Evaluation of Soil Fumigants Applied by Drip Irrigation for *Liatris* Production

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ABSTRACT

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Cut-flower growers need alternatives to methyl bromide (MB) for pathogen and weed control. The efficacy of alternative chemicals applied by drip irrigation was tested in a cut-flower production system. In 2002, seven chemical formulations were tested: chloropicrin, iodomethane + chloropicrin, 1,3-dichloropropene + chloropicrin, sodium azide, metham sodium, furfural + allyl isothiocyanate, and furfural + metham sodium. In 2003, an additional treatment, dimethyl disulfide, was added. Most treatments reduced populations of *Pythium ultimum* and *Fusarium oxysporum* and increased stem height compared with the nontreated controls. Metham sodium, furfural + metham sodium, sodium azide, and chloropicrin significantly reduced incidence of *Liatris* stem rot caused by *Sclerotinia sclerotiorum*. Weed control was not acceptable either year for any treatments. Viable alternatives to MB for cut-flower production will require better treatments for weed control than was achieved in this study.

In 2002, California growers produced cut flowers and cut cultivated ornamental greens with a wholesale value of almost \$300 million. Crops were produced under 2,900 acres of covered area and on 8,500 acres of open ground (7). Nationally, the three top-valued cut-flower categories are lilies, roses, and tulips, with hundreds of other cut-flower crops also produced in California.

The broad-spectrum biological activity of methyl bromide (MB) when used with chloropicrin (CP) makes it a key production tool for the control of pathogens, weeds, and nematodes in ornamental production systems. The imminent MB phase-out will eliminate its use in these crops (5). These crops are very expensive to establish and bring to maturity, and growers require a tool such as MB:CP to reduce the risk of great financial loss that would result from a crop failure. Chemical companies have been reluctant to register herbicides for ornamental crops because of the relatively few acres involved and the high risk due to the crop value. Many ornamental crops have a relatively short growing period (less than 3 months) and, often, a grower will follow one crop with a different species or

plant multiple crops in a small area. This practice limits the products that might be used due to residual chemical effects and the high sensitivity of some ornamentals to these chemicals. Another important use of MB:CP for ornamental producers is control of volunteer plants from bulbs, tubers, or rhizomes left from the previous crop to maintain crop purity and reduce pathogen populations. After planting, an herbicide that controls the rogue bulb also could kill the crop, and fungicides for pathogens often are ineffective in storage tissues like bulbs, tubers, and rhizomes.

Testing of MB alternatives in ornamental production systems is in its infancy and only a few studies have been published. Preliminary tests, conducted in microplots, showed variable results (14), and subsequent field trials also were inconsistent (13). Recently, more promising results were obtained in a trial where the alternative chemicals were applied by drip irrigation on a single ornamental crop (16). Most of the alternative fumigants have lower vapor pressures and higher boiling points than MB:CP, reducing their movement through the soil when applied through traditional shank injection. Drip-irrigation systems are well suited for the delivery of alternative chemicals and may improve the distribution of the chemicals through the soil profile (3).

Alternative fumigants have been tested extensively in strawberry and vegetable crops (2,9,12,15,17–20). These studies have shown that compounds not traditionally thought of as efficacious for weed control, such as 1,3-dichloropropene and chloropicrin, have provided weed control as good as or better than MB when used in combination with each other or with a methyl isothiocyanate generator (2,10,11,

17–20,23). It is most probable that no one chemical will be found to replace MB, but combinations may be available that will.

Without MB:CP fumigation, cut-flower and bulb producers throughout the United States will face serious production limitations. Feasible alternatives to MB:CP are needed to ensure the continued existence of the industry. Competition from Central and South American producers has greatly impacted California producers. These foreign producers will not be affected by the MB phase-out for another 10 years (5). The loss of MB will increase production costs for U.S. growers and render them less competitive with the foreign producers. The objective of this study is to test the efficacy of MB alternative fumigants applied by drip irrigation, a practice termed chemigation (3), in a field-grown cut-flower production system.

MATERIALS AND METHODS

Site description. This study was carried out in Ventura County approximately 11 km southeast of Carpinteria, CA on a commercial flower field. The grower performed all field preparation, and planted and cultivated the crop of his choice, using normal methods. The field soil is Pico sandy loam (sand: 58%, silt: 25%, clay: 17%, organic matter: 1.7%). Plot design was a randomized complete block with six replications. Four 120-m-long beds (91 cm wide and 122 cm between bed centers) were used for the trial. Plots in each block were randomized across each of the beds. The 2002 trial had 8 treatments and each plot was 9 m in length; the 2003 trial had 12 treatments and each plot was 6 m in length. The trials were in the same field, approximately 50 m apart.

Fumigants and irrigation water were applied through four high-flow (5 liters/h/m) drip tapes (Ro-Drip #5-8-40; Roberts Irrigation Products, San Marcos, CA) per bed buried approximately 2 cm deep. Each tape was cut at the ends of each plot and connected to a water delivery manifold made with 9.5-mm (i.d.) polyethylene tubing with fittings at one end and sealed at the other end. Each of the manifolds from plots of like treatments was connected together with 21 mm of tubing so that there was one tube that emerged from the field for each treatment.

Chemigation. Each bed was covered with high-density polyethylene sheeting before chemigation (0.03-mm thickness). All rate calculations are based on the 91-cm bed width and the weight of active

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ingredients. The fumigant chemicals were applied through the drip irrigation tapes in water at 50 liter/m². The fumigants were injected and thoroughly mixed into the irrigation stream, then injected into the 21-cm polyethylene tubing by the method previously described (3). The chemical manufacturers formulated the chemicals with emulsifiers, except for the metham sodium and sodium azide formulations, both of which are sufficiently soluble in water. All rates listed are for active ingredients. The 2002 treatments were (i) iodomethane at 128 kg/ha plus chloropicrin at 299 kg/ha (Midas; Arvesta, San Francisco); (ii) chloropicrin at 337 kg/ha (Tri-Clor EC; TriCal Inc., Hollister, CA); (iii) 1,3-dichloropropene (1,3-D) at 369 kg/ha plus chloropicrin at 209 kg/ha (InLine; Dow AgroSciences, Indianapolis, IN); (iv) sodium azide at 112 kg/ha (SEP-100; American Pacific Inc. Las Vegas, NV); (v) metham sodium at 478 kg/ha (Vapam HL; AMVAC Chemical Inc., Los Angeles); (vi) furfural at 454 kg/ha plus allyl isothiocyanate at 152 kg/ha (Multiguard FFA Harborchem, Cranford, NJ); (vii) furfural at 337 kg/ha (Multiguard Protect Harborchem, Cranford, NJ) plus metham sodium at 337 kg/ha; and (viii) a nontreated water-only control. A standard MB:CP treatment could not be included in the trial because the small size of the plots precluded a shank application.

In an effort to improve weed control, the 2003 treatments were changed slightly and dimethyl disulfide (DMDS; Cerexagri Inc., King of Prussia, PA) was included. The 2003 treatments were (i) iodomethane at 213 kg/ha plus chloropicrin at 213 kg/ha, (ii) metham sodium at 356 kg/ha, (iii) chloropicrin at 355 kg/ha followed a week later with metham sodium at 356 kg/ha, (iv) 1,3-D at 153 kg/ha plus chloropicrin at 83.6 kg/ha, (v) the same 1,3-D-plus-chloropicrin treatment followed a week later with metham sodium at 178 kg/ha, (vi) the same 1, 3-D-plus-chloropicrin followed a week later with metham sodium at 356 kg/ha, (vii) sodium azide at 112 kg/ha, (viii) furfural at 674 kg/ha, (ix) furfural at 337 kg/ha plus metham sodium

at 337 kg/ha, (x) DMDS at 473 kg/ha, (xi) DMDS at 237 kg/ha plus chloropicrin at 237 kg/ha, and (xii) a nontreated water-only control. Each application required 140 min and was followed by a 30-min flush with irrigation water. The applications were made on 18 and 19 November 2002 and 7 November 2003.

Crop production. Two weeks following the chemical applications, the plastic mulch was removed. The plots were planted with corns of *Liatris spicata* (L.) cv. Callilepis (gay-feather) at a density of approximately 100 plants/m² on 30 December 2002 and 8 December 2003. Unlike most other crops, where many cultivars are planted together to provide a variety of color, *Liatris* was chosen because it is of a single cultivar and is grown on a large-enough area so that a trial of this size is possible. Harvest of the crops began on 21 April 2003 and 19 April 2004.

Soil sampling and soil fungal populations. Following removal of the plastic, five soil samples (2 cm in diameter) were collected from the surface 15 cm of each plot. The five samples were pooled and mixed, returned to the laboratory, and allowed to air dry at room temperature for 2 weeks. Populations of *Pythium ultimum* and *Fusarium oxysporum* were estimated in an attempt to determine the relative efficacy of each treatment in controlling soilborne fungal pathogens. Populations of *P. ultimum* were determined from these samples by the soil-drop technique (25) and populations of *F. oxysporum* were determined by dilution plating on Komada's medium (22).

Weed control. Weed populations were determined in the 2002 trial on 21 January 2003 and in the 2003 trial on 14 January 2004. Counts of weeds were made from the center square meter of each plot. When possible, all weed species were identified visually and counted separately. For the 2002 trial, all plots were hand weeded on 22 April 2003. The same field worker weeded all the plots within a block, and the weeding times were recorded to estimate the relative cost of hand weeding for each treatment. At the end of the season

for the 2003 trial, the percent of each plot covered by weeds was estimated.

Disease, crop vigor, and yield. Stem rot caused by *Sclerotinia sclerotiorum* appeared in the 2002 trial and counts of diseased plants in each whole plot were made on 19 March. No disease occurred in the 2003 trial; therefore, an estimate of vigor was made on 6 April 2004. On a continuous scale of 1 to 5, each plot was rated so that the least vigorous plot in the trial received a value of 1 and the most vigorous plot received a value of 5. Near the end of the season (22 April 2003 and 6 April 2004), stem length was estimated by averaging the height of five typical plants in the center square meter of each plot. Yield was estimated on the same dates by counting the number of inflorescences in the center square meter of each plot.

Data analysis. Analysis of variance was performed using the PROC GLM of the SAS software package (SAS Institute, Cary, NC) and means were separated according to Fisher's protected least significant difference for all data except for the disease data. These data were found to fit a negative binomial distribution and were analyzed by PROC GENMOD, and single degree-of-freedom contrasts were used to make specific comparisons between the control and all other treatments.

RESULTS

2002 trial. Most chemical treatments significantly reduced the populations of both *P. ultimum* and *F. oxysporum* compared with the control (Table 1). Populations of *F. oxysporum* were not significantly reduced by the iodomethane + chloropicrin treatment or the furfural + allyl isothiocyanate treatment (Table 1).

The most prevalent weeds were cheese-weed (*Malva* sp. L.), mustard (*Brassica* sp. L.), and knotweed (*Polygonum* sp. L.). None of the treatments controlled cheese-weed (Table 1). All treatments reduced mustard compared with the control, but populations were low overall. Knotweed, which was the most prevalent weed, was controlled to some extent by all the treatments except furfural + allyl isothiocy-

Table 1. Populations of *Pythium ultimum* and *Fusarium oxysporum* (CFU/g dry soil) in soil samples collected 2 weeks after treatment, mean number of weeds (per m²) counted in center square meter of each plot (3 weeks after planting), and average time (minutes) to hand weed each plot (4 weeks after planting) from the 2002 trial

Treatment	<i>P. ultimum</i>	<i>F. oxysporum</i>	<i>Malva</i> sp.	<i>Brassica</i> sp.	<i>Polygonum</i> sp.	Weeding time
Iodomethane + chloropicrin	52	1,159	13	1	70	52
Chloropicrin	0	1,000	12	2	168	82
1,3-Dichloropropene + chloropicrin	0	840	10	1	41	24
Sodium azide	0	790	9	2	108	55
Metham sodium	3	850	4	0	31	18
Furfural + allyl isothiocyanate	0	1,197	5	3	308	81
Furfural + metham sodium	0	433	10	1	59	20
Control	123	1,437	14	9	306	146
<i>P</i> value ^a	0.0015	0.0010	0.0830	0.0292	0.0002	<0.0001
LSD ^b	59	409	ns	5	132	30

^a *P* value obtained from the analysis of variance.

^b LSD = least significant difference; ns = not significant.

anate. Weeding times were less for all treatments compared with the control; the best were the metham sodium treatments with or without furfural (Table 1).

Stem rot incidence was less in the metham sodium with or without furfural, sodium azide ($P = 0.05$), chloropicrin, and chloropicrin + iodomethane ($P = 0.1$) plots compared with the control (Table 2). All treatments except for chloropicrin and furfural + allyl isothiocyanate had significantly taller plants than the control (Table 2). There were no significant differences between the mean numbers of inflorescences per plot, but the trend was that all treatments increased the numbers (Table 2).

2003 trial. Significant differences were observed for average *P. ultimum* populations among treatments in the 2003 trial (Table 3). The iodomethane + chloropicrin, chloropicrin + metham sodium, furfural + metham sodium, and metham sodium alone had the lowest *P. ultimum* populations. Furfural alone, sodium azide, DMDS + chloropicrin, and DMDS alone did not control *P. ultimum*. The soil assays showed that no treatments reduced the population of *F. oxysporum*, and the nontreated control actually had the lowest counts (Table 3).

Weed pressure was extremely heavy in this trial and over 15 weed species were

observed, with clover (*Trifolium* sp. L.), annual bluegrass (*Poa annua* L.), and cheese-weed being the most prevalent. In general, no significant differences were present between treatments and no treatment reduced weed populations compared with the control (Table 3). At the end of the season, no significant difference existed for percent weed cover as estimated visually (Table 4).

Plant vigor was greater for the iodomethane + chloropicrin, both 1,3-D + chloropicrin and 1,3-D + metham sodium, sodium azide, and furfural + metham sodium treatments than the nontreated control (Table 4). Average plant height was significantly greater for all treatments than the nontreated control, except for the two furfural treatments, 1,3-D + chloropicrin, metham sodium, and the DMDS alone treatment (Table 4). The average number of inflorescences was not significantly different among any of the treatments (Table 4).

DISCUSSION

All of the materials tested in the trials have lower vapor pressures than MB. The drip application method allows for a good distribution even with the low-vapor-pressure materials. The application process

is also a closed system, improving worker safety and reducing the risk of chemical exposure. A standard MB:CP treatment could not be included in the trial because the small size of the plots precluded a shank application. The best weeding time for the small plots in the 2002 trial (18 minutes for approximately 10 m²) indicates that the best treatment, as far as weed control, is far below what would be expected for MB:CP fumigation (24).

All of the treatments reduced the population of *P. ultimum* compared with the control. This was especially true in 2002, but was a clear trend in 2003. Although *F. oxysporum* is not a reported pathogen of *Liatris*, its population was measured as an indication of how well the fumigants controlled soilborne fungi. Most treatments reduced the population of *F. oxysporum* in the 2002 trial but not in the 2003 trial. The counts in the 2003 trial were highly variable, ranging from 122 to 4,033, but it is evident that this organism is more difficult to eliminate than *P. ultimum*, as has been reported previously (21). This will have to be considered by growers trying to control this fungus because of rotational crops that might be susceptible.

The occurrence of stem rot was somewhat of a surprise in the 2002 trial. The two treatments containing metham sodium and the sodium azide treatment were particularly good at controlling this disease. Previously, Adams et al. (1) reported that metham sodium killed 100% of sclerotia of *S. minor* in the laboratory and significantly reduced the incidence of lettuce drop in the field.

Weed control, although better the first year, was not adequate in either trial. Weed pressure was much greater in the second year and control was minimal. Treatments similar to the ones in this study have provided much better weed control in several strawberry trials (15). The weed population surrounding this trial site was very high and the lack of weed control in the 2003 trial could have been due to weed seed infesting the trial after the plastic

Table 2. Number of plants per plot affected by *Sclerotinia sclerotiorum*, average height (cm) of plants, and number of inflorescences per square meter at harvest from the 2002 trial

Treatment	Disease ^a	Height	No. of inflorescences
Iodomethane + chloropicrin	1.9*	66	90
Chloropicrin	1.8*	57	80
1,3-Dichloropropene + chloropicrin	3.5	67	82
Sodium azide	0.3**	60	83
Metham sodium	0.0**	62	89
Furfural + allyl isothiocyanate	3.1	58	83
Furfural + metham sodium	0.5**	66	90
Control	5.0	52	79
<i>P</i> value ^b	0.0034	0.0003	0.7335
LSD ^c	...	6	ns

^a Data were analyzed by PROC GENMOD and single degree-of-freedom contrasts were used to make specific comparisons between the control and all other treatments. Values followed by * and ** are significantly different from the control at the $P = 0.1$ and 0.05 level, respectively.

^b *P* value obtained from the analysis of variance.

^c LSD = least significant difference; ns = not significant.

Table 3. Populations of *Pythium ultimum* and *Fusarium oxysporum* (CFU/g dry soil) in soil samples collected 2 weeks after treatment and mean number of weeds (per m²) counted in center square meter of each plot 5 weeks after planting in the 2003 trial

Treatment	<i>P. ultimum</i>	<i>F. oxysporum</i>	<i>Trifolium</i> sp.	<i>Poa annua</i>	<i>Malva</i> sp.	Total weeds
Iodomethane + chloropicrin	0	1,113	16	8	14	78
Chloropicrin + metham sodium	1	1,217	22	5	9	50
1,3-Dichloropropene (1,3-D) + chloropicrin	8	1,205	23	2	13	109
1,3-D + chloropicrin + metham sodium (178 kg/ha)	7	1,559	44	1	12	112
1,3-D + chloropicrin + metham sodium (356 kg/ha)	21	1,420	40	2	16	172
Sodium azide	40	1,900	21	23	11	139
Metham sodium	5	1,160	39	2	12	90
Furfural	53	775	53	68	12	128
Furfural + metham sodium	2	749	26	6	19	219
Dimethyl disulfide	57	620	39	46	10	95
Dimethyl disulfide + chloropicrin	34	1,489	54	9	21	154
Control	59	562	43	10	7	78
<i>P</i> value ^a	0.0023	0.3515	0.0750	0.0003	0.0795	0.1643
LSD ^b	37	ns	ns	30	ns	ns

^a *P* value obtained from the analysis of variance.

^b LSD = least significant difference; ns = not significant.

Table 4. Percent weed cover, average height (cm) of plants, vigor rating (1 to 5), and number of salable inflorescences (No. of inflor.) per square meter from the 2003 trial^a

Treatment	Weed cover (%)	Vigor	Height	No. of inflor.
Iodomethane + chloropicrin	16	3.8	93	70
Chloropicrin + metham sodium	22	3.1	93	71
1,3-Dichloropropene (1,3-D) + chloropicrin	23	3.4	92	63
1,3-D + chloropicrin + metham sodium (178 kg/ha)	44	3.9	93	70
1,3-D + chloropicrin + metham sodium (356 kg/ha)	40	3.9	96	62
Sodium azide	21	3.8	95	62
Metham sodium	39	3.1	92	63
Furfural	53	3	86	69
Furfural + metham sodium	26	3.7	91	71
Dimethyl disulfide	39	3.1	89	65
Dimethyl disulfide + chloropicrin	54	3.3	93	59
Control	43	3.0	88	65
<i>P</i> value ^b	0.1003	0.0031	0.0001	0.7367
LSD ^c	ns	0.6	4	ns

^a All data collected near harvest.

^b *P* value obtained from the analysis of variance.

^c LSD = least significant difference; ns = not significant.

mulch was removed. It is common for cut-flower growers to use farm labor to perform hand weeding. This study shows that weeding time can be greatly reduced, compared with the nontreated control, with alternative chemicals applied through drip irrigation, but the shortest weeding time, 18 min for 9 m of bed length, would still be too expensive for production of this crop. In several treatments in the 2003 trial, metham sodium was applied 7 days after the initial treatment in an effort to improve weed control, but this measure did not improve the results. Fennimore et al. (15) previously reported no additional weed control with sequential applications of metham sodium, but Ajwa and Trout (2) reported that this approach produced the yield of strawberry equivalent to standard MB:CP fumigation. Yield was not significantly increased by any treatment in these studies; however, the increase in plant height, because of longer stems, might affect crop value.

Although the results look promising for disease control, only metham sodium, chloropicrin, and 1,3-D are labeled at this time. The 1,3-D + chloropicrin rate used in the 2002 study, if calculated on the 122-cm row spacing, would be a label rate for strawberry. The rates of these products used in the 2003 trial were the label rates calculated on bed treated area, and the results were not as good. If efficacy at higher rates can be demonstrated in cut-flower production systems, a special local-need label should be pursued for these crops. Field trials are underway with other ornamental crops to determine efficacious rates.

Iodomethane lacks registration at this time. In these studies, the compound was tested in combination with chloropicrin and this is how the material is expected to be used if and when registration is granted. Over the years, California strawberry growers, the largest users of MB (6), have changed the formulation of MB:CP from a

75:25 ratio to 55:45 ratio as a means of reducing cost as the price of MB has increased (8). It is expected that the price of iodomethane will be greater than that of MB; therefore, so we tested a 33:67 ratio of iodomethane:chloropicrin the first year and a 50:50 ratio the second year. Both of these formulations are being considered for development (4). The rate of iodomethane in the 50:50 ratio is greater than the MB rate now being used by California strawberry growers (8). This formulation probably would be the choice of most growers, but it may not be affordable.

From these results, it appears that several of the alternatives tested could be used for disease control in this flower crop, but weed control is lacking. Additional benefit might be obtained by pre-irrigating several days before treatment so that weed seed would have germinated, or by using virtually impermeable film mulch. Both of these approaches are possible with the drip-applied fumigants.

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