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Weed Control in Strawberry Provided by Shank- and Drip-applied Methyl Bromide Alternative Fumigants

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***Abstract*. The loss of methyl bromide (MB) as a soil fumigant has created the need for new weed management systems for crops such as strawberry (*Fragaria ×ananassa* Duchesne). Potential alternative chemicals to replace methyl bromide fumigation include 1,3-D, chloropicrin (CP), and metam sodium. Application of emulsified formulations of these fumigants through the drip irrigation system is being tested as an alternative to the standard shank injection method of fumigant application in strawberry production. The goal of this research was to evaluate the weed control efficacy of alternative fumigants applied through the drip irrigation system and by shank injection. The fumigant 1,3-D in a mixture with CP was drip-applied as InLine (60% 1,3-D plus 32% CP) at 236 and 393 L·ha^{-1} or shank injected as Telone C35 (62% 1,3-D plus 35% CP) at 374 L·ha^{-1}. Chloropicrin (CP EC, 95%) was drip-applied singly at 130 and 200 L·ha^{-1} or shank injected (CP, 99%) at 317 kg·ha^{-1}. Vapam HL (metam sodium 42%) was drip-applied singly at 420 and 700 L·ha^{-1}. InLine was drip-applied at 236 and 393 L·ha^{-1}, and then 6 d later followed by (fb) drip-applied Vapam HL at 420 and 700 L·ha^{-1}, respectively. CP EC was drip-applied simultaneously with Vapam HL at 130 plus 420 L·ha^{-1} and as a sequential application at 200 fb 420 L·ha^{-1}, respectively. Results were compared to the commercial standard, MB : CP mixture (67:33) shank-applied at 425 kg·ha^{-1} and the untreated control. Chloropicrin EC at 200 L·ha^{-1} and InLine at 236 to 393 L·ha^{-1} each applied singly controlled weeds as well as MB : CP at 425 kg·ha^{-1}. Application of these fumigants through the drip irrigation systems provided equal or better weed control than equivalent rates applied by shank injection. InLine and CP EC efficacy on little mallow (*Malva parviflora* L.) or prostrate knotweed (*Polygonum aviculare* L.) seed buried at the center of the bed did not differ from MB : CP. However, the percentage of weed seed survival at the edge of the bed was often higher in the drip-applied treatments than in the shank-applied treatments, possibly due to the close proximity of the shank-injected fumigant to the edge of the bed. Vapam HL was generally less effective than MB : CP on the native weed population or on weed seed. The use of Vapam HL in combination with InLine or CP EC did not provide additional weed control benefit. Chemical names used: 1,3-dichloropropene (1,3-D); sodium N-methyldithiocarbamate (metam sodium); methyl bromide; trichloronitromethane (chloropicrin).**

For the past 40 years, soil fumigation with methyl bromide (MB) has been the basis for pest management in California strawberry (*Fragaria ×ananassa* Duchesne) production (Wilhelm and Paulus, 1980). Application of MB in combination with chloropicrin (CP) has provided consistent cost-effective control of soilborne diseases, nematodes and weeds. Nearly all conventionally produced strawberries in California are grown in soil fumigated with a mixture of MB and CP (MB : CP). In the United States, soil fumigation consumes 35 million pounds of methyl bromide each year; ≈50% is used in California and 35% in Florida [U.S. Dept. of Agriculture (USDA), 2000]. Methyl bromide has been classified as an ozone-depleting substance, and under the provisions of the U.S. Clean Air Act and international treaty, MB use in the United States will be phased out by 2005 (USDA, 2000). Effective alternatives must be found to control soilborne diseases and weeds, otherwise the impact of the MB phaseout could cause severe economic distress for the strawberry industry (Carter, 2001).

Profitable strawberry production depends on effective weed management. Strawberries are extremely vulnerable to weed competition, and weeds can harbor pathogens and insects that are deleterious to the crop (Agamalian et al., 1994; Lange, 1985). Effective weed control in California strawberries has been accomplished through a combination of field selection, crop rotation, sanitation, hand weeding, mulching, preplant soil fumigation, and occasionally, herbicides (California Strawberry Commission, 1999). Common weeds of strawberry controlled by 360 kg·ha^{-1} of 2 MB : 1 CP include pigweeds (*Amaranthus* sp.), common lambsquarters (*Chenopodium album* L.), shepherd's-purse (*Capsella bursa-pastoris* L. Medik.), common purslane (*Portulaca oleracea* L.), common chickweed [*Stellaria media* (L.) Vill.], and hairy nightshade (*Solanum sarrachoides* Sendtner) (Wilhelm and Paulus, 1980). Serious weed pests in strawberry that are not controlled by this treatment are little mallow (*Malva parviflora* L.), California burclover (*Medicago polymorpha* L.), Indian sweetclover [*Melilotus indica* (L.) All.], redstem filaree [*Erodium dircutarium* (L.) L Herr. ex. Ait], and purple cudweed (*Gnaphalium purpureum* L.) (Agamalian et al., 1994; Wilhelm and Paulus, 1980). Both burclover and little mallow have hard seed coats that contribute toward their persistence in the soil seedbank (Makowski and Morrison, 1989; Porqueddu et al., 1996). The mechanisms by which burclover and little mallow resist MB : CP fumigation are unknown. However, it is likely that the hard seed coat either partially or fully prevents a lethal concentration of fumigant from penetrating the seed and killing the embryo (Egley, 1986). Weeds in strawberry fields not controlled by fumigants must be pulled by hand because plastic mulches preclude the use of mechanical tillage (Agamalian et al., 1994). If alternative fumigants do not provide weed control at levels previously provided by MB : CP fumigation, yield will be reduced and hand-weeding expense will increase.

Commercially available alternatives to MB are CP, 1,3-D, and metam sodium (Ajwa et al., 2001). Chloropicrin became a partner with MB in the late 1950s, when it was learned that the combination of both fumigants was very effective in controlling soilborne pathogens, insects, and weeds (Wilhelm, 1999; Wilhelm and Paulus, 1980). Although the efficacy of CP on soilborne pathogenic fungi is well documented (Wilhelm, 1999), limited information is available on its performance on weeds. The weed control spectrum of CP applied alone or 1,3-D plus CP in combination have not been well defined. Limited laboratory studies indicate that CP or 1,3-D can provide adequate control of some weed species such as redroot pigweed (*Amaranthus retroflexus* L.) (Pieczarka and Warren, 1959, 1960). However, recent evidence indicates that shank injected CP and 1,3-D do not control other weeds such as nutsedge (*Cyperus* sp.), a species that MB does control (Locascio et al., 1997). Metam sodium itself is not active on weeds, but it quickly breaks down after application to methyl isothiocyanate (MITC), a compound active against weeds such as large crabgrass (*Digitaria sanguinalis* L. Scop.) (Teasdale and Taylorson, 1986), burning nettle (*Urtica urens*

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L.), common chickweed and pigweeds. MITC may also provide partial control of burclover and little mallow (Agamalian et al., 1994) and nutsedge (Locascio et al., 1997).

Alternative fumigants must provide economical control of nematodes, soil pathogens and weeds. Methyl bromide not only provides weed control, but control of nematodes and soil pathogens (Wilhelm and Paulus, 1980). Chloropicrin has a high level of activity against insects and many fungi, but is less active against nematodes than MB : CP (Duniway et al., 2001; Johnson and Feldmesser, 1987; Johnson et al., 1979; Wilhelm and Paulus, 1980). The activity of 1,3-D on nematodes and some insects is high, but activity against soil pathogens is less consistent (Noling and Becker, 1994). Metam sodium provides control of nematodes and soil borne pathogens (Johnson et al., 1979; McCarter et al., 1976).

A Univ. of California economic analysis projects that California strawberry industry revenues will decline by 15% from current levels after implementation of the MB phaseout (Carter, 2001). Therefore, it is essential that alternative fumigant treatments allow growers to remain economically viable. Estimated costs of alternative fumigants are $600 per hectare for a 700 L·ha^{-1} metam sodium application, $1700 per hectare for a 317 kg·ha^{-1} shank-applied CP treatment and ≈$3200 per hectare for a 374 L·ha^{-1} shank-applied 1,3-D plus CP treatment (Rachael Goodhue, personal communication, Table 1). Compared to MB : CP fumigation costs at $4200/ha, these alternative fumigant treatments are cheaper (Klonsky and De Moura, 2001).

Methyl bromide is typically applied to soil or raised soil beds by injection through hollow shanks that are pulled through the soil at a depth of 20 to 30 cm. The soil is covered by plastic mulch film immediately after application. Although alternative soil fumigants such as CP or mixtures of 1,3-D and CP can be applied by shank injection (Locascio et al. 1997), their volatilization and distribution in soil may be limited by their lower vapor pressure and higher boiling point compared to MB (EXTOXNET – CP, 2001; EXTOXNET – MB 2001; Lakes Environmental Software, 2000). Fumigants such as TeloneC35 (Dow Agro Sciences, Redeck, N.C.) (62% 1,3-D and 35% CP) or CP alone can be more effective when applied with water through the drip irrigation system than when applied by shank injection. Ajwa et al. (2001) proposed drip fumigation as an alternative method of fumigant application for drip-irrigated crops such as strawberries. Long-term research by Ajwa and Trout (2000) reported that soil beds drip fumigated with emulsifiable concentrate (EC) of TeloneC35 (InLine) at 393 L·ha^{-1} applied singly, produced strawberry yields equivalent to 67 MB : 33 CP shank fumigation at 425 kg·ha^{-1}. Other advantages of drip fumigation over shank injection include a more uniform distribution of chemicals, reduced applicator exposure, and lower rates (Ajwa et al., 2002). Although application of available alternative fumigants through the drip irrigation system may be an option in irrigated crops such as strawberry, little information is available regarding the weed control efficacy of this fumigation method. The first objective of this research was to evaluate the weed control efficacy of preplant drip fumigation with 1,3-D plus CP in mixture, CP, and metam sodium. The second objective was to evaluate the effect of combining 1,3-D plus CP mixture or CP alone with a metam sodium treatment. The third objective was to compare the weed control efficacy at equal rates of drip-applied and shank-applied 1,3-D plus CP mixture.

Table 1. Fumigant rate, application method, irrigation water volume, and cost estimates.

Treatment	Rate/ha	Application method	Irrigation vol (L·m^{-2})	Cost estimates ($/ha)[z]
MB : CP	425 kg	shank	---	2623
Telone C35 (62% 1,3-D and 35% CP)	374 L	shank	---	3212
CP (99%)	317 kg	shank	---	1673
InLine (60% 1,3-D and 32% CP)	236 L	drip	43	1450
InLine followed by (fb)[y]				
Vapam (metam sodium 42%)	236 fb 420 L	drip	43 fb 26	1802
InLine	393 L	drip	26, 43, 61	2414
InLine fb Vapam	393 fb 700 L	drip	61 fb 26	3001
CP EC (95%)	130 L	drip	43	1134
CP EC (95%)	200 L	drip	43	1745
CP EC + Vapam	130 + 420 L	drip	43	1487
CP EC fb Vapam	200 fb[y] 420 L	drip	43 fb 26	2097
Vapam	420 L	drip	43	352
Vapam	700 L	drip	26, 43, 61	587
Untreated	0	---	---	---

[z]Cost estimates based on a survey of commercial dealers in California. Application costs were not included.

[y]fb = followed by Vapam 6 d later.

Materials and Methods

Site description and treatment application. Field studies were conducted in Salinas and Watsonville, Calif., for two consecutive years, Sept. 1998 through July 1999 (1999 growing season) and Oct. 1999 through Aug. 2000 (2000 growing season). Both sites were located in a major strawberry production district on the central coast of California. Soil at both locations had not been fumigated for at least 10 years prior to initiation of this research. The soil at

Table 2. Effect of MB : CP and alternative fumigants on weed fresh weight. Total mean weed fresh weight g·m^{-2} of shank-applied MB : CP was compared to CP, Inline, Telone C35, or Vapam HL applied through the drip irrigation system or by shank injection at Salinas and Watsonville. The weed biomasses in the InLine and CP EC treatments with and without Vapam HL were contrasted to determine if sequential applications of Vapam HL improved weed control. Weed biomass in the InLine and Telone C35 treatments were also contrasted.

Treatment	Rate/ha	Application method	Salinas 1999	Watsonville 2000
			g·m^{-2}	
Contrast single treatments vs. MB : CP standard				
MB : CP standard	425 kg	shank	39.0	20.3
Telone C35	374 L	shank	48.3 (0.81)[z]	50.0 (0.17)
Inline	236 L	drip	25.5 (0.98)	14.9 (0.80)
Inline	393 L[y]	drip	17.3 (0.55)	7.1 (0.44)
CP EC	130 L	drip	31.3 (0.78)	10.8 (0.65)
Vapam HL	420 L	drip	98.9 (<0.01)	15.6 (0.82)
Vapam HL	700 L[x]	drip	89.2 (<0.01)	4.8 (0.40)
Untreated	0	---	516.6 (<0.01)	186.7 (<0.01)
Contrast fumigant applied alone vs. fumigant followed by (fb) Vapam HL				
Inline	236 L	drip	25.5	14.9
Inline fb Vapam HL	236 L fb 420 L	drip	53.3 (0.17)[w,v]	56.6 (0.06)
Inline	393 L[y]	drip	17.3	7.1
Inline fb Vapam HL	393 L fb 700 L	drip	15.5 (0.91)[w]	---
CP EC	130 L	drip	31.3	10.8
CP EC fb Vapam HL	130 L fb 420 L	drip	79.2 (0.02)[w]	15.3 (0.83)
Contrast Inline drip vs. Telone C35 shank				
Inline	393 L[y]	drip	17.3	7.1
Telone C35	374 L	shank	48.3 (0.41)[u]	50.0 (0.02)

[z]P value of single df contrasts comparing weed biomass weights with the MB : CP standard.

[y]Average weed biomass of Inline at 393 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43, and 61 L·m^{-2}.

[x]Average weed biomass of Vapam HL at 700 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43, and 61 L·m^{-2}.

[w]Inline or CP EC were applied simultaneously in 1999.

[v]*P* value of single df contrasts comparing the weed biomass of Inline or CP EC treatments applied with a sequential application of Vapam HL were compared to Inline or CP applied without Vapam HL.

[u]*P* value of single df contrasts comparing the weed biomass from the Inline drip-applied treatment to the Telone C35 shank-applied treatment.

Salinas was classified as a Chualar sandy loam (fine-loamy, mixed, thermic, Typic Argixerolls) with a pH of 6.5 and organic matter content of 0.7%. The soil in Watsonville was classified as an Elder sandy loam (coarse-loamy, mixed, thermic, Cumulic Haploxerolls) with a pH of 6.1 and organic matter content of 0.6%. Commercial cultural practices for the area were followed (Calif. Strawberry Commission, 1999). The soil was tilled and beds were formed in both locations at 132-cm center-to-center spacing (76 cm wide × 30 cm high). Slow release fertilizer (27N–10P–12K) was applied to the beds at the rate of 400 kg·ha^{-1}. A drip irrigation system was installed that consisted of two drip tapes (Netafim Streamline 60; Netafim, Fresno, Calif.), with emitters spaced 30 cm apart and an emitter flow rate of 0.87 L/min at 70 KPa, placed 8 cm (in Watsonville) or 13 cm (in Salinas) from the bed center at a soil depth ranging from 2 to 5 cm. This arrangement placed the drip tapes 30 cm from the edge of the bed in Watsonville and 25 cm from the edge of the bed in Salinas. Preplant treatments (Table 1) were applied to the same beds each year in late September (1999 season) or early October (2000 season), ≈4 weeks before planting. The treatments were arranged in a randomized complete-block design with four replicates in Watsonville and three in Salinas. Plots were 1 bed wide × 10 m long at Watsonville and 1 bed wide × 33 m long at Salinas. At the time of fumigation, the average daily soil temperature within the raised bed ranged between 16 to 20 °C, and the average soil water content was <85% of field capacity (soil matric potentials ranged between –7.5 and –8.5 KPa).

The fumigants used in this study were commercial grade formulations. Metam sodium (Vapam HL formulation, 42% sodium N-methyldithiocarbamate) was provided by AMVAC, Newport Beach, Calif. Chloropicrin, without and with an emulsifier (CP 99% and CP EC 95%), was provided by Niklor Chemical Co., Long Beach, Calif. Telone C35, a mixture of 1,3-D and CP (62% 1,3-D and 35% CP) and an emulsified formulation of this 1,3-D and CP mixture (InLine, 60% 1,3-D and 32% CP) were provided by Dow AgroSciences, Redeck, N.C. The 67 MB : 33 CP formulation was provided by Tri-Cal., Hollister, Calif.

At both locations, 67 MB : 33 CP, Telone C35, and CP were shank injected 25 to 30 cm deep with two chisels spaced 35 cm apart into soil beds that were immediately covered with green or brown high-density polyethylene mulch (0.03-mm thickness). Metam sodium, Inline, and CP EC were applied through the drip irrigation system into soil beds covered with polyethylene mulch. Chemicals were injected into the irrigation water throughout the irrigation period following procedures described by Ajwa et al. (2002). Briefly, the fumigants were injected in a closed system directly from nitrogen-pressurized cylinders and metered into irrigation water with a flow meter (Key Instruments, Trevose, Pa., McMaster Carr Supply, Los Angeles). A static mixing devise (TAH Industries, Robbinsville, N.J.) was installed at the point of injection to mix fumigants with irrigation water before distribution in the irrigation system. A backflow device (Amiad Filtration Systems, Oxnard, Calif.) was used to prevent contamination of the water source. InLine and metam sodium (as Vapam HL) were applied through the drip irrigation system at the maximum label rates, 393 L·ha^{-1} and 700 L·ha^{-1}, in three volumes of water (26, 43, and 61 L·m^{-2}) or at 60% of the maximum rates in 43 L·m^{-2}. Combination treatments were applied simultaneously in 1999 and sequentially in 2000. In 1999 the combination treatments, i.e., InLine plus Vapam HL or CP plus Vapam HL, were applied simultaneously into the irrigation water. For the 2000 growing season, Vapam HL was applied as a sequential application 6 d after application of InLine or CP. Before planting, at least 25 mm of water were applied through the drip irrigation systems to wash any residual fumigants or breakdown products from the planting zone. The Salinas irrigation water had an electrical conductivity of 0.63 mS·cm^{-1} and 425 ppm dissolved salts, and the irrigation water at Watsonville had a conductivity 0.6 mS·cm^{-1} and 241 ppm dissolved salts. Strawberry variety 'Selva' was planted 4 to 5 weeks after fumigation at a density of 49,697 plants/ha. Overhead sprinklers were used for up to four weeks to establish the strawberry transplants, and ≈25 mm of water per week was applied. In 2000, the plastic mulch was removed after planting to allow for better estimate of weed control by the various treatments.

Weed control assessments. Fumigant efficacy on weeds was assessed by two methods: 1) biomass of the native weed population, and 2) viability of buried weed seed samples. Weeds were uprooted and shaken to remove residual soil from the roots and then fresh weights were measured to determine weed biomass. Weeds were separated by species only at Salinas in 2000. Weed samples were taken during the period 3 to 5 months after strawberry planting when their populations were at their peak.

For seed viability tests, 50 seeds of little mallow, prostrate knotweed and common purslane were placed in 8 × 12-cm heat-sealed nylon mesh bags (Delnet, Middletown, Del.). The little mallow seed was obtained from Valley Seed, Fresno, Calif., and the prostrate knotweed and common purslane seed were gathered from agricultural fields near Salinas, Calif. Two seed bags were buried per plot at a depth of 5 cm deep, one at the center and a second at the edge of the bed. Seed bags were installed 1 to 2 d prior to fumigation to allow the seeds to equilibrate with the soil moisture. Seed bags were retrieved ≈10 d after fumigation, and seed viability was determined using the tetrazolium assay described in Grabe (1970).

Statistical analysis. Weed biomass and seed viability data were analyzed using the SAS general linear model (GLM) procedure (SAS Institute, Cary, N.C.). Data within fumigant rates were pooled across irrigation water volumes where there were no differences be-

Table 3. California burclover and common chickweed fresh weight g·m^{-2} resulting from MB : CP compared to CP, CP EC, Inline, Telone C35 and Vapam HL applied through the drip irrigation system or by shank injection at Salinas in 2000. The weed biomass in the Inline or CP treatments with and without sequential applications of Vapam HL was contrasted to determine if sequential applications of Vapam HL improved weed control. Weed biomass in the drip-applied Inline or shank-applied Telone C35 applications were also contrasted.

Treatment	Rate/ha	Application method	California burclover	Common chickweed
			g·m^{-2}	
Contrast single treatments vs. MB : CP standard				
MB : CP standard	425 kg	shank	168.9	7.3
Telone C35	374 L	shank	141.7 (0.31)[z]	6.3 (0.98)[z]
Inline	236 L	drip	71.8 (<0.01)	9.8 (0.97)
Inline	393 L[y]	drip	56.9 (<0.01)	6.9 (0.99)
CP	317 kg	shank	153.3 (0.56)	47.6 (0.58)
CP EC	200 L	drip	36.1 (<0.01)	15.7 (0.91)
Vapam HL	420 L	drip	82.2 (<0.01)	152.9 (0.05)
Vapam HL	700 L[x]	drip	81.4 (<0.01)	93.2 (0.15)
Untreated	0	---	60.5 (<0.01)	461.0 (<0.01)
Contrast fumigant applied alone vs. fumigant followed by (fb) Vapam HL				
Inline	236 L	drip	71.8	9.8
Inline fb Vapam HL	236 L fb 420 L	drip	91.6 (0.61)[w]	35.6 (0.72)
Inline	393 L[y]	drip	56.9	6.9
Inline fb Vapam HL	393 L fb 700 L	drip	54.8 (0.93)	2.2 (0.94)
CP EC	200 L	drip	31.6	15.7
CP EC fb Vapam HL	200 L fb 420 L	drip	63.2 (<0.01)	12.0 (0.96)
Contrast Inline drip vs. Telone C35 shank				
Inline	393 L[y]	drip	56.9	6.9
Telone C35	374 L	shank	141.7 (<0.01)[v]	6.3 (0.99)

[z]*P* value of single degree of freedom contrasts comparing weed biomass weights with the MB:CP standard.

[y]Average weed biomass of Inline at 393 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43, and 61 L·m^{-2}.

[x]Average weed biomass of Vapam HL at 700 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43, and 61 L·m^{-2}.

[w]*P* value of single df contrasts comparing the weed biomass of Inline or CP EC treatments applied with a sequential application of Vapam HL were compared to Inline or CP EC applied without Vapam HL.

[v]*P* value of single df contrasts comparing the weed biomass from the Inline drip-applied treatment to the Telone C35 shank-applied treatment.

Table 4. Efficacy of CP, CP EC, Inline, Telone C35 and Vapam HL on prostrate knotweed seed viability compared to MB : CP at Salinas in 2000. The data are percentage viable seed buried in the center and edge of a 1-m bed. The seed viability in the Inline or CP EC treatments with and without sequential applications of Vapam HL were compared to determine if sequential applications of Vapam HL improved weed control. Seed viability in the drip applications of Inline and shank applications of Telone C35 were also contrasted. The center vs. edge *P* value indicates whether treatment effect on seed viability at the center vs. edge of the bed differed.

		Application	Prostrate knotweed		
Treatment	Rate/ha	method	Center	Edge	Center vs. edge
			— — — % viable	— — —	*P* value
Contrast single treatments vs. MB : CP standard					
MB : CP standard	425 kg	shank	14.18	24.07	0.69
Telone C35	374 L	shank	1.67 (0.33)[z]	29.82 (0.86)	0.16
Inline	236 L	drip	0.50 (0.24)	11.54 (0.64)	0.39
Inline	393 L[y]	drip	1.32 (0.22)	7.16 (0.41)	0.40
CP	317 kg	shank	86.40 (<0.01)	92.69 (0.04)	0.79
CP EC	200 L	drip	27.95 (0.52)	54.04 (0.39)	0.40
Vapam HL	420 L	drip	46.66 (0.17)	96.90 (0.02)	0.04
Vapam HL	700 L[x]	drip	72.42 (<0.01)	96.61 (<0.01)	0.04
Untreated	0	---	95.50 (<0.01)	99.50 (<0.01)	0.65
Contrast fumigant applied alone vs. fumigant followed by (fb) Vapam HL					
Inline	236 L	drip	0.50	11.54	---
Inline fb Vapam HL	236 L fb 420 L	drip	0.50 (1.00)[w]	52.53 (0.20)	0.02
Inline	393 L[y]	drip	1.32	7.16	---
Inline fb Vapam HL	393 L fb 700 L	drip	0.50 (0.83)	0.65 (0.52)	0.98
CP EC	200 L	drip	27.95	54.04	---
CP EC fb Vapam HL	200 L fb 420 L	drip	0.50 (0.08)	60.71 (0.85)	0.02
Contrast Inline drip vs. Telone C35 shank					
Inline	393 L[y]	drip	1.32	7.16	---
Telone C35	374 L	shank	1.07 (0.95)[v]	29.82 (0.30)	---

[z]*P* value of single degree of freedom contrasts comparing weed biomass weights with the MB : CP standard.

[y]Average weed biomass of Inline at 393 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43 and 61 L·m^{-2}.

[x]Average weed biomass of Vapam HL at 700 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43 and 61 L·m^{-2}.

[w]*P* value of single df contrasts comparing the weed biomass of Inline or CP treatments applied with a sequential application of Vapam HL were compared to Inline or CP applied without Vapam HL.

[v]*P* value of single df contrasts comparing the weed biomass from the Inline drip-applied treatment to the Telone C35shank-applied treatment.

tween irrigation treatments. Single degree-of-freedom contrasts were used to make specific comparisons between treatments. The standard MB : CP was compared to alternative chemical treatments. The effect of a fumigant applied singly was compared to the effect of the same fumigants applied in combination with Vapam HL. The efficacy of drip-applied InLine was compared to shank-applied Telone C35. To determine if there were spatial differences in weed control across the planting beds, the viability of weed seed buried in the center of the bed was compared to that of seed buried at the edge of the bed. Statistical analyses were performed on the weed fresh weight data without transformation. Weed seed viability data were arcsine transformed before analysis to normalize variances. Means were converted to original units after analysis.

Results

Fumigant efficacy on native weeds. Statistical analysis indicated that the weed control and weed seed viability values resulting from drip-applied InLine at 393 L·ha^{-1} applied in 26, 43, and 61 L·m^{-2} of water were not significantly different, so these data were pooled. Similarly, the data from the Vapam HL 700 L·ha^{-1} 26, 43, and 61 L·m^{-2} treatments were also pooled. InLine, CP EC or Telone C35 alone did not significantly differ from MB : CP in control of native weeds (Table 2). Vapam HL applied alone provided poor weed control at Salinas in 1999, but provided effective control at Watsonville. Application of Vapam HL after InLine or CP EC did not significantly improve the control of native weeds beyond the level of control provided by InLine or CP EC applied alone. In 1999 at Salinas, weed control was reduced by the addition of Vapam HL when it was applied simultaneously with CP EC. Drip-applied InLine at 393 L·ha^{-1} was found to provide significantly better weed control than shank injected Telone C35 at 374 L·ha–1 at Watsonville, but at Salinas there was no significant difference between application methods (Table 2).

At Salinas in 2000, the weeds were separated and biomass measured for individual species. The most abundant weeds were California burclover and common chickweed. The biomass of California burclover was significantly higher for the MB : CP treatment than the untreated one (Table 3). The InLine, CP EC, or Vapam HL treatments had significantly lower California burclover biomass than the MB : CP standard. Application of Vapam HL 6 d after InLine or CP EC did not improve the efficacy of these chemicals on California burclover. Furthermore, CP EC applied singly, had significantly lower California burclover biomass than CP EC followed by Vapam HL. InLine had lower California burclover biomass than shank-applied Telone C35. The control of common chickweed provided by InLine, Telone C35, CP EC, and CP treatments were not significantly different ($P < 0.05$) than MB : CP (Table 3). Vapam HL alone at 420 L·ha^{-1} resulted in significantly greater common chickweed biomass than MB : CP. Applications of Vapam HL after InLine or CP EC did not improve the common chickweed control provided by each chemical applied singly. Also, InLine at 393 L·ha^{-1} and Telone C35 at 374 L·ha^{-1} did not differ significantly in common chickweed control.

Fumigant efficacy on weed seed. There were significant differences in fumigant efficacy on the weed seed in the center of the bed compared to the edge of the bed. The single Vapam HL applications, or combination treatments of InLine at 236 L·ha^{-1} or CP EC followed by Vapam HL provided significantly better control of prostrate knotweed seed in the bed center than at the edge of the bed (Table 4).

The effect of InLine, Telone C35 or CP EC on prostrate knotweed seed viability did not differ significantly from the MB : CP standard (Table 4). Shank-applied CP provided significantly less control of prostrate knotweed seed than MB : CP, regardless of seed location in the bed. Vapam HL at 420 L·ha^{-1} provided significantly less control of prostrate knotweed seed on the bed edge than MB : CP, and Vapam HL at 700 L·ha^{-1} provided significantly less control of prostrate knotweed seed in either the bed center or edge compared to MB : CP. The prostrate knotweed control provided by InLine or CP EC was not improved by application of Vapam HL. InLine and Telone C35 applied at maximum labeled rate did not significantly differ in efficacy on prostrate knotweed seed. At Salinas in 2000, all of the fumigants reduced the viability of common purslane seed to near zero, and none of the fumigants (including MB : CP) reduced little mallow seed viability compared to the untreated (data not shown).

At Watsonville, all of the single fumigant treatments provided control of prostrate knotweed seed buried at the bed center equivalent to MB : CP (Table 5). However, for seed buried at the edge of the bed, all but Telone C35 provided significantly less control of prostrate knotweed seed than MB : CP. Application of Vapam HL in combination with InLine or CP EC did not improve control of prostrate knotweed seed. Furthermore, the combination treatment of InLine at 236 L·ha^{-1} followed by Vapam HL at 420 L·ha^{-1} had significantly less activity on prostrate knotweed seed than InLine applied singly at 236 L·ha^{-1}. Applications of Vapam HL after CP EC provided significantly better prostrate knotweed seed control in the center of the bed than at the edge. InLine and Telone C35 did not differ in controlling prostrate knotweed on the center or edge of the beds.

Treatments that provided significantly better control of little mallow seed in the bed center than MB : CP were InLine at 393 L·ha–1 and CP EC at 130 L·ha^{-1} and Vapam HL alone at 420 or 700 L·ha^{-1} (Table 6). However, the percentage of viable seed was too high in these treatments to be considered effective control. At the edge of the bed, none of the

Table 5. Efficacy of CP, CP EC, Inline, Telone C35 and Vapam HL on prostrate knotweed seed viability compared to MB : CP at Watsonville in 2000. The data are percentage viable seed buried in the center and edge of a 1-m bed. The seed viability in the Inline or CP treatments with and without sequential applications of Vapam HL were compared to determine if sequential applications of Vapam HL improved weed control. Seed viability in the drip applications of Inline and shank applications of Telone C35 were also contrasted. The center vs. edge *P*-value indicates whether treatment effect on seed viability at the center vs. edge of the bed differed.

Treatment	Rate/ha	Application method	Prostrate knotweed Center	Prostrate knotweed Edge	Center vs. edge
			___ viable (%)	___	*P* value
Contrast single treatments vs. MB : CP standard					
MB : CP standard	425 kg	shank	0.13	1.77	0.73
Telone C35	374 L	shank	0.25 (0.92)[z]	26.82 (0.26)	0.08
Inline	236 L	drip	0.06 (0.95)	88.63 (<0.01)	<0.01
Inline	393 L[y]	drip	0.07 (0.95)	49.38 (0.04)	<0.01
CP EC	130 L	drip	1.83 (0.52)	89.27 (0.03)	<0.01
Vapam HL	420 L	drip	5.45 (0.20)	91.70 (<0.01)	<0.01
Vapam HL	700 L[x]	drip	3.17 (0.29)	90.48 (<0.01)	<0.01
Untreated	0	---	98.3 (<0.01)	79.80 (<0.01)	0.28
Contrast fumigant applied alone vs. fumigant followed by (fb) Vapam HL					
Inline	236 L	drip	0.06	88.63	---
Inline fb Vapam HL	236 L fb 420 L	drip	18.46 (<0.01)[w]	23.91 (.07)	0.81
CP EC	130 L	drip	1.83	89.27	---
CP EC fb Vapam HL	130 L fb 420 L	drip	0.06 (0.48)	64.42 (0.25)	<0.01
Contrast Inline drip vs. Telone C35 shank					
Inline	393 L[y]	drip	0.07	49.38	---
Telone C35	374 L	shank	0.25 (0.85)[v]	26.82 (0.43)	0.08

[z]*P* value of single degree of freedom contrasts comparing weed biomass weights with the MB : CP standard.

[y]Average weed biomass of Inline at 393 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43 and 61 L·m^2.

[x]Average weed biomass of Vapam HL at 700 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43 and 61 L·m^2.

[w]*P* value of single df contrasts comparing the weed biomass of Inline or CP treatments applied with a sequential application of Vapam HL were compared to Inline or CP applied without Vapam HL.

[v]*P* value of single df contrasts comparing the weed biomass from the Inline drip-applied treatment to the Telone C35shank-applied treatment.

treatments, had a significant effect on little mallow seed viability. The application of Vapam HL after InLine or CP EC did not improve the control of little mallow seed. At the bed center, InLine provided significantly better control of little mallow seed than Telone C35.

Discussion

Results from our studies suggest that the following treatments can provide weed control equivalent to shank injection of MB : CP: 1) drip fumigation with InLine at 236 or 393 L·ha^{-1}; 2) CP EC at > 130 L·ha^{-1}; and 3) shank injection of Telone C35 at 374 L·ha^{-1}. At times, drip fumigation with InLine provided better weed control than shank injection with the same rates of Telone C35 or CP (Tables 2, 3, and 6). This may be due to increased retention of the fumigant in the soil where drip application was used (Ajwa and Trout, 2000). The advantage of the shank application compared to the drip application, may be in weed control on the edge of the bed. The shank-applied materials were injected with shanks spaced 35 cm apart (20 cm from the edge of the bed) that resulted in fairly uniform concentrations of the fumigant across the bed (H. Ajwa, unpublished results). With drip fumigation, the distribution of chemicals was controlled by initial water distribution. Fumigants applied through the drip irrigation system must move with water so that the fumigant can be delivered to the target zone where the fumigant contacts and kills the weed seeds. At Salinas, the weed control provided by InLine on the edge of the bed did not differ from MB : CP (Table 4). At Watsonville, InLine provided poor control of prostrate knotweed seed at the edge of the bed (Table 5). Similar to InLine, the CP EC treatment was less effective in controlling weeds at the edge of the bed than MB : CP (Table 5). In Salinas, the amount of water used to apply the fumigant (>43 L·m^{-2}) was sufficient to move the chemicals to the edge of the raised bed, which resulted in better control of weed seeds. In Watsonville, this amount of water did not move to the edge of the raised bed (Ajwa, unpublished).

At Watsonville, lateral water movement could also have been limited due to channels in the bed caused by fertilizer shanks or due to placement of the drip tape too close to the bed center. The drip tapes at Watsonville were 30 cm from the edge of the bed, and at Salinas were 25 cm from the edge of the bed. Drip tape placement and soil type and conditions may have resulted in poor lateral movement of the application water to the edge of the bed. The poor weed control at the edge of the bed in drip fumigation treatments at the Watsonville location may indicate that the distance that a fumigant can move with the irrigation water is limited. Once the critical distance has been exceeded, e.g. at the edge of the bed, the fumigant dose drops below concentrations lethal to weed seeds and poor weed control results.

In both locations, Vapam HL alone did not provide sufficient control of weed seed on the edges of the beds compared to MB : CP (Tables 4 and 5). This could be due to the fast generation and dissipation of MITC during and immediately after Vapam HL application. Inadequate lateral movement of the application water may have contributed to the poor weed control at the edge of the bed. Other studies have reported that Vapam HL is generally more effective when applied in irrigation water (chemigation) than by shank injection (Baines et al., 1957; McGovern et al. 1998; Noling and Becker, 1994; Roberts et al., 1988). Our results indicate that the efficacy of MITC generated from Vapam HL during and after drip fumigation may differ from other chemigation practices (such as sprinkler application), and that drip irrigation systems should be designed for optimum lateral soil distribution of Vapam HL rather than for irrigation purposes only.

When CP EC and Vapam HL were applied simultaneously for the 1999 growing season, the weed control efficacy was diminished (Table 2). This may be due to rapid degradation/hydrolysis of CP and Vapam HL in the irrigation water such that fumigant efficacy was reduced (Trout and Ajwa, 1999). Because of this chemical incompatibility, Vapam HL treatments in 2000 were applied as sequential treatments 6 d after the application of InLine or CP EC. However, the small contribution of Vapam HL to weed control after drip fumigation with InLine or CP EC may indicate that these fumigants have greater activity in the water phase against weeds than Vapam HL. The results presented here suggest that application of Vapam HL after drip fumigation with InLine or CP EC is not needed. However, in other research we have found that weed densities and hand weeding times were reduced when Vapam HL was applied after shank injection of CP (Fennimore et al., 2001). Also, the combination treatments resulted in excellent control of soilborne pathogens and produced strawberry yields equivalent to MB : CP treatments (Ajwa and Trout, 2000). Further research will be necessary to determine if the economic benefits of sequential applications of Vapam HL are justified in commercial fields.

The amount of California burclover in the MB : CP treatment was greater than that found in the untreated check. Two possible explanations for this result are: 1) that California burclover in the MB : CP plots were not subjected to the competition from other easily controlled weeds such as common chickweed that were abundant in the untreated plots, thus the California burclover plants grew larger in the MB : CP plots, and/or 2) that the MB : CP stimulated California burclover seed germination and thus there were more California burclover plants in the MB : CP plots. While there is no direct evidence of MB : CP stimulation of seed germination, it has been demonstrated that low doses of metam sodium stimulate the germination of dormant large crabgrass seed (Teasdale and Taylorson, 1986). It is possible that MB : CP stimulates the germination of dormant California burclover seed. Biomass of California burclover from the drip-applied 1,3-D:CP or CP treatments did not differ from the

Table 6. Efficacy of CP, CP EC, Inline, Telone C35, and Vapam HL on little mallow seed viability compared to MB : CP at Watsonville in 2000. The data are percentage viable seed buried in the center and edge of a 1-m bed. The seed viability in the 1,3-D:CP or CP treatments with and without sequential applications of Vapam HL were contrasted to determine if sequential applications of Vapam HL improved weed control. Seed viability in the drip applications of Inline and shank applications of Telone C35 were also contrasted. The center vs. edge *P* value indicates whether treatment effect on seed viability at the center vs. edge of the bed differed.

		Application	Little mallow		
Treatment	Rate/ha	method	Center	Edge	Center vs. edge
			% viable		*P* value
Contrast single treatments vs. MB : CP standard					
MB : CP standard	425 kg	shank	88.66	83.50	0.20
Telone C35	374 L	shank	86.84 (0.59)[z]	79.65 (0.39)	0.09
Inline	236 L	drip	85.71 (0.39)	85.11 (0.76)	0.88
Inline	393 L[y]	drip	76.90 (<0.01)	78.71 (0.20)	0.30
CP EC	130 L	drip	80.65 (0.03)	84.69 (0.39)	0.34
Vapam HL	420 L	drip	80.71 (0.03)	83.87 (0.50)	0.46
Vapam HL	700 L[x]	drip	82.02 (0.03)	79.22 (0.22)	0.37
Untreated	0	---	82.80 (0.12)	80.00 (0.46)	0.51
Contrast fumigant applied alone vs. fumigant followed by (fb) Vapam HL					
Inline	285.6	drip	85.71	85.11	---
Inline fb Vapam HL	285.6 fb 212	drip	82.58 (0.40)[w]	78.39 (0.34)	0.35
CP EC	130 L	drip	80.65	84.69	---
CP EC fb Vapam HL	130 L fb 420 L	drip	80.02 (0.88)	75.59 (0.11)	0.34
Contrast Inline drip vs. Telone C35 shank					
Inline	393 L[y]	drip	76.90	78.71	---
Telone C35	374 L	shank	86.84 (<0.01)[v]	79.65 (0.82)	---

[z]*P* value of single degree of freedom contrasts comparing weed biomass weights with the MB : CP standard.
[y]Average weed biomass of Inline at 393 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 4,3 and 61 L·m^{-2}.
[x]Average weed biomass of Vapam HL at 700 L·ha^{-1} applied by drip irrigation in three application volumes: 26, 43, and 61 L·m^{-2}.
[w]*P* value of single df contrasts comparing the weed biomass of Inline or CP EC treatments applied with a sequential application of Vapam HL were compared to Inline or CP EC applied without Vapam HL.
[v]*P* value of single df contrasts comparing the weed biomass from the Inline drip-applied treatment to the Telone C35 shank-applied treatment.

untreated control, although weed competition was reduced, suggesting that these fumigants do not stimulate weed seed, as does MB : CP. Another possibility is that InLine or CP EC are more active on California burclover seed than MB : CP, and thus kill more weed seed. Further research is needed before a definite conclusion can be made.

In conclusion, drip fumigation and shank injection with CP or a mixture of 1,3-D and CP (InLine and Telone C35) were highly active on the same weed species that MB : CP readily controls such as common chickweed. These fumigants were not effective on hard-to-control weeds such as little mallow, a weed that is also difficult to manage with MB : CP. Drip fumigation with InLine or CP EC alone may provide better control of California burclover than MB : CP. Drip fumigation with InLine may provide better weed control than shank injection of Telone C35 at equivalent rates. Under the conditions in this research, the application of Vapam HL 6 d after drip fumigation with InLine or CP EC was not justified for weed control. Estimates suggest that costs for most of these alternative fumigant treatments will be less than MB : CP (Table 1). For example, the cost of InLine fb Vapam HL at 236 fb 420 L·ha^{-1} was estimated at $1,802 (Table 1). Further research is needed to evaluate whether the use of Vapam HL following InLine or CP EC is a justifiable expense in terms of reduced hand weeding time as well as crop yield. Another line of research that should be followed is the order of fumigant application. For example, drip application of Vapam HL followed by InLine or CP EC application, may allow for reduced fumigant rates or improved efficacy. Teasdale and Taylorson (1986) found that low rates of metam sodium stimulated the germination of dormant large crabgrass seed. If low doses of metam sodium can be used to stimulate germination of dormant weed seed, then a sequential application of a fumigant such as drip-applied CP can be used to kill the germinating weed seed. This strategy may result in improved weed control.

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