

Chloropicrin effect on weed seed viability

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Abstract

Chloropicrin is a potential replacement for methyl bromide as a preplant soil fumigant. Its weed control efficacy was evaluated in a laboratory dose–response study and in a commercial strawberry field. Laboratory studies found that an increase in chloropicrin concentration and exposure time reduced the percentage of viable *Stellaria media* (L.) Mill., *Portulaca oleracea* L. and *Polygonum aviculare* L. seed. Chloropicrin applied to the field at 83, 110, 138, 165 and 220 kg/ha reduced the percentage of viable *P. aviculare*, *P. oleracea* and *S. media* seed. The seed of *Malva parviflora* L. and *Erodium cicutarium* (L.) L'Her was not affected. Metam sodium applied at 4681/ha after chloropicrin improved weed control compared to chloropicrin alone. Standard polyethylene or virtually impermeable tarpaulin was used to cover beds after fumigation. The type of tarpaulin resulted in only a small reduction in the percentage of viable *M. parviflora* seed.

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1. Introduction

Preplant soil fumigation with methyl bromide and chloropicrin has been used widely around the world to control the soil-borne pests of many vegetable, fruit, nut and nursery crops. Much of the methyl bromide used for soil fumigation escapes into the atmosphere (Wang and Yates, 1998; Yagi et al., 1993) where it contributes to ozone depletion (Albritton et al., 1998). Concern for the atmospheric ozone layer led 160 nations to agree to a phase-out of methyl bromide use in developed countries by 2005 and in developing countries by 2015 (US Department of Agriculture, 2000). The loss of methyl bromide could have a severe negative economic impact on growers and consumers. The largest users of methyl bromide in the US are strawberry (*Fragaria* × *ananassa* Duch.), tomato (*Lycopersicon esculentum* Mill.) and bell pepper (*Capsium annuum* L.) growers. These crops account for approximately 30%, 19% and 14%, respectively, of US annual methyl bromide consumption (US Department of Agriculture, 2000). The National

Center for Food and Agriculture Policy estimates the potential annual loss to US strawberry producers and consumers at over 100 million dollars a year (US Department of Agriculture, 2000). While many of the crops that depend on methyl bromide are considered minor parts of the agricultural economy they are economically important on a regional basis (Wilhelm and Paulus, 1980). One of these regions is the state of California where half of the US methyl bromide is used and half of the strawberry crop grown (US Department of Agriculture, 2001).

As the phase-out nears completion the need for methyl bromide replacements grows more urgent. In California three fumigants are registered and available for use: chloropicrin, metam sodium and 1,3-dichloropropene (1,3-D) (Ajwa and Trout, 2000). Non-chemical alternatives to methyl bromide such as solarization, organic amendments or biocontrol agents are currently not viable replacements for fumigation for the vast majority of growers (Hartz et al., 1993; Smith et al., 2001) and compounds such as 3-bromopropene (propargyl bromide) and iodomethane are potential replacements not yet commercially available. Each of the registered options has advantages and disadvantages, and none is likely to serve as a complete replacement for

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methyl bromide (Shaw and Larson, 1999). 1,3-D is regarded as effective on nematodes, but weak on weeds and fungi (Himelrick and Dozier, 1991). In California use of 1,3-D is restricted because of air quality and health concerns (Carpenter et al., 2001). Metam sodium has several advantages: it is cost effective, active on a broad spectrum of soil-borne pests (Adams et al., 1983; Teasdale and Taylorson, 1986), does not harm the ozone layer, is easily applied through drip irrigation systems (Ajwa and Trout, 2000) and eventually degrades to harmless products in the soil (Smelt and Leistra, 1974; Gerstl et al., 1977). However, the initial breakdown product and active agent, methylisothiocyanate, is a potential surface and ground water pollutant. The EPA has classified metam sodium as a probable human carcinogen and it appears on the state of California's list of harmful chemicals (Proposition 65) (CADPR, 2001). Among the currently available alternatives to methyl bromide, chloropicrin has the fewest obstacles and is likely to be used extensively in the future. It is affordable and because it has long been applied in combination with methyl bromide means that applicators are familiar with this compound. Chloropicrin does not deplete the ozone layer and degrades rapidly in the soil and atmosphere into environmentally benign products (Gan et al., 2000; Castro and Belser, 1981). Chloropicrin is generally regarded as effective on fungal pests, but less effective on nematodes and weeds than methyl bromide (Himelrick and Dozier, 1991; Noling and Becker, 1994). The literature is mixed with regard to the weed control efficacy of chloropicrin. Low rates provided poor control of purple (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.) (Locascio et al., 1997). Harris (1990) found that a 112 kg/ha treatment resulted in more weeds than an untreated control or a higher, 448 kg/ha, rate. Csinos et al. (2000) reported that 92 kg/ha controlled a number of weeds as well as methyl bromide including volunteer peanut (*Arachis hypogaea* L.), common chickweed, Carolina geranium (*Geranium carolinianum* L.), purple cudweed (*Gnaphalium purpureum* L.), dog fennel (*Eupatorium capillifolium* (Lam.) Small) and (*Oenothera laciniata* Hill.).

Weed control will be an important consideration for any methyl bromide replacement. In strawberry, weeds lower yield through competition and serve as alternate hosts of insect, disease and nematode pests (Chandler, 1990; Himelrick and Dozier, 1991). Although chloropicrin has been used as a soil fumigant for more than 40 years, few studies have evaluated its weed control efficacy. The development of fumigant systems based on chloropicrin alone will require information such as the minimum time of exposure and the effective concentration for weed control. Our first objective was to evaluate the weed control efficacy of chloropicrin alone and in combination with metam sodium under standard film or virtually impermeable film (VIF) under

field conditions. During fumigation the soil is covered with a polyethylene tarpaulin which retains the fumigant in the soil. VIF is a recent innovation made of polyethylene with additional layers of ethylene vinyl alcohol, nylon or polyamides (Wang et al., 1997; Gan et al., 2000). VIF is used to reduce the rate of fumigant emission and increase the effectiveness of fumigants and possibly allow lower concentrations to be used (Wang and Yates, 1998). A second objective was to characterize the response of weed seed to the concentration of chloropicrin and length of exposure. The rates and fumigation time needed for weed control can be based on the relationship between concentration and exposure time. This information can help establish the rates and exposure times needed for weed control and can be used to evaluate the effectiveness of new products and practices such as VIF or application of fumigants through the drip irrigation system.

2. Methods and materials

2.1. Field trials

A study was initiated October 1999 in a commercial field near Santa Maria, CA and repeated at the same location beginning in September 2000. Soil was a sandy loam with 69% sand, 25% silt, 6% clay, 0.6% organic matter and a neutral pH. Standard cultural practices for the area were followed. Raised beds were formed having a width of 107 cm at the top and a distance of 163 cm from center-to-center of adjacent beds. Drip irrigation lines with emitters spaced 30 cm apart and a flow rate of 5.01/h/m were buried 2–5 cm deep at 28 cm on either side of the bed center.

Seed of weeds common to strawberry were selected for study. *Portulaca oleracea* L., *Malva parviflora* L. and *Polygonum aviculare* L. were used in 1999 and 2000. *Stellaria media* (L.) Vill. and *Erodium cicutarium* (L.) L'Her were added in 2000. *S. media*, *M. parviflora* and *E. cicutarium* seed were purchased (Valley Seed Service, P.O. Box 9335, Fresno, CA 93791). *Portulaca oleracea* and *P. aviculare* seed were obtained from Salinas Valley, CA field weeds transplanted and grown in a greenhouse. Fifty seeds of each species were placed in a 7.6 × 15.2 cm² mesh bag (Delnet[®] Applied Extrusion Technologies Inc., 601 Industrial Drive, Middletown, DE 19709). Bags were heat sealed and a strip of flagging tape and a steel washer were attached to aid in relocation. Dormant seed was used to prevent germination before treatment and germination tests indicated that seed was >90% dormant. Approximately 24 h before fumigation samples were buried 5 cm deep at the center of each plot length and 23 cm from the center of each plot width. Sample location was chosen to avoid the shank path during fumigation.

Commercial formulations of fumigants were applied by shank injection or with water through the drip irrigation system. A commercial applicator injected chloropicrin (99% trichloronitromethane) at rates of 0, 82.5, 110, 137.5, 165 and 220 kg/ha and methyl bromide plus chloropicrin were mixed 67:33 (w/w) at 336 kg/ha. Fumigants were injected into the soil at a depth of 20 cm through three shanks spaced 38 cm apart. One of two types of plastic tarpaulin was placed over the soil during fumigation: (1) a standard (STD) clear polyethylene tarpaulin 0.032 mm thick (Omega Plastics, Mount Clemens, MI) or (2) a VIF 0.035 mm thick (Klerks Plastics, Belgium). Five days after shank injection, metam sodium (Vapam[®] HL, 42%) was applied through the drip irrigation system at a rate of 468 l/ha in a volume of 40 l/m² of irrigation water (Ajwa et al., 2002).

Seed samples were retrieved 2 weeks after metam sodium application. Seed was removed from bags, sorted by species and viability determined using a tetrazolium assay (Grabe, 1970). Seed was allowed to imbibe on filter paper, Whatman[®] no. 1, moistened with 1 ml of sterile deionized water in plastic Petri dishes (15 mm in height and 100 mm in diameter). Petri dishes were sealed with parafilm[®] and placed in a germination cabinet at 21°C in darkness for 20–24 h. Imbibed seed was cut with a scalpel and placed in another Petri dish, cut side down, on filter paper moistened with 1 ml of a 0.1% (w/v) 2,3,5-tetrazolium chloride solution. Petri dishes were sealed again with parafilm and returned to the germination cabinet for another 20–24 h, and then evaluated under a microscope for staining of the embryo.

The experimental design was a split-split-strip plot with three replications. Main plots measured 61 m long and 13 m wide and were either treated or not treated with metam sodium. Main plots were divided into eight strips measuring 1.6 m wide and 61 m long. Each strip was treated with chloropicrin, methyl bromide plus chloropicrin or remained untreated. One half of the length of each strip was covered with STD polyethylene tarp, the other half with VIF. Data were subjected to analysis of variance (ANOVA) using SAS mixed procedure (Littell et al., 1996). Significant interaction between treatments and year was not found and data were pooled. Mean separation was accomplished with paired *t*-tests at the *P* = 0.05 level of significance.

2.2. Laboratory dose-response

The response of weed seed to chloropicrin dosage was tested in the laboratory. Twenty-five seed of the same five weed species tested in the field were placed in plastic mesh bags cut to 6.5 cm² in size and heat sealed. Seed samples were placed in half-pint (236.5 ml) canning jars filled with a moist soil mixture. The soil was a 1:1 (v/v)

mixture of topsoil (49% sand, 34% silt, 17% clay, 2.5% organic matter and pH 8.0) and finely chipped redwood (redwood soil conditioner, Sun Land Garden Products Inc., 90 Pioneer Road, Watsonville, CA 95706). Oven dried soil and redwood were autoclaved for 1 h at 122°C and 1.4 kg/cm² pressure, then adjusted to 14% (w/w) moisture with deionized water. Percentage soil moisture was selected based on methods described by Zhang et al. (1998). Preliminary studies indicated that dry seeds of *S. media*, *P. oleracea* and *P. aviculare* were not sensitive to chloropicrin, but seed saturated with water was sensitive. Seed of *M. parviflora* and *E. cicutarium* was not sensitive dry or wet (data not reported). Samples were buried 2.5 cm below the jar top, jars were closed with canning lids and seed was allowed to imbibe for 24 h at room temperature (25 ± 1°C). Jars were opened, chloropicrin was added by syringe at the bottom then jars were immediately sealed with a new lid.

The commercial formulation of chloropicrin was used to achieve final concentrations of 40, 100, 200, 300, 400, 1000, 2000, 3000, 4000 or 6000 µM in each jar. These rates correspond to field applied rates of 11.2, 28.0, 56.0, 84.1, 112.1, 280.2, 560.4, 840.6, 1120.8 and 1681.2 kg/h. Jars were opened under a fume hood after 0, 1.5, 3, 6, 12, 24, 48, 60 and 72 h and allowed to aerate for 12 h. Seed packets were then removed, seed was sorted by species and viability tested as described above. Dose-response data were subjected to probit analysis using SAS probit procedure (SAS Institute, 1989). The fitted probit curves were used to estimate the time required for a chloropicrin concentration to reduce seed viability by 50 (LD₅₀) or 90 (LD₉₀) percent. A separate curve was fitted for each chloropicrin concentration with percentage viable seed the dependent variable and time of exposure the independent variable. The relationship between chloropicrin concentration and LD₅₀ was described using SAS regression procedure (Littell et al., 1991).

3. Results

3.1. Field trials

Metam sodium reduced the percentage of viable *P. aviculare*, *P. oleracea* and *S. media* seed, but did not affect the viability *E. cicutarium* or *M. parviflora* seed (Table 1). Without metam sodium, the percentage of viable seed was 36.4% for *P. aviculare*, 20.0% for *P. oleracea* and 33.7% for *S. media*. With the addition of metam sodium viable seed was reduced to 2.7%, 0.3% and 0.1%, respectively.

Species sensitive to metam sodium were also sensitive to chloropicrin (Table 2). The percentage of viable *P. aviculare*, *P. oleracea* and *S. media* seed was lower for chloropicrin treated seed compared to seed untreated

Table 1
Effect of 468 l/ha of metam sodium on percentage of viable weed seed^a

Treatment	<i>Erodium cicutarium</i>	<i>Malva parviflora</i>	<i>Polygonum aviculare</i>	<i>Portulaca oleracea</i>	<i>Stellaria media</i>
Metam sodium	92.6 ^b a	74.3 a	2.7 b	0.3 b	0.1 b
No metam sodium	94.9 a	79.7 a	36.4 a	20.0 a	33.7 a

^aMeans are averaged over sub-plot and sub-sub-plot effects.

^bTreatment means separated with pair-wise *t*-tests ($P = 0.05$). Means within a column followed by the same letter do not significantly differ.

Table 2
The effect of chloropicrin and methyl bromide plus chloropicrin on the percentage of viable weed seed^a

Fumigant	Rate (kg/ha)	<i>Erodium cicutarium</i>	<i>Malva parviflora</i>	<i>Polygonum aviculare</i>	<i>Portulaca oleracea</i>	<i>Stellaria media</i>
Chloropicrin	0	94.5 ^b a	78.8 a	48.6 a	45.4 a	48.3 a
	83	93.9 a	76.9 a	29.6 ab	9.4 b	8.5 bc
	110	93.8 a	76.7 a	19.7 b	7.1 b	14.9 bc
	138	94.4 a	74.0 a	21.0 b	5.9 b	29.8 ab
	165	94.0 a	77.6 a	4.6 bc	2.0 b	0.0 c
	220	93.0 a	77.8 a	13.8 b	0.6 b	16.3 bc
Methyl bromide + chloropicrin	336	92.7 a	77.4 a	0.0 c	0.7 b	0.2 c

^aMeans are averaged over main and sub-sub-plot effects.

^bTreatment means separated with pair-wise *t*-tests ($P = 0.05$). Means within a column followed by the same letter do not significantly differ.

with chloropicrin. Chloropicrin alone or with methyl bromide did not affect the viability of *M. parviflora* or *E. cicutarium* seed. The percentage of viable *P. aviculare* seed was reduced by chloropicrin at rates of 110 or more kg/ha, but the level of control, except for the 165 kg/ha treatment, was less than that achieved by the methyl bromide plus chloropicrin mixture. Chloropicrin at rates of 83–220 kg/ha reduced *P. oleracea* seed to $\leq 9.4\%$ viable, compared to 45.4% for seed untreated with chloropicrin. The level of *P. oleracea* control achieved with chloropicrin did not differ from the standard methyl bromide and chloropicrin treatment. The percentage of viable *S. media* seed was reduced by all but the 138 kg/ha treatment. With the exception of this rate, chloropicrin did not differ from the methyl bromide plus chloropicrin treatment.

The effect of metam sodium on *M. parviflora* differed between the types of tarpaulin. Metam sodium affected viability of *M. parviflora* seed under VIF, but not under STD (Table 3). Interaction between chloropicrin and metam sodium was found for *P. aviculare*, *P. oleracea* and *S. media* seed. Application of chloropicrin followed by metam sodium was more effective than chloropicrin alone. When metam sodium was applied, the low rates of chloropicrin were as effective as the high rates (Table 4).

3.2. Chloropicrin dose-response

The time required to kill 50% or 90% of weed seed was estimated for each chloropicrin concentration. As concentration and exposure time increased the percentage of viable seed decreased (Table 5). *S. media* and *P.*

Table 3
Effect of metam sodium and film type on the percentage of viable *Malva parviflora* seed. Two types of tarp were used to cover the soil: (1) standard (STD) polyethylene and (2) VIF^a

Metam sodium (l/ha)	Tarp type	Viable seed (%)
0	VIF	81.3 ^b a
0	STD	78.1 ab
468	VIF	73.2 b
468	STD	75.4 b

^aMeans are averaged over sub-plot effects.

^bTreatment means separated with pair-wise *t*-tests ($P = 0.05$). Means within a column followed by the same letter do not significantly differ.

Table 4
The effect of metam sodium and six rates of chloropicrin on the percentage of viable weed seed^a

Metam sodium (l/ha)	Chloropicrin (kg/ha)	<i>Polygonum aviculare</i>	<i>Portulaca oleracea</i>	<i>Stellaria media</i>
0	0	97.1 ^b a	90.5 a	96.7
0	83	58.6 b	18.7 b	17.0 cd
0	110	39.4 bc	14.2 bc	29.4 bcd
0	138	32.5 bcd	11.8 bc	59.7 b
0	165	0.8 e	3.8 c	0.0 d
0	220	26.3 cde	0.9 c	32.7 bc
468	0	0.2 e	0.4 c	0.0 d
468	83	0.4 e	0.1 c	0.0 d
468	110	0.0 e	0.0 c	0.5 d
468	138	9.5 de	0.1 c	0.0 d
468	165	0.1 e	0.3 c	0.0 d
468	220	0.1 e	0.2 c	0.0 d

^aMeans are averaged over sub-sub-plot effects.

^bTreatment means separated with pair-wise *t*-tests ($P = 0.05$). Means within a column followed by the same letter do not significantly differ.

Table 5
Mean time (\pm SE) required to achieve LD₅₀ or LD₉₀ percent of weed seed for several concentrations of chloropicrin (μ M)

Chloropicrin (μ M)	<i>Portulaca oleracea</i>		<i>Stellaria media</i>		<i>Polygonum aviculare</i>	
	LD ₅₀ (h)	LD ₉₀ (h)	LD ₅₀ (h)	LD ₉₀ (h)	LD ₅₀ (h)	LD ₉₀ (h)
100	28.1 (\pm 22.1)	112.3 (\pm 70.1)	—	—	—	—
150	19.0 (\pm 4.5)	50.5 (\pm 12.1)	59.8 (\pm 19.6)	—	—	—
200	10.8 (\pm 3.3)	35.5 (\pm 10.9)	23.4 (\pm 6.6)	111.1 (\pm 41.6)	—	—
500	<1.5	<1.5	1.8 (\pm 0.7)	8.0 (\pm 2.2)	—	—
1000	<1.5	<1.5	<1.5	<1.5	11.3 (\pm 2.4)	27.5 (\pm 6.7)
1500	<1.5	<1.5	<1.5	<1.5	6.9 (\pm 1.7)	19.9 (\pm 5.8)
2000	<1.5	<1.5	<1.5	<1.5	6.0 (\pm 0.6)	14.0 (\pm 1.9)
3000	<1.5	<1.5	<1.5	<1.5	3.0 (\pm 0.4)	8.1 (\pm 1.3)

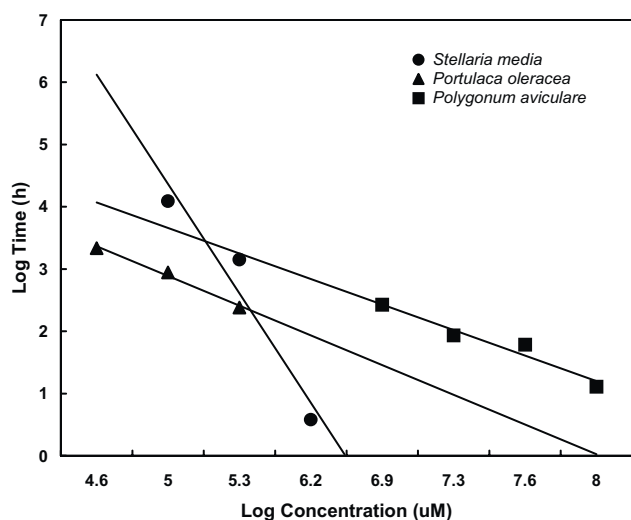


Fig. 1. Log fumigation time (h) and log chloropicrin concentration (μ M) required achieve LD₅₀ for *Polygonum aviculare*, *Portulaca oleracea* and *Stellaria media* seed. Parameters for the regression: *S. media*, $y = 7.8771 - 1.7566x$; *P. oleracea*, $y = 3.8419 - 0.4771x$ and *P. aviculare*, $y = 4.4775 - 0.4098x$.

oleracea were more sensitive than *P. aviculare*. The lowest concentration to kill 50% of the seed in 72 h of exposure was 100 μ M for *P. oleracea*, 150 μ M for *S. media* and 1000 μ M for *P. aviculare*. Rates of 500 and 1000 μ M killed 90% of *P. oleracea* or *S. media* seed, respectively, in less than 1.5 h. The relationship between concentration and LD₅₀ time for each species was described by linear regression (Fig. 1). Parameters for the linear regression model are $y = 4.4775 - 0.4098x$ for *P. aviculare*, $y = 3.8419 - 0.4771x$ for *P. oleracea* and $y = 7.8771 - 1.7566x$ for *S. media*.

4. Discussion

The seed of different weed species varied in sensitivity to the treatments. *Polygonum aviculare*, *P. oleracea* and *S. media* were sensitive to chloropicrin and metam sodium, but *E. cicutarium* and *M. parviflora* were not.

Malva parviflora and *E. cicutarium* are also known to survive methyl bromide fumigation (Agamalian et al., 1994; Smith et al., 2001). Seed coat hardness and impermeability are thought to be primarily responsible for resistance to fumigation (Egley, 1986), although other seed tissues or metabolism could be involved. Our study found *P. oleracea* seed to be very sensitive to chloropicrin and metam sodium, but Zhang et al. (1997) found *P. oleracea* to be among the most resistant seeds to fumigation with iodomethane or methyl bromide. Differences between the studies may be due to the type of fumigant or the variety of *P. oleracea*. We suspect based on the source that *P. oleracea* seed used by Zhang et al., was a vegetable variety while we used a weedy variety.

Correlation between chloropicrin rate and effect was not apparent in field trials. Chloropicrin reduced the percentage of viable seed, but was not consistently effective even at the highest rates. Field application may not be as precise as desired, or the range of rates may not have been wide enough to cause different results. Because we were interested in the benefits of a supplemental metam sodium application and VIF, the rates tested in this study were below the label maximum of 336–560 kg/ha. It is possible that higher rates of chloropicrin may be more effective on weeds. The metam sodium alone or in combination with chloropicrin provided consistent and effective control of weed seed. If the disease control properties of chloropicrin are effective at lower rates than those required for weed control, it may be appropriate to choose the dose based on disease and nematode control needs and add metam sodium for weed control.

The only observed effect of tarpaulin type was in the form of an interaction with metam sodium on *M. parviflora* seed. The reduction in the percentage of viable seed, while significant, is not low enough to be considered an effective treatment. VIF should offer a benefit to weed control because it retains the fumigant in the soil giving it more time to work. The lack of a benefit for VIF in this study may be due to the sensitivity of weed seeds or the short half-life of chloropicrin in the

soil. Sensitive seeds were killed without VIF and the additional exposure time provided by VIF did not affect insensitive seed. The average half-life of chloropicrin in soil is approximately 1 day and the benefit of retaining chloropicrin may be small relative to the rate at which chloropicrin is broken down (Ajwa et al., 2002).

Results of the dose response study suggest that less than the label maximum rate of chloropicrin is needed to effectively kill *S. media* or *P. oleracea* seed, and that the maximum label rate is required to kill *P. aviculare* seed. Relative sensitivity of species to chloropicrin is expressed by the strength of the concentrations that resulted in LD₅₀ and LD₉₀ values and in the relationship between concentration and LD₅₀ time. Comparison of slopes for regression lines that describe this relationship indicates that *P. oleracea* and *P. aviculare* are less sensitive to changes in chloropicrin concentration than *S. media*. The relationship between iodomethane or methyl bromide concentration and LD₅₀ time for *Lolium multiflorum* L. has been reported to have slopes of -0.89 and -0.87 (Zhang et al., 1998); indicating a level of sensitivity intermediate to that found for the seed used in this study to chloropicrin.

Results of field studies suggest that chloropicrin in combination with drip applied metam sodium offers the growers of strawberry and other crops that rely on fumigation a method of weed control equivalent to that obtained by methyl bromide. At the rates tested, chloropicrin reduced the percentage of viable seed, but not always to a level that can be considered effective control. Drip applied metam sodium was very effective on weed seeds. If chloropicrin is more effective on soil-borne diseases than metam sodium, then a combination of chloropicrin and metam sodium may be an effective method of pest control.

Efficacy can vary depending on soil type and soil moisture. In general, fumigants are more effective in coarser soils (Munnecke and Van Grundy, 1979). Seeds and fungi are more sensitive to fumigants when moist (Piecarka and Warren, 1959; Munnecke and Van Grundy, 1979; Zhang et al., 1998). Moisture content may be even more important for chloropicrin efficacy than for methyl bromide (Munnecke et al., 1982). The importance of moisture in seed sensitivity may be a benefit of the drip irrigation method of application. It is possible that the efficacy of metam sodium observed in the field is due in part to its application in water.

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