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Evaluation of Propargyl Bromide as a Soil Fumigant

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Abstract. **The cut flower and bulb industry in California is an important part of the state's agricultural economy and it has relied heavily upon the use of methyl bromide as a treatment to control soil-borne pests. With the phase out of methyl bromide, it is important to develop alternatives that will maintain crop productivity. This report describes research testing the efficacy of propargyl bromide against selected nematode, fungal, and weed species. Three sites were selected in California to represent different soil types and environments. Propargyl bromide was applied to soil in large, buried containers at rates ranging from 28 to 168 kg·ha^{-1} and compared with standard soil fumigants. The citrus nematode (*Tylenchulus semipenetrans* Cobb) and an isolate of *Fusarium oxysporum* Schlechtend:Fr were both controlled at the lowest rate of propargyl bromide tested: 28 kg·ha^{-1}. Weed species varied greatly in their sensitivity to propargyl bromide. A 100% reduction in common purslane (*Portulaca oleracea* L.) and pigweed (*Amaranthus retroflexus* L.) germination occurred at 112 kg·ha^{-1} propargyl bromide, regardless of geographical location. Results for annual bluegrass (*Poa annua* L.) control were more variable across locations and years, but more than 90% control was consistently achieved with 168 kg·ha^{-1} propargyl bromide. Cheeseweed (*Malva parviflora* L.) and field bindweed (*Convolvulus arvensis* L.) were never consistently controlled by propargyl bromide. When compared with the soil fumigants methyl bromide, iodomethane, and metam sodium, propargyl bromide provided comparable control of all soil-borne pests, but at much lower rates. Although higher rates of propargyl bromide, more than 112 kg·ha^{-1}, were needed to control weeds, these rates still were almost half that required of the other standard fumigants.**

The California floriculture industry is a large and important component of the state's agricultural economy, with a reported value of about $1 billion in 2004 [U.S. Department of Agriculture–National Agricultural Statistics Service (NASS)]. In California, floriculture crops are grown on ≈2900 acres of covered land and 8000 acres of open ground. Cut flowers and bulbs are high-value crops that require large expenditures of capital to establish and bring to commercial maturity. The cut flower and bulb industry has relied heavily upon the use of methyl bromide/chloropicrin (MBC) as a key soil treatment for crop production. It has been used as a preplant fumigant to control soil-borne fungi, nematodes, bacteria, and weeds, as well as to kill the soil-borne remnants of previous crops (e.g., bulbs) that can sprout and contaminate the next crop.

The ozone depletion potential of methyl bromide has resulted in the phase-out of this chemical except for a few specific uses. Without methyl bromide, or an equally efficacious alternative, cut flower and bulb producers face potentially serious production limitations. It is extremely important that alternatives be developed to manage the pests formerly managed by methyl bromide. However, because of the diversity of the crops represented and the comparatively small acreage involved, the floriculture industry has received inadequate methyl bromide alternative research compared with other crops. Furthermore, although it is too soon to know, there are concerns that floricultural crops will not compete favorably against large-acreage crops for alternate materials like 1,3-dichloropropene, which have "township caps" limiting their use within geographical areas.

Propargyl bromide is one of many compounds being considered as a methyl bromide alternative (Allaire et al., 2005; Ma et al., 2001; Schneider et al., 2006). In 1957, Dow Chemical Company was granted a patent for propargyl bromide as a soil fumigant. However, it subsequently was taken off the market because of unstable handling characteristics. The handling characteristics of propargyl bromide continue to be a challenge for its commercialization. However, its physical properties make it attractive as a soil fumigant because it moves readily through soil, has a short soil degradation time, has strong biocidal properties, and does not have ozone-depleting characteristics (Yates and Gan, 1998). In the midlate 1990s, it was suggested that propargyl bromide should be revisited as a viable methyl bromide alternative, and the U.S. Department of Agriculture decided to sponsor research that would evaluate the efficacy and environmental fate of the chemical used as a soil fumigant. This research was undertaken as part of the efficacy testing and sought 1) to evaluate propargyl bromide against a diversity of soil-borne pests, 2) to determine propargyl bromide efficacy in three different geographical environments, and 3) to compare propargyl bromide with MBC, iodomethane, and metam sodium.

Materials and Methods

The handling of soil-borne organisms was identical for all experiments. Soil-containing nematodes, fungal spores, or weed seeds was placed in 3.8 × 7.6-cm sachets made of 40-mesh nylon cloth. The sachets were sealed closed with hot glue and had a length of colored nylon string attached to denote the intended depth of placement in the plot (5, 15, or 30 cm).

Nematode. Five grams of soil infested with mixed stages of the citrus nematode (*Tylenchulus semipenetrans* Cobb), collected from an olive orchard in Orland, CA, was placed in each sachet. Extra sachets were prepared for each field trial to quantify the number of nematodes per gram of soil before burial. Sachets were kept at 4 °C until use, usually within days. When sachets containing nematodes were recovered from field experiments, they were processed within 48 h of removal from field soil. Live nematodes were extracted by placing the sachets on a mesh support on a Baermann funnel for 72 h (Ingham, 1994). The total number of citrus nematodes retrieved per sachet was determined.

Fusarium. Inoculum of *Fusarium oxysporum* Schlechtend:Fr was prepared by streaking spores onto a series of potato dextrose agar plates. The plates were incubated

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at 25 °C under lights for 5 to 7 d until the fungus was actively growing and producing abundant spores. Plates were then flooded with sterile, distilled water, rubbed with a glass rod to dislodge spores, and the resulting spore suspension was decanted into a beaker. The concentration of spores in the resulting harvest solution was determined using a hemocytometer. A spore suspension containing 10^5 to 10^8 spores then was poured onto sterile field soil and mixed by hand. This process was repeated several times, after which the soil was allowed to air-dry slowly to promote the formation of chlamydospores as the surviving propagules. After drying, the soil was mixed thoroughly to achieve even distribution of inoculum, and the resulting inoculum level was determined by dilution plating to ensure that 10^4 to 10^5 colony forming units (cfu)/g of soil could be recovered. This stock soil was then stored in a cool, dry, dark place. Before placing soil into sachets for experimental use, several aliquots of the stored, infested soil were suspended in sterile water blanks and then pipetted onto agar media to verify that population levels were holding stable. Five grams of dry infested soil was added to each fungal sachet, and the sachets were prepared as described earlier. *Fusarium oxysporum* sachets were prepared several weeks before burial in pots and stored at 4 °C until use.

When sachets containing *F. oxysporum* were recovered from field experiments, they were initially air-dried on a laboratory bench for about 1 week, after which they were cut open with sterile scissors and the soil was placed in a plastic weigh boat in which any small clods were broken up using a surface-sterilized pestle. The dry, pulverized soil was then stored in a sealed, labeled glass vial at room temperature until assayed for viable propagules. Assays consisted of preparing serial dilutions that were then spread onto Petri dishes containing Komada's medium (Komada, 1975). Each soil solution was spread onto three series of plates. Plates were incubated at 25 °C under lights, and fungal colonies were counted at 3 and 6 d of incubation. The total number of *Fusarium* colonies that resulted was counted to provide an estimate of propagule survival.

Weeds. Seeds of field bindweed (*Convolvulus arvensis* L.), redroot pigweed (*Amaranthus retroflexus* L.), common purslane (*Portulaca oleracea* L.), annual bluegrass (*Poa annua* L.) and cheeseweed (*Malva parviflora* L.) (Valley Seed Co., Fresno, CA) were treated in a similar manner. Three samples of 100 seeds of each species were weighed to determine a mean weight per 100 seeds. Then, 100 seeds (by weight) of each species were placed individually into sachets, and were sealed and tagged as described earlier. When sachets containing weed seeds were removed from the field, they were cut open and the seeds were placed on a single sheet of moistened filter paper in a 100 × 15-mm plastic Petri dish. The filter paper was remoistened over time as needed. Dishes containing redroot pigweed, field bindweed, and common purslane were incubated at room temperature. Petri dishes containing annual bluegrass and cheeseweed were placed in a germinator at 30 °C and set to provide 8 h/16 h day/night lighting. Germinated seeds were counted and removed over a 2-week period. If the radicle was present, a seed was considered germinated. After 2 weeks, the ungerminated seeds were tested to determine their viability. Representative samples for each species were cut and treated with a 0.25% tetrazolium solution for 12 h. Seeds were then examined to determine whether staining occurred, indicating viability. This result also was compared with a squeeze test during which slight pressure was applied to seeds with tweezers. If a seed was hard, it was counted as viable; if soft, it was considered dead. These two methods were found to be comparable for field bindweed and cheeseweed.

Container experiments. Field experiments were done during 2000 and 2001 at three locations in California representing a range of climates and soil types. The soils were a Yolo loam (Davis, CA), 1.08% organic matter (OM), 42% sand, 40% silt, 18% clay; Elder sandy loam [Monterey Bay Academy (MBA), CA], 0.98% OM, 64% sand, 21% silt, 15% clay; and Watsonville silt loam (Watsonville, CA), 2.6% OM, 17% sand, 59% silt, 24% clay.

The experiments were carried out in large plastic pots (75 L) buried in the fields so that different fumigants could be tested in small plots without concern of lateral diffusion confounding the results of adjoining replicates (Fig. 1). The pots were installed by setting them into trenches cut in the soil with a backhoe. The pots were then placed in the trenches and the trenches backfilled around the pots, leaving ≈8 cm of the pot rim extended above the soil grade. After backfilling, soil was hand packed into the bottoms of the pots to form a layer 30 cm below soil grade. At this point, one set of sachets including citrus nematode, *F. oxysporum*, and each of the weed species was set in the pot on the surface of the packed soil, with labeled strings extending upward out of the pots. The sachets were then covered with more soil that again was added and packed until the level in the pots was 15 cm below grade. At this point, another set of sachets was laid in place, with strings and tags extending up out of the pot. More soil was then added and packed to bring the surface to 5 cm below grade, where the last layer of sachets was installed. These were capped with a final layer of soil that brought the soil in the pot up to the external grade level. As each soil layer was added, it was sprinkled lightly with water.

After installation of the test organisms and soil, all pots were irrigated by hand so that they all could drain and stabilize at about field capacity. Pots in "tarped" treatments were then covered with clear 1.1-mm-thick polyethylene tarp (Leco Industries, St. Laurent, Quebec) held in place by a heavy rubber strap stretched around the exposed lip of each pot. In all experiments, probes were installed at 5, 15, and 30 cm so that soil temperatures could be recorded at 10-min intervals with microloggers (Onset Computer Corporation, Pocasset, MA).

Fumigant application. At each geographical location, each chemical treatment was applied immediately after the placement of sachets in pot. The experimental design was a complete randomized block with four replications. The same treatments were applied at all three sites, and the experiments were repeated over 2 years. The treatments included 28, 56, 84, 112, and 168 kg·ha^{-1} propargyl bromide (90%; Albemarle Corp.,

Fig. 1. Experimental setup of container experiments testing the efficacy of propargyl bromide and other soil fumigants against soil-borne pests.

Baton Rouge, LA), 364 kg·ha^{-1} MBC (87%/33%; Dow AgroSciences, Indianapolis), 168 and 263 kg·ha^{-1} iodomethane (100%; Arvesta Corp., San Francisco), and 358 kg·ha^{-1} metam sodium (Amvac, Los Angeles). Tarped and "untarped" untreated controls were included.

Methyl bromide/chloropicrin was applied to a depth of 30 cm through the plastic from a pressurized cylinder. Propargyl bromide and iodomethane also were applied through the plastic to a depth of 30 cm using a gas-tight syringe with a stainless steel needle. Tape was applied to close the holes created in the plastic tarps by fumigant injection. In 2000, metam sodium was applied using a syringe and was injected from the surface into a 0.95-cm hole that extended down to the 30-cm depth. In 2001, one-third of the metam sodium dosage was applied at each of the 30-, 15-, and 5-cm depths, with different injection holes for each depth. Treated pots were left covered for 7 d, after which the plastic was removed. Pots were allowed to ventilate for 1 d before removal of the sachets. All retrieved sachets were immediately placed in an insulated plastic cooler and transported to the laboratory for analysis.

Statistical analyses. The percent reduction in the number of viable citrus nematodes was determined by comparing viable survivors with the number of viable nematodes recoverable from sachets before burial. The percent reduction in viable *Fusarium* propagules was expressed as a percentage of the numbers recovered from treated plots relative to the numbers recovered from the untarped, untreated controls. The percent reduction in viable weed seeds was determined by counting the numbers of seeds (out of 100) that failed to germinate or that tested negative for viability. Differences in pest survival among amendment treatments were determined by a ranked analysis of variance, and means were separated by Tukey's adjustment for multiple comparisons ($P < 0.05$). Data were log transformed, when appropriate, to meet the assumptions of normality and homogeneity of variance (SAS, Cary, NC).

Results

While carrying out these experiments, we found that the survival results from the 5-cm depth could not be used reliably to compare fumigant treatments. This was because at all sites, the tarping treatment alone caused soil temperatures to increase, leading to confounding thermal effects. At the 5-cm depth, tarped treatments had soil temperatures that generally were 10 °C hotter than untarped treatments (Table 1). At 15 cm, this difference was about halved, and at 30 cm there was only a 0 to 2 °C difference. As a result, citrus nematode populations were reduced by more than 91% at the 5-cm depth at all sites during both years. Likewise, *F. oxysporum* survival was always less in the tarped versus untarped controls. Although less pronounced at 15 cm, there still was some tarping effect, at least at Davis during 2001, where climatic conditions led to the highest soil temperatures (Table 1). This tarping effect led to a 54% greater reduction in citrus nematode survival and a 33% greater reduction in *Fusarium* survival at 15 cm compared with the untarped treatment. There was no independent influence of tarping at 15 or 30 cm at any of the other sites. For this reason, only data from the 15- and 30-cm depths are presented.

Nematodes. The populations of viable citrus nematodes were reduced 100% by virtually all fumigant treatments at all sites during both years. The only exception was at Watsonville during 2000 (Table 2), where there was no nematode reduction at 30 cm with 368 kg·ha^{-1} metam sodium. The lack of control at 30 cm, with complete control at 15 cm, suggests some sort of experimental error in this datum point.

Fusarium. At the Davis and MBA sites during both years, *Fusarium* populations were reduced more than 98% and 83% respectively for all fumigant treatments at all depths ($P > 0.1$). At Watsonville, results were more variable, although not significantly so (Table 2). During both years at 15 cm, *Fusarium* reduction was slightly less with the two lowest rates of propargyl bromide (28 and 56 kg·ha^{-1}). This effect was not observed at 30 cm. Also, as observed for the citrus nematode at Watsonville during 2000, there was no reduction of *Fusarium* in the 358 kg·ha^{-1}, 30-cm metam sodium treatment (Table 2).

Weeds. In contrast to the citrus nematode and *Fusarium*, the weed species varied greatly in their susceptibility to propargyl bromide (Fig. 2). These differences were observed both years at all locations and were similar at 15 and 30 cm; therefore, data from 15 cm are presented.

Comparing all propargyl bromide treatments at the 15-cm depth (Fig. 2) shows that good annual bluegrass control was achieved in all trials at treatment rates at or more than 56 kg·ha^{-1}, with the exception of MBA in 2001. The reason for the extreme divergence in the data between 2000 and 2001 at MBA is unknown, but a strong divergence was also noted in the response of field bindweed at MBA (Fig. 2). There was a significant dose response of annual bluegrass to propargyl bromide in both years, with only the three highest treatment doses consistently yielding results that were not significantly different from MBC (Table 3). At Watsonville there was a significant dose response of annual bluegrass to iodomethane in both 2000 (Table 3) and 2001, where only the highest

Table 1. Maximum soil temperatures during fumigation experiments in three California soils.

		Temperature (°C)[z]		
Location	Treatment	Soil depth, 5 cm	Soil depth, 15 cm	Soil depth, 30 cm
Davis 2000	Untarped	NT[y]	35	33
	Tarped[x]	49	40	32
Monterey Bay Academy 2000	Untarped	34	33	29
	Tarped	44	36	30
Watsonville 2000	Untarped	38	34	24
	Tarped	47	40	26
Davis 2001	Untarped	44	35	30
	Tarped	53	42	32
Monterey Bay Academy 2001	Untarped	37	34	28
	Tarped	45	37	30
Watsonville 2001	Untarped	39	30	26
	Tarped	48	35	26

[z]Measured at 10-min intervals by Onset Stowaway microloggers.
[y]Not tested.
[x]Six-day tarping period.

Table 2. Percent citrus nematode (*Tylenchulus semipenetrans*) and *Fusarium* spp. reduction[z] during 2 years at Watsonville, CA.

	Citrus Nematode				*Fusarium* spp.			
	2000		2001		2000		2001	
Treatment	15 cm	30 cm	15 cm	30 cm	15 cm	30 cm	15 cm	30 cm
Untarped	3 a[y]	0 a	28 a	0 a	0 a	0 a	3 a	1 a
Tarped	0 a	6 a	59 a	18 a	0 a	35 a	29 a	19 a
Propargyl bromide 28 kg·ha^{-1}	100 b	100 b	100 b	100 b	83 b	100 b	74 b	100 b
Propargyl bromide 56 kg·ha^{-1}	100 b	100 b	100 b	100 b	95 b	100 b	89 b	100 b
Propargyl bromide 84 kg·ha^{-1}	100 b	100 b	100 b	100 b	100 b	100 b	100 b	100 b
Propargyl bromide 112 kg·ha^{-1}	100 b	100 b	100 b	100 b	100 b	100 b	91 b	100 b
Propargyl bromide 168 kg·ha^{-1}	100 b	100 b	100 b	100 b	100 b	100 b	100 b	100 b
Iodomethane 168 kg·ha^{-1}	100 b	100 b	100 b	100 b	99 b	91 b	81 b	79 b
Iodomethane 263 kg·ha^{-1}	100 b	100 b	100 b	100 b	100 b	100 b	96 b	95 b
MBC[x] 364 kg·ha^{-1}	100 b	100 b	100 b	100 b	100 b	100 b	100 b	100 b
Metam sodium 358 kg·ha^{-1}	100 b	0 a	100 b	100 b	94 b	0 a	100 b	82 b

[z]Percent reduction is related to the untarped control.
[y]Means followed by the same letter within a column are not significantly different according to Tukey's adjustment for multiple comparisons ($P < 0.001$).
[x]Methyl bromide/chloropicrin (87%/33%).

rate of iodomethane (263 kg·ha^{-1}) yielded reductions in seed viability that were not significantly different from MBC.

Pigweed seed viability was reduced with increasing rates of propargyl bromide, but the exact dose response varied between 2000 and 2001 (Fig. 2). In 2000, there was a more than 85% reduction in pigweed viability at the lowest rate of propargyl bromide at all sites, and 100% reduction at higher rates. In 2001, rates three times higher were required for the same result. At Watsonville during 2000, pigweed germination was reduced by more than 87% at all depths by all fumigants (Table 3). Only metam sodium at 30 cm differed from the other fumigant treatments, similar to that observed for the citrus nematode and *Fusarium* (Table 2). Results were similar at the other two sites, with more than 78% and 84% reductions in pigweed by the other soil fumigants at MBA and Davis respectively.

A significant ($P < 0.01$) dose response to propargyl bromide by common purslane was only observed at Watsonville during 2001 (Fig. 2). At all sites during both years there was 100% reduction in common purslane germination with rates at or more than 112 kg·ha^{-1} propargyl bromide. At Watsonville during 2000, fumigant treatments were not different from each other (Table 3). In general, similar results were observed at the other sites during both years, with more than 80% reduction in common purslane germination. An exception was metam sodium, which performed poorly at MBA during 2000 at the 30-cm depth.

Cheeseweed and field bindweed proved to be the least sensitive to propargyl bromide of all the weed species tested. There generally was no detectable response to increasing rates within the range of rates used in these experiments ($P > 0.1$). Across all rates, locations, and years, the percent reduction of seed viability for these two species usually was less than 50% and rarely approached 80% (Table 3, Fig. 2). The only site and year where there was a significant treatment effect ($P < 0.001$) was MBA during 2000 (Fig. 2), where the greatest loss of cheeseweed seed viability (up to 51% reduction) was with 168 kg·ha^{-1} propargyl bromide.

There were no significant differences ($P > 0.05$) between the efficacy of propargyl bromide and the other fumigants for field bindweed control. At Watsonville during 2000 (Table 3) and 2001, MBA during 2001, and Davis during 2000, there was never more than a 52% reduction of field bindweed seed viability by any fumigant. During 2000 at MBA and 2001 at Davis, the maximum reduction in field bindweed seed viability by any fumigant ranged from 49% to 90% regardless of depth. In most cases, fumigant treatments were not consistently different from the controls at any site or depth for field bindweed control (data not shown).

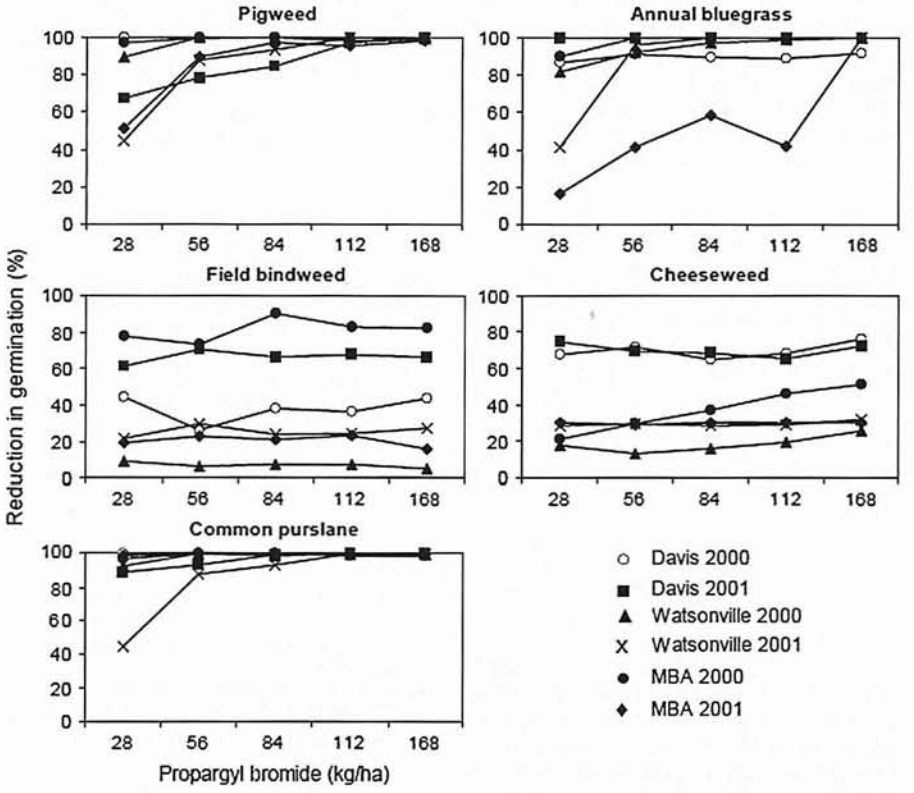

Fig. 2. Percent weed species reduction (percentage of seed not germinating out of an initial 100 seeds) across a range of propargyl bromide application rates at Monterey Bay Academy (MBA), Watsonville, and Davis, CA, during 2 years. Each value is the average of four replications.

Discussion

These experiments showed that soil-borne pests varied greatly in their susceptibility to propargyl bromide. Although propargyl bromide at relatively low dosages proved highly efficacious against the citrus nematode and *F. oxysporum*, and very efficacious against pigweed, annual bluegrass, and common purslane, it was relatively ineffective against field bindweed and cheeseweed. These results for propargyl bromide are not unique, because weeds are generally considered more resistant to fumigants than plant-parasitic nematodes or fungi (Ohr et al., 1996). Also, only *F. oxysporum* was used as a fungal test organism, even though fungal species are known to vary in sensitivity to fumigants

Table 3. Percent weed reduction after fumigant treatment at Watsonville, CA during 2000[z].

	Annual bluegrass		Pigweed		Cheeseweed[y]		Field bindweed[y]		Common purslane	
Treatment	15 cm	30 cm	15 cm	30 cm	15 cm	30 cm	15 cm	30 cm	15 cm	30 cm
Untarped	3 a[x]	3 a	10 a	3 a	25	20	14	20	6 a	4 a
Tarped	2 a	3 a	22 a	7 a	21	33	10	17	4 a	9 a
Propargyl bromide 28 kg·ha^{-1}	82 b	74 b	100 b	99 c	18	16	9	5	93 b	95 b
Propargyl bromide 56 kg·ha^{-1}	93 bc	86 bc	100 b	99 c	13	19	6	2	100 b	98 b
Propargyl bromide 84 kg·ha^{-1}	97 c	94 cdef	100 b	100 c	16	22	7	4	99 b	100 b
Propargyl bromide 112 kg/ha	99 cd	97 def	100 b	100 c	20	14	7	5	100 b	100 b
Propargyl bromide 168 kg·ha^{-1}	100 d	100 ef	100 b	100 c	25	22	5	4	100 b	100 b
Iodomethane 168 kg·ha^{-1}	91 c	92 cde	100 b	97 c	14	17	0	7	100 b	99 b
Iodomethane 263 kg·ha^{-1}	99 d	100 f	100 b	100 c	33	18	7	5	100 b	100 b
MBC[w] 364 kg·ha^{-1}	99 cd	99 ef	100 b	99 c	17	16	9	3	100 b	100 b
Metam sodium 358 kg·ha^{-1}	90 bc	88 bcd	92 b	87 b	18	18	13	12	93 b	90 b

[z]Reduction is the percentage not germinating out of 100 seed. Similar results were observed at Watsonville during 2001.
[y]No significant difference ($P > 0.05$) between treatments for these weed species.
[x]Means followed by the same letter within a column are not significantly different according to Tukey's adjustment for multiple comparisons ($P < 0.001$).
[w]Methyl bromide/chloropicrin (87%/33%).

such as iodomethane and methyl bromide (Hutchinson et al., 2000a).

A notable aspect of this research was that it tested propargyl bromide in a nonlaboratory environment, whereas most previous research has emphasized laboratory experiments. For example, laboratory studies determined that the concentration of propargyl bromide needed to kill 50% (LC_{50}) of a population of barnyardgrass [*Echinochloa crus-galli* (L.) Brauv] was about four times lower than that for *F. oxysporum* (Ma et al., 2001). The estimated propargyl bromide concentration needed to kill 90% (LC_{90}) of a barnyardgrass population was 10 kg·ha^{-1}. Although we did not test barnyardgrass, we found that propargyl bromide did not effectively control weeds at the rates less than 56 kg·ha^{-1}, and results were more consistent at rates of 112 kg·ha^{-1} and above. We also found that field bindweed and cheeseweed were not completely controlled even at the highest rate of propargyl bromide: 168 kg·ha^{-1}. In another laboratory study, the relative order of sensitivity of soil-borne organisms to propargyl bromide demonstrated that the citrus nematode was the most sensitive, followed by barnyardgrass then *F. oxysporum* (Allaire et al., 2005). In our field study, citrus nematode and *F. oxysporum* were always more sensitive to propargyl bromide compared with the weed species tested. Ma et al. (2001) reported an LC_{90} value of 50 kg·ha^{-1} to control *F. oxyspoum* in loamy sand and sandy loam soils. However, in our experiments, the rate of propargyl bromide required to reduce *F. oxysporum* survival by more than 80%, regardless of soil type, was 28 kg·ha^{-1}.

Soil physical and chemical properties, as well as moisture and temperature, can play a significant role in determining the fate of soil fumigants by influencing the rate of fumigant diffusion as well as abiotic and biological degradation processes (Gan et al., 1994; Zhang et al., 1998). Considerable research has been conducted regarding the environmental and physical factors that may influence the efficacy of propargyl bromide as a soil fumigant (Ma et al., 2001; Papiernik and Yates, 2002; Papiernik et al., 2000; Wang et al., 1999; Yates and Gan, 1998). Although we found no consistent difference in propargyl bromide efficacy between the geographical locations of this study, it has been shown that propargyl bromide is 20 times less effective in an organic matter-rich muck soil than in a sandy loam or loamy sand (Ma et al., 2001).

Probably the biggest environmental factor that distinguished our locations was soil temperature. Soil solarization is known to be an effective pest management strategy (Elmore, 1991). The sustained soil temperatures of more than 37 °C at our 5-cm depths were sufficient to result in nematode and fungal mortality. Although elevated temperatures were achieved at 15 cm, they were not sustained for as long a period compared with the shallower depth. Soil temperature can also influence fumigant performance. Increasing temperature during fumigation increased the efficacy of iodomethane and methyl bromide (Zhang et al., 1998). We did not observe a consistent influence of temperature on the performance of propargyl bromide at any depth.

Methyl bromide and iodomethane efficacy also are influenced by soil moisture (Zhang et al., 1998), with efficacy of both fumigants being greatest in soil having a 14% moisture content. The moisture of our soils, during both years, ranged from 10% to 13%. Because propargyl bromide is structurally similar to iodomethane and methyl bromide (Papiernik et al., 2000), the soil moisture achieved in our container trials was adequate to promote diffusion of all fumigants tested.

Propargyl bromide is structurally similar to methyl bromide and iodomethane, but propargyl bromide and iodomethane have lower ozone-depleting potential (Papiernik et al., 2000). Few comparisons have been made in a field setting between propargyl bromide and standard soil fumigants. Shank-injected or drip-applied propargyl bromide, at a rate much higher than those used in this study (>207 kg·ha^{-1}) provided control of plant-parasitic nematodes throughout the first growing season similar to control achieved with methyl bromide (507 kg·ha^{-1}) (Schneider et al., 2006). In laboratory experiments propargyl bromide controlled yellow nutsedge (*Cyperus esculentus* L.) equal to or better than methyl bromide (Hutchinson, 2000; Hutchinson et al., 2000b). However, when propargyl bromide was applied in the field for nutsedge control there was poor or no control compared with methyl bromide. Lack of control was attributed to inadequate knowledge regarding application technology (Hutchinson, 2000). This result also may have been the result of propargyl bromide formulation. In our study, propargyl bromide performed differently between 2000 and 2001. In 2000, a toluene (20%) formulation of propargyl bromide was used. However, in 2001 a different formulation was used in which the stabilizers were expected to be biologically inert. In general, the 2001 formulation was less effective at controlling weeds at the lower rates. It is possible that toluene in the 2000 formulation played a role in propargyl bromide toxicity to weed seeds.

We found that the degree of control of the citrus nematode and *F. oxysporum* at a propargyl bromide rate of 28 kg·ha^{-1} was comparable with standard soil fumigants. Although there were significant differences in weed control between propargyl bromide and the other fumigants at some sites during some years, these differences were not consistent. In general, to achieve control of annual bluegrass, pigweed, and common purslane comparable with the other fumigants, propargyl bromide had to be applied at $\geq$ 112 kg·ha^{-1}. It is important to note, however, that although higher rates of propargyl bromide were required, the rates still were half that required of the other standard fumigants. Cheeseweed and field bindweed proved to be difficult to control with propargyl bromide and the other tested soil fumigants.

These experiments showed that propargyl bromide was an effective fumigant in comparison with other soil fumigants. However, larger scale tests are needed. Unfortunately, until the handling characteristics of this product can be improved, it is unlikely that this compound will be pursued for registration.

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