumigated with either methyl bromide or methyl iodide produced at least 161 and 181% more marketable carrots without nematode damage, respectively, than plants in control plots. Methyl iodide was an effective alternative to methyl bromide for nematode control in carrot production.

Additional keywords: *Daucus carota*, 1,3-dichloropropene, *Meloidogyne incognita*, metam sodium, methyl bromide, soil fumigation

Methyl bromide fumigation has been a reliable and effective treatment to control pests in horticultural production since the 1950s. Methyl bromide is a broad-spectrum pesticide that controls plant parasitic nematodes, plant pathogenic fungi, and weeds in a single application prior to crop planting. Recently, however, methyl bromide has been implicated in contributing to the destruction of the ozone layer (1). In 1987, the Montreal Protocol, an international treaty sponsored by the United Nations Environment Programme (UNEP), was created to protect the stratospheric ozone layer from substances with high ozone-depleting potentials (ODP). At the Ninth Meeting of the Parties to the Montreal Protocol in 1997, the phase-out date of methyl bromide was set at 2005 in developed countries (14). In the United States, however, the Clean Air Act Amendments of 1990 (title VI) further restrict production and importation of methyl bromide

beyond January 1, 2001, because of its relatively high ODP. Additionally, in the United States, production of methyl bromide was frozen at 1991 levels (13).

With the impending loss of methyl bromide, methyl iodide has been investigated as a possible alternative fumigant to methyl bromide (8). Methyl iodide has been considered a replacement for methyl bromide for three reasons. First, unlike methyl bromide, methyl iodide is destroyed by ultraviolet radiation before it can interact with stratospheric ozone; therefore, its ozone-depleting potential is low (1,5,8,12). Secondly, like methyl bromide, methyl iodide controls a broad spectrum of pests including plant parasitic nematodes (2,3), weeds (16), and plant pathogenic fungi (8). Lastly, methyl iodide is a possible replacement for methyl bromide because it can function in roles similar to those of methyl bromide without requiring alternative application equipment or changes in crop production practices. For agricultural industries that rely on soil fumigation for production of high-value crops, a methyl bromide alternative that provides reliable broad-spectrum pest control without modifying application equipment or changing production practices would be invaluable.

In this study, the efficacy of methyl iodide against root-knot nematode was investigated in a carrot production system.

Nematode control with methyl iodide was compared with the three fumigant nematocides currently registered for use in carrot (*Daucus carota* L.) production: methyl bromide, metam sodium, and 1,3-dichloropropene (1,3-D).

MATERIALS AND METHODS

Experimental design and treatments.

Two carrot field trials were conducted in growers' fields near Bakersfield, California. At each site, a randomized complete block experimental design with four replications was used. Plots were one bed wide and 6.1 m long. Carrot beds were centered on 0.76 m, with one row of untreated beds separating each replication of treated beds. Soil texture at each field site was a sandy loam with 6 and 9% soil moisture at the time of fumigation in trial 1 and 2, respectively. The eight treatments included a non-fumigated control; methyl bromide (Great Lakes Chemical, West Lafayette, IN) at 112 and 224 kg ha⁻¹; methyl iodide (D. S. M. Fine Chemicals, Saddle Brook, NJ) at 112, 168, 224, and 336 kg ha⁻¹; and a commercially applied nematicide. For the commercially applied nematicide treatment, four plots were randomly chosen in the grower's field surrounding the research plot. In trial 1, the commercially applied nematicide was sodium methyldithiocarbamate (373 liters ha⁻¹; 42.0% a.i.; metam sodium; AMVAC, Newport Beach, CA). Metam sodium was applied through sprinkler irrigation. The application was followed with 5.0 cm of irrigation water without metam sodium. In trial 2, 1,3-D (112 liters ha⁻¹; 1,3-D; Dow, Inc., Indianapolis, IN) was commercially shank applied 46 cm below the soil surface.

Hot-gas fumigation. Methyl bromide and methyl iodide fumigant treatments were applied to plots using a hot-gas fumigation applicator. With this fumigation method, 1.25-cm-diameter drip tape with 30-cm hole spacing was placed on the soil surface in the middle of each bed in each plot. A coupler was attached to one end of the drip tape and the opposite end was sealed. The plots were covered with clear, 4-mil polyethylene tarp (4 mil = 0.1 mm). The edges of the tarp were buried with soil in the trenches between beds to seal the tarp edges. A 1.9-cm-diameter hose ran from the coupler on the drip tape to the gas outlet on the hot-gas applicator. For hot-gas fumigation, either methyl iodide or

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chilled methyl bromide (-56°C) was dispensed into chilled 1-liter plastic bottles hooked in-line to a nitrogen gas source. Nitrogen gas (0.84 kg cm^{-2}) forced the liquid fumigant out of the plastic bottle and through coiled copper tubing in a sealed boiler unit (82°C) before propelling the heated gas to soil in plots through the drip line. The line was purged with nitrogen for 90 sec after the last of the fumigant was forced into the line from the plastic bottle. In trials 1 and 2, fumigants were applied on 24 January 1997 and 27 August 1997, respectively. Soil temperature at 15 cm depth at the time of hot-gas fumigation was 12 and 28°C for trials 1 and 2, respectively. Tarps were left in place for 4 days. In both trials, pest control measures over the season followed standard pest control guidelines for carrot production.

Nematode sampling and bioassay. Soil samples were taken prior to fumigant application, approximately 2 weeks after fumigation, and at carrot harvest. Six soil cores were taken to a depth of 25 cm in each plot using a soil probe with an internal diameter of 2.5 cm. Soil samples from individual plots were combined, mixed,

and either used for bioassays or extracted (50 cm^3 subsample) on a Baermann funnel for enumeration of second-stage juveniles. After 4 days on the Baermann funnel, *M. incognita* juveniles were counted with the aid of a dissecting microscope.

For both field trials, a bioassay was used to monitor nematode populations in soil samples. In trial 1, the pre-fumigation soil sample and the post-treatment soil sample collected on 24 January 1997 and 5 February 1997, respectively, were bioassayed. In trial 2, the carrot harvest soil sample collected on 2 February 1998 was bioassayed. For the bioassay experiment, soil from the soil cores collected in each plot was mixed with blow sand at a 2:1 ratio and used to fill fiber pots (10 cm^2 top dimension, 400 cm^3 volume). Tomato (*Lycopersicon esculentum* Mill.) cv. Pixie plants were transplanted into each pot and grown in the greenhouse under ambient light and temperature (25 to 28°C daytime maximum). After 8 weeks, roots were washed free of soil, plant tops removed, and roots weighed. The roots were placed in $94.6\text{ }\mu\text{M}$ erioglaucine for 12 h to stain the egg masses (9). After

staining, the roots were washed and egg masses counted.

Carrot production and rating. In trial 1, 21 days before carrot planting, 7-10-44 (NPK) fertilizer (851 kg ha^{-1}) was incorporated into the field. In trial 2, the carrot field was fertilized 29 days before carrot planting with 7-10-44 (NPK) fertilizer (784 kg ha^{-1}). In trials 1 and 2 at mid-season, 18-0-4-2 (NPKS) fertilizer was applied through irrigation water at 841 and $795\text{ liters ha}^{-1}$, respectively. Carrot (cv. Caropak) was seeded eight rows per bed with a commercial planter on 2 February 1997 and 5 September 1997 for trials 1 and 2, respectively. Carrots were harvested from 1 m of the bed in the center of each plot on 20 May 1997 and 2 February 1998 for trials 1 and 2, respectively. Harvested carrots in each treatment were rated in the following four categories based on size, gall formation, and branching or splitting of the main taproot: marketable with no nematode damage (MNN); marketable with nematode damage (MWN); non-marketable with no nematode damage (NMNN); and non-marketable with nematode damage (NMWN). Carrots in each category were counted, weighed, and reported in metric tons per hectare.

Statistical analysis. Data for all experiments presented were analyzed with the SAS analysis of variance procedure (SAS Institute, Cary, NC). The means were separated with the Fisher's protected least significant difference procedure.

RESULTS

Nematode populations. Both trials were uniformly infested with *M. incognita* before the application of nematicides (Table 1). In trial 1, post-fumigation sampling revealed that all fumigants significantly reduced nematode populations compared with the non-fumigated control. However, at harvest, nematode populations in control and metam sodium plots were not significantly different. In trial 2, nematode populations in all fumigated plots were below the detection level at post-fumigation and time of carrot harvest compared with the untreated control.

Marketable carrot production. In trial 1, total marketable carrot weight harvested from plants from the metam sodium treatment was significantly less than all other treatments (Table 2). In trial 2, total marketable carrot production was similar in all treatments except for significantly lower yields when treated with methyl bromide or methyl iodide at 224 kg ha^{-1} . Mean MNN carrot production in trial 1 for fumigated treatments not including metam sodium was 52.8 MT ha^{-1} , an increase of 196% over the control treatment. In trial 1, plants in the metam sodium treatment produced significantly less MNN carrot weight than plants in all other treatments. In trial 2, production of MNN carrots followed similar trends as in trial 1, with

Table 1. Effect of fumigants on *Meloidogyne incognita* populations

Treatment ^x	Trial 1 ^w			Trial 2		
	Pre EM	Post EM	Harvest J2	Pre J2	Post J2	Harvest EM
Control	24.0 a ^y	28.3 a	89.3 a	87.0 a	135.0 a	6.0 a
MB 112	8.8 a	0.0 c	0.0 c	88.5 a	0.0 b	0.0 b
MB 224	12.5 a	2.5 b	4.0 b	171.8 a	0.0 b	0.0 b
MI 112	6.8 a	0.0 c	0.0 c	129.3 a	0.0 b	0.0 b
MI 168	10.0 a	0.0 c	0.0 c	105.8 a	0.0 b	0.0 b
MI 224	24.8 a	0.3 b	0.0 c	177.0 a	0.0 b	0.0 b
MI 336	19.5 a	0.0 c	0.3 b	107.5 a	0.0 b	0.0 b
1,3-D	NT ^z	NT	NT	NT	0.0 b	0.0 b
MS	NT	7.3 b	122.5 a	NT	NT	NT

^w Pre = nematode population prior to fumigation. Post = nematode population after soil fumigation. Harvest = nematode population at carrot harvest. EM = bioassay, number of egg masses. J2 = Baermann funnel extraction of second-stage juveniles.

^x Fumigation with MB = methyl bromide and application rate (kg ha^{-1}); MI = methyl iodide and application rate (kg ha^{-1}); or MS = metam sodium.

^y Numbers within a column followed by different letters are significantly different based on least significant difference mean separation test, $P < 0.05$.

^z Not tested.

Table 2. Effect of fumigants on marketable carrot production (MT ha^{-1})

Treatment ^x	Total marketable carrot weight ^w		Marketable carrot weight (no nematodes)		Marketable carrot weight (with nematodes)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Control	54.4 a ^y	63.4 a	26.9 c	22.1 d	27.5 a	41.3 a
MB 112	57.6 a	61.5 a	56.0 a	47.6 abc	1.6 b	13.9 c
MB 224	56.4 a	43.7 b	52.6 ab	35.6 c	3.8 b	8.1 cd
MI 112	57.1 a	69.1 a	54.4 ab	55.9 a	2.7 b	13.2 c
MI 168	55.8 a	62.2 a	54.5 ab	49.9 ab	1.3 b	12.3 cd
MI 224	57.8 a	45.9 b	57.2 a	39.9 bc	0.6 b	5.8 d
MI 336	43.2 a	57.0 ab	42.4 b	46.0 abc	0.8 b	11.0 cd
1,3-D	NT ^z	74.1 a	NT	46.7 abc	NT	27.4 b
MS	35.1 b	NT	10.4 d	NT	24.7 a	NT

^w Sum of both marketable categories.

^x Fumigation with MB = methyl bromide and application rate (kg ha^{-1}); MI = methyl iodide and application rate (kg ha^{-1}); or MS = metam sodium.

^y Number within a column followed by different letters are significantly different based on least significant difference mean separation test, $P < 0.05$.

^z Not tested.

plants in the fumigated treatments producing more MNN carrot weight compared with plants in the non-fumigated control.

MWN carrot production trends were similar in trials 1 and 2, with more MWN carrot weight produced in the non-fumigated control plots than the methyl iodide and methyl bromide treatments (Table 2). In trial 1, the MWN carrot weight produced in the non-fumigated control and metam sodium treatments were similar. In trial 2, plants in methyl bromide and methyl iodide treatments produced significantly fewer MWN carrots than plants in either the control or 1,3-D treatments.

Non-marketable carrot production. In trial 1, plants treated with metam sodium or methyl iodide (336 kg ha⁻¹) produced significantly less total non-marketable carrot weight than all other treatments (Table 3). Significantly more NMNN carrot weight was observed in trial 1 in plots treated with methyl iodide (336 kg ha⁻¹) compared with all other treatments. In trial 2, plants in the 1,3-D treatment produced significantly less total non-marketable carrot weight than the control and methyl bromide (224 kg ha⁻¹) treatments. In trial 2, the control carrot treatment produced less NMNN carrot weight than all other treatments except 1,3-D.

In trial 1, plots treated with metam sodium produced significantly more NMWN carrot weight than plants in all other treatments. Plants in the control treatment in trial 2 produced more NMWN carrot weight compared with all other treatments. The control treatment plots in trial 2 produced 433% more NMWN carrot weight compared with the mean of all other treatments combined.

DISCUSSION

The lowest rates of methyl bromide and methyl iodide applied were effective in controlling nematodes and producing significantly more marketable carrots without nematode damage compared with the controls. Methyl iodide was as effective in controlling nematodes as methyl bromide. Total marketable carrot production with either methyl iodide or methyl bromide was similar in trial 1. In trial 2, a reduction in total marketable carrot production caused by phytotoxicity of the fumigant was observed with the methyl bromide (224 kg ha⁻¹) and methyl iodide (224 kg ha⁻¹) treatments. Phytotoxicity reduced total marketable carrot production by increasing the production of carrots rated as NMNN due to reduced size. This is attributable to not enough time after removal of the tarps before planting because of production scheduling by the grower.

Because of differences in the application procedure of the nematicides, direct comparisons cannot be made between the metam sodium and 1,3-D treatments and the hot-gas applied treatments. The hot-gas application was made under tarp, which is

not the normal practice for fumigant application in carrot production. This technique is likely to have optimized the efficacy of the fumigants compared with the standard commercial methyl bromide application procedure. However, hot-gas application enables the precise placement of small volumes of test fumigants which allowed direct comparisons to be made between the efficacy of the treatments. The grower-applied nematicide treatment was used as a grower standard reference.

Nematode populations varied between the two field trials because of the time at which each trial was planted. In trial 1, carrots were planted in February when soil temperatures were relatively cool and harvested in May when soil temperatures were warmer. As a consequence, *M. incognita* populations were low early in the season, requiring a bioassay on tomato to monitor nematode populations. Population densities during the season also influenced the type of damage observed on carrots at harvest. The population of *M. incognita* did not increase until late in the season; therefore, nematode damage was limited to secondary roots resulting in carrots in the control treatments rated as MWN (Tables 2 and 3). Conversely, in trial 2, carrots were planted in September when soil temperatures, nematode activity, and population were increased relative to trial 1. The majority of nematode damage occurred early in the growing season when soil temperatures remained relatively warm and *M. incognita* were active. Early infection of the carrot seedling caused forking and splitting in mature carrots, resulting in greater NMWN carrot ratings.

In trial 1, the grower-applied metam sodium did not provide season-long nematode control, even though it had previously been reported to be an effective means of controlling *Meloidogyne* spp. in vegetable production (10,11). Metam sodium is a difficult compound to distribute uniformly throughout the soil profile, which could contribute to differences in nematode con-

trol (6). The sprinkler application of metam sodium reduced *M. incognita* populations in the post-planting soil samples compared with controls (Table 1). The combination of the lack of comparative *M. incognita* control in the metam sodium treatments compared with the other fumigant treatments, potential upward movement of *M. incognita* from untreated soil depths, and the reduction of nematode predators by fumigation may be responsible for the relatively high *M. incognita* populations in these plots and the carrot damage observed.

In comparison, 1,3-D was effective in reducing season-long *M. incognita* populations. Plants in plots fumigated with 1,3-D produced more MWN carrot weight than plants in control plots. 1,3-D has been an effective method of controlling *Meloidogyne* spp. in carrot production (4,15). In 1996, 1,3-D was applied to 9% of the approximately 43,700 ha of carrots grown in the United States (7). Comparatively, in 1996, only 3% of the carrot acreage in the United States was treated under special permit with methyl bromide. In carrot production, the loss of methyl bromide can be offset by the use of 1,3-D and metam sodium.

However, the impending loss of methyl bromide will increase the demand for 1,3-D and metam sodium in crop production systems accustomed to using methyl bromide. For instance, in California, 99% of the approximately 10,200 ha in strawberry production in 1996 was treated with methyl bromide. In Florida, 94% of the approximately 16,200 ha in fresh market tomato production in 1996 was treated with methyl bromide (7). California has limits on the amount of 1,3-D that can be used in a township because of air-quality concerns. Increased 1,3-D demand in California caused by application in more cropping systems may force some growers to either change crops or pesticides where economically feasible because of imposed limits on use.

Table 3. Effect of fumigants on non-marketable carrot production (MT ha⁻¹)

Treatment ^x	Total non-marketable carrot weight ^w		Non-marketable carrot weight (no nematodes)		Non-marketable carrot weight (with nematodes)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Control	6.0 b ^y	19.7 ab	3.1 d	2.8 d	2.9 b	16.9 a
MB 112	10.3 b	15.3 abc	9.2 b	10.5 bc	1.1 b	4.8 bc
MB 224	7.1 b	20.7 a	6.5 bcd	18.1 a	0.6 b	2.6 c
MI 112	8.0 b	14.3 bc	6.8 bcd	10.9 b	1.2 b	3.4 bc
MI 168	10.8 b	14.8 abc	10.1 b	11.1 b	0.7 b	3.7 bc
MI 224	9.0 b	15.8 abc	8.5 bc	12.6 ab	0.5 b	3.2 c
MI 336	22.4 a	16.0 abc	22.0 a	12.1 b	0.4 b	3.8 bc
1,3-D	NT ^z	11.6 c	NT	5.0 dc	NT	6.6 b
MS	17.8 a	NT	4.7 cd	NT	13.1 a	NT

^w Sum of both non-marketable categories.

^x Fumigation with MB = methyl bromide and application rate (kg ha⁻¹); MI = methyl iodide and application rate (kg ha⁻¹); and MS = metam sodium.

^y Number within a column followed by different letters are significantly different based on least significant difference mean separation test, *P* < 0.05.

^z Not tested.

In conclusion, continued production of food at the quantity and quality level demanded by the public requires effective pest control options. This research has shown that methyl iodide is as effective as methyl bromide in controlling *M. incognita* in horticultural crop production. Registration of this compound would provide vegetable producers with a replacement for methyl bromide while reducing environmental concerns. In crop production areas that rely on fumigation for horticultural crop production, methyl iodide is a potential replacement for methyl bromide.

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