Weed Control Efficacy and Economics of 1,3-Dichloropropene and Chloropicrin Applied at Reduced Rates under Impermeable Film in Strawberry Beds

Jayesh B. Samtani and Husein A. Ajwa

Department of Plant Sciences, University of California–Davis, 1636 East Alisal Street, Salinas, CA 93905

Rachael E. Goodhue

Department of Agricultural and Resource Economics, University of California–Davis, One Shields Avenue, Davis, CA 95616

Oleg Daugovish

University of California Cooperative Extension, Ventura, CA 93003

Zahanghir Kabir

U.S. Department of Agriculture-NRCS, Davis, CA 95616

Steven A. Fennimore¹

Department of Plant Sciences, University of California–Davis, 1636 East Alisal Street, Salinas, CA 93905

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Abstract. Fumigants are used to control soilborne pests before planting high-value crops such as strawberry. The use of specialized tarps during fumigation can reduce fumigant emissions and mitigate the need for large buffer zone requirements mandated by regulators. Increased fumigant retention by use of barrier films during fumigant application may increase fumigant retention and allow use of lower fumigant rates to control soil pests than would be needed with permeable film. The objective of this study was to determine the minimum effective rates of the alternative fumigants, 1,3-dichloropropene (1,3-D) + chloropicrin (Pic), and Pic required under virtually impermeable film (VIF) and a high-density polyethylene (HDPE) tarp to provide weed control equivalent to methyl bromide:chloropicrin (67/33% v/v MBPic) standard soil fumigation at 392 kg·ha⁻¹ under HDPE. A second objective was to determine fumigant rates under VIF and HDPE tarps needed to provide weed control and the economic costs of using VIF and reduced rates of the alternative fumigants. In 2002–2003 and 2003–2004 growing seasons, the fumigants 1,3-D + Pic and Pic were tested at 0, 56, 112, 224, 336, and 448 kg·ha⁻¹ under HDPE and VIF tarps at Oxnard and Watsonville, CA. An untreated control and a MBPic standard at 392 kg·ha⁻¹ were also included in the study. Weed control was assessed using weed propagule viability bioassays for four common weeds, time required for hand weeding, and weed fresh biomass. The fumigant rate that would be needed for a 90% reduction in viability (GR₉₀) for all weeds was 21% to 84% less for 1,3-D + Pic under VIF compared with the HDPE tarp. For Pic, the GR₉₀ values were 5% to 64% less under VIF compared with the HDPE tarp. Hand weeding times and weed biomass decreased with increasing fumigant rates. With the exception of Pic in 2002–2003 at Oxnard, VIF reduced the rate required for weed control compared with the HDPE tarp for both fumigants and at both locations. Economic benefits of VIF relative to the HDPE tarp were not consistent and additional work is needed to quantify these relationships and the production conditions under which VIF will be beneficial.

California strawberries account for over 85% of the total U.S. production, and in 2009, the California strawberry industry was valued at \$1.7 billion for the 16,107 harvestable hectares under production (Agricultural Marketing Resource Center, 2010; Economic Research Service–U.S. Department of Agriculture, 2010). The long strawberry growing period in California fields means that the crop must be protected from weed infestations for as long as 15 months. In addition to

competing with strawberries, weeds can harbor pathogens and insects that could affect the crop. All but a few fumigant-tolerant weed seed species such as California burclover (*Medicago polymorpha* L.) and common mallow (*Malva neglecta* Wallr.) are controlled by MB and Pic mixtures. Pre-plant mixtures of MBPic have been widely used since the 1960s in California strawberries to control soilborne diseases, nematodes, and weeds (Wilhelm and Paulus, 1980). However, MB has been classified as a Class I stratospheric ozone-depleting chemical and was phased out starting in 2005 under the Montreal Protocol (U.S. Environmental Protection Agency, 1993). Critical use exemptions for MB in strawberry and some other uses are still permitted under the Montreal Protocol terms (Duniway, 2002).

Currently approximately two-thirds of the strawberry acreage use alternatives to MB, but finding a complete replacement for MB has proven difficult for the strawberry industry as a result of numerous reasons (U.S. Environmental Protection Agency, 2009). The lack of MB may result in revenue decline of 25% for California strawberry growers (Goodhue et al., 2005). Chemical alternatives to MB include 1,3-D, Pic, and metam sodium (Duniway, 2002; Medina et al., 2006). The fumigant 1,3-D alone controls nematodes and some soilborne insects but has limited activity against soilborne plant pathogens and weeds (Noling and Becker, 1994). Pic controls pathogens but is less effective in controlling weeds and nematodes than MB (Noling and Becker, 1994; Wilhelm, 1999). The weed control effectiveness of 1,3-D + Pic is better than that of Pic alone (Fennimore et al., 2003), yet strawberry yields from the alternatives, 1,3-D + Pic and Pic have been comparable to MB treatments (Medina et al., 2006). Total annual applications of 1,3-D are however restricted in an area of 93.2 km² (defined as township) in California as a result of air quality concerns (California Department of Pesticide Regulation, 2009). Chloropicrin being volatile and toxic can also contribute to air pollution (Gan et al., 2000). Given these considerations, it is essential that fumigants be applied in a way that minimizes their impact on human health and the environment (Papiernik and Yates, 2002).

Under California's fumigant use regulations, the use of drip irrigation to apply fumigants and the use of specialized tarps such as VIF during fumigation reduce the required buffer zones (Ajwa et al., 2002). VIF differs from a HDPE tarp because VIF has additional gas-impermeable layers (such as ethylene vinyl alcohol, nylon, or polyamides) between polyethylene layers (Wang et al., 1997). The use of VIF can minimize fumigant emissions, increase fumigant retention over time, and reduce the rate needed for effective pest control (Gamliel et al., 1998; Minuto et al., 1999; Nelson et al., 2001).

Higher fumigant concentrations of 1,3-D and Pic were measured under VIF compared with a low-density polyethylene (LDPE) tarp 1 to 4 d after drip fumigation (Desaeger and Csinos, 2005). Improved retention of fumigants in soil under VIF also provides more

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¹To whom reprint requests should be addressed; e-mail safennimore@ucdavis.edu.

opportunity for soil degradation of fumigants rather than release into the atmosphere (Wang and Yates, 1998). Use of VIF as a tarp can reduce 1,3-D + Pic needed for effective soil disinfestations by 50% (De Cal et al., 2004; Medina et al., 2006). Santos et al. (2005, 2007) found that reducing MBPic rates by one-half under VIF or metalized mulches provided nutsedge control similar or superior to application made at 392 kg-ha⁻¹ under LDPE or HDPE tarps. Desaegeer et al. (2004) studied the movement of 1,3-D and Pic under an LDPE tarp in raised sandy beds and found that fumigant concentrations were higher in the bed center than at the edge of the bed.

Weeds that escape on the edges of the beds can be problematic. The challenge is to drive fumigants to the edge of the planting bed in a concentration sufficiently high to kill the weed propagules there. Our study addressed the question whether 1,3-D + Pic and pure Pic applied under VIF has the potential to improve weed control in bedded strawberry compared with similar treatments applied under an HDPE tarp. The objectives of this study were to determine 1) the minimum effective rates of the alternative fumigants, 1,3-D + Pic and Pic, under VIF and an HDPE tarp required to control weeds equivalent to 67/33% v/v MBPic standard soil fumigation at 392 kg-ha⁻¹ under an HDPE tarp. A second objective was to determine fumigant rates under VIF and HDPE tarps needed to provide weed control and the economic costs of using VIF and reduced rates of the alternative fumigants.

Materials and Methods

Soil at the Oxnard site in the 2002–2003 season was a Hueneme sandy loam (coarse-loamy, mixed, calcarius, thermic, Cumulic Haploxeroll) with 60% sand, 28% silt, a pH of 7.8, and organic matter of 0.7%. In 2003–2004 at Oxnard, soil was a Camarillo loam (fine-loamy, mixed, calcareous, thermic, Aquic Xerofluvents) with 53% sand, 35% silt, a pH of 7.8, and organic matter of 1.4%. In both seasons, the Watsonville soil was an Elder sandy loam (coarse-loamy, mixed, thermic, Cumulic Haploxerolls) with 70% sand, 16% silt, pH of 6.6, and organic matter of 0.9%.

Fumigants tested were an emulsified formulation of 1,3-D and Pic mixture (InLine™, 60% 1,3-D and 32% Pic; Dow AgroSciences, Redek, NC) and Pic plus an emulsifier (Pic EC 95%; Niklor Chemical Co., Long Beach, CA). 1,3-D + Pic and Pic EC and were applied at 0, 56, 112, 224, 336, and 448 kg-ha⁻¹ in

water through the drip irrigation system into soil beds covered with tarp. Dates of fumigant application for the two seasons at both locations are listed in Table 1. Fumigants were injected into the irrigation water 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, CA). A static mixing device (TAH Industries, Inc., Robbinsville, NJ) was installed at the point of injection to mix fumigants with irrigation water before distribution in the drip irrigation system. A backflow device (Amiad Filtration Systems, Oxnard, CA) was used to prevent contamination of the water source. The commercial standard, MBPic 67/33% v/v, was applied at 392 kg-ha⁻¹. In 2002 at both Oxnard and Watsonville, MBPic was shank-injected 25 to 30 cm deep with two chisels spaced 35 cm apart into soil beds that were immediately covered with mulch. In 2003, the MBPic was applied at both locations by drip application as described previously for 1,3-D + Pic and Pic EC. Two types of tarp were used: standard HDPE (Pliant 38 µm; Pliant Corp., Washington, GA) and VIF (Bromostop 40 µm; Bruno Rimini Ag Ltd., London, U.K.). Each treatment was replicated four times using a split-plot design (with tarps as the main plot and fumigation treatments as subplots) arranged in a randomized complete block. Each subplot was one bed wide by 45.7 m long. Beds were 1.7 m wide (furrow to furrow) at Oxnard and 1.4 m wide at Watsonville as per standard commercial practices in each region. Strawberry transplanting dates at each location are presented in Table 1.

Weed control assessments. Weed control was assessed by three methods: 1) weed propagule viability bioassays; 2) timing of hand weeding by commercial crews; and 3) fresh weed biomass. For weed propagule viability tests, 50 seeds of common chickweed [*Stellaria media* (L.) Vill.], common purslane (*Portulaca oleracea* L.), prostrate knotweed (*Polygonum aviculare* L.), and 10 tubers of yellow nutsedge (*Cyperus esculentus* L.) were placed in 8 × 12-cm heat-sealed nylon mesh bags (Delnet, Middletown, DE). All seeds and tubers were gathered from agricultural fields near Salinas, CA, or propagated from weeds transplanted from agricultural fields and allowed to set seed on greenhouse benches. Four weed propagule bags were installed per subplot at depths of 5 and 15 cm,

at the center, and 4 cm from the edge of the beds. Seed bags were installed 1 week to 10 d before fumigation to allow the seeds and tubers to equilibrate with the soil moisture. Seed bags were retrieved ≈14 d after fumigation, and propagule viability was determined using the tetrazolium assay described in Peters (2000). Time for a worker to weed a specified length of the subplot was measured five to eight times per season, depending on the grower's decisions regarding weeding the surrounding commercial field. Weed fresh biomass (shoot and root) was collected and weighed during the event of hand weeding. The hand weeding time and weed biomass was recorded from bed length of 30 and 27 m in Oxnard in 2002–2003 and 2003–2004, respectively. At Watsonville, the weeding time and weed biomass data were recorded from length of 27 and 24 m in 2002–2003 and 2003–2004 growing seasons. Dates of yellow nutsedge and weed seed burial and retrieval as well as hand weeding and weed biomass collection dates are listed in Table 1.

Statistical analysis. For the weed seed viability data, the season × location interaction was not considered for both locations because the study was conducted at two different sites in Oxnard in the two growing seasons. The location × treatment interaction was observed and found significant ($P < 0.0001$) for all weed species (Tables 2 through 4). Separate regression analysis was performed for each location using Proc Probit in SAS (SAS Institute Inc., Cary, NC) to calculate the rate required to achieve a 50% and 90% reduction in the viability (GR₅₀ and GR₉₀, respectively) at 15-cm depth near the edge of the bed. Weed samples from this position were chosen because they had the highest survival.

Hand weeding time and weed biomass in MBPic plots were used as reference standards to estimate 1,3-D + Pic and Pic rates needed to be equal to MBPic under the HDPE tarp. Because labor and material costs varied across locations, data for hand weeding times were analyzed separately for each location. Barrier films such as VIF are coming into use in California primarily to limit fumigant emissions, but the impact of VIF on fumigant efficacy cannot be ignored (California Department of Pesticide Regulation, 2010). A separate analysis of the VIF and standard films was therefore necessary to assess their individual effects on pests such as weeds. Separate analysis of the tarps also made it possible to determine the economic feasibility of the VIF

Table 1. Date of fumigation, strawberry cultivars, strawberry transplanting date, weed data collection, and other significant information pertaining to the method of study.

Significant dates	Oxnard		Watsonville	
	2002–2003	2003–2004	2002–2003	2003–2004
Weed samples installed	3 Sept. 2002	20 Aug. 2003	19 Sept. 2002	16 Sept. 2003
Fumigation date	16 Sept. 2002	27 Aug. 2003	1 Oct. 2002	24 Sept. 2003
Weed samples retrieved	1 Oct. 2002	18 Sept. 2003	16 Oct. 2002	7 Oct. 2003
Cultivar	Camarosa	Plant Sciences 269	Camarosa	Camarosa
Transplanting date	7 Oct. 2002	3 Oct. 2003	25 Oct. 2002	20 Oct. 2003
Hand weeding timed and weed biomass collected	25 Nov. 2002, 14 Jan., 24 Feb., 25 Mar., 8 May 2003	30 Oct., 20 Nov., 18 Dec. 2003, 27 Jan., 1 Mar., 1 Apr., 22 Apr., 18 May 2004	3 Dec. 2002, 18 Feb., 2 Apr., 2 May, 9 June 2003	2 Dec. 2003, 21 Jan., 8 Mar., 7 Apr., 12 May 2004

with the two fumigants. Data for each fumigant were also analyzed separately to identify precise rates that would be needed to replace the MBPic standard. The weed biomass data were not used for determining the economic aspect of the study and so the biomass data were pooled over locations and tarps because both the three-way, location $\times$ tarp $\times$ dose, and the two-way, tarp $\times$ dose, interactions were not significant.

Before running the regression analysis, the $\log_{10}(x)$ transformation was used for both hand weeding time and weed biomass to meet the assumptions of normality for regression analysis. Analysis was run on the transformed data using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA). Response of the hand weeding time and biomass to fumigant rates were best defined by exponential or linear trends taking R^2 values into consideration and using SigmaPlot 11.0. The 1,3-D + Pic and Pic rates under the two tarps that would be needed to replace the MBPic standard were calculated using 1) exponential equations $f = y_0 + a \cdot \exp(-bx)$ or $f = a \cdot \exp(-bx)$ where f = hand weeding time or weed biomass for the MBPic standard soil fumigation at 392 kg-ha⁻¹ under the HDPE tarp, a and b are the parameters, and x = rate for the alternative fumigants under either VIF or HDPE tarps needed to replace MBPic standard soil fumigation at 392 kg-ha⁻¹ under HDPE tarp; and 2) linear equation $f = y_0 + ax$ where f = hand weeding time or weed

biomass for the MBPic standard soil fumigation at 392 kg-ha⁻¹ under the HDPE tarp, y_0 = intercept (the value of f when $x = 0$), a = slope of the line, and x = rate for the alternative fumigants under either VIF or HDPE tarps needed to replace MBPic standard soil fumigation at 392 kg-ha⁻¹ under HDPE tarp.

Results and Discussion

Weed sample viability. Standard soil fumigation with MBPic controls most weed species with the exception of weeds such as common mallow and burclover (Daugovich and Fennimore, 2008; Wilhelm and Paulus, 1980). In our study MBPic standard soil fumigation at 392 kg-ha⁻¹ under the HDPE tarp killed common chickweed, common purslane, knotweed, and yellow nutsedge weed propagules positioned at 15 cm depth near the edge of the bed, except at Oxnard in the 2002–2003 season where viability of common chickweed, common purslane, and knotweed was 25%, 40%, and 35%, respectively. Rates of alternative fumigants that controlled weeds equivalent to MBPic were estimated using the GR₉₀ values of the alternative fumigants under the two tarps. The GR₅₀ values are also presented because proc probit predictions are most accurate at that level.

At Oxnard, GR₉₀ and GR₅₀ values of common chickweed over both seasons for 1,3-D + Pic were 22% to 49% less under VIF as com-

pared with HDPE tarp (Table 2). At Watsonville, GR₉₀s and GR₅₀s for 1,3-D + Pic were 74% to 83% less for the two seasons under VIF as compared with the HDPE tarp. For Pic, over both seasons, the GR₅₀s and GR₉₀s at Oxnard were 18% to 52% less under VIF as compared with the HDPE tarp. At Watsonville, the GR₉₀s and GR₅₀s for Pic under VIF were reduced in the range of 5% to 48% as compared with the HDPE tarp.

Common purslane GR₉₀ and GR₅₀ values followed similar trends as common chickweed with rates for 1,3-D + Pic at Oxnard reduced in the range of 21% to 47% under VIF as compared with the HDPE tarp over the two seasons (Table 3). At Watsonville, GR₉₀s and GR₅₀s for 1,3-D + Pic were 48% to 73% less under the VIF tarp compared with the HDPE tarp over the two seasons. For Pic in 2002–2003 at Oxnard, the GR₉₀ value was reduced by 22% under VIF compared with the HDPE tarp, but in 2003–2004, a 10% increase in the Pic GR₉₀ value was observed under VIF as compared with the HDPE tarp. For both seasons, however, the GR₅₀ value for Pic was 12% and 18% less for VIF than the HDPE tarp. At Watsonville, in 2002–2003, the Pic GR₉₀ and GR₅₀ values were reduced by 54% and 41%, respectively, under the VIF tarp in comparison with the HDPE tarp.

For knotweed, at Oxnard, the GR₉₀ and GR₅₀ values over the two seasons for 1,3-D + Pic

Table 2. Effect of 1,3-D + Pic and Pic under VIF and HDPE tarps on common chickweed viability at 15-cm depth near the edge of the bed, at Oxnard and Watsonville, CA.

		VIF		HDPE	
		GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)	GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)
Location	Season	(kg·ha ⁻¹)			
1,3-D + Pic					
Oxnard	2002–2003	177.0 (169.6, 184.6) ^z	304.8 (292.6, 318.5)	346.3 (335.6, 357.6)	534.5 (514.3, 557.8)
Oxnard	2003–2004	146.3 (134.6, 157.8)	415.2 (391.8, 442.6)	228.1 (214.6, 241.8)	530.5 (500.5, 566.0)
Watsonville	2002–2003	48.5 (45.0, 52.0)	88.9 (83.5, 95.4)	188.3 (176.8, 200.1)	401.8 (380.0, 427.2)
Watsonville	2003–2004	71.6 (66.3, 82.1)	85.3 (76.8, 104.6)	315.4 (300.8, 331.3)	513.8 (486.6, 546.3)
Pic					
Oxnard	2002–2003	241.8 (233.5, 250.2)	389.4 (375.8, 404.9)	295.8 (282.7, 310.0)	561.2 (531.8, 595.6)
Oxnard	2003–2004	120.3 (109.6, 130.7)	351.7 (331.1, 375.6)	251.9 (241.6, 262.4)	451.9 (433.2, 473.2)
Watsonville	2002–2003	156.3 (149.5, 163.2)	262.7 (251.3, 275.5)	232.2 (218.1, 247.1)	500.8 (469.8, 537.6)
Watsonville	2003–2004	207.9 (195.8, 220.5)	380.2 (360.0, 404.1)	233.3 (222.1, 244.6)	400.0 (381.9, 420.4)

^zValues in parentheses beside the GR₅₀ and GR₉₀ values indicate their lower and upper 95% fiducial limits in kg-ha⁻¹.

1,3-D = 1,3-dichloropropene; Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene.

Table 3. Effect of 1,3-D + Pic and Pic under VIF and HDPE tarps on common purslane viability at 15-cm depth near the edge of the bed, at Oxnard and Watsonville, CA.

		VIF		HDPE	
		GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)	GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)
Location	Season	(kg·ha ⁻¹)			
-----1,3-D + Pic-----					
Oxnard	2002–2003	221.1 (214.7, 227.8) ^z	311.4 (301.9, 322.7)	417.5 (406.9, 428.9)	565.8 (544.4, 590.5)
Oxnard	2003–2004	228.5 (217.2, 240.0)	480.2 (456.9, 507.1)	286.5 (272.1, 302.0)	608.8 (573.7, 650.4)
Watsonville	2002–2003	169.4 (160.3, 178.5)	327.0 (312.1, 343.8)	360.3 (342.1, 379.8)	627.8 (589.5, 674.7)
Watsonville	2003–2004	84.7 (75.3, 94.1)	193.0 (178.0, 211.3)	314.8 (301.8, 328.3)	476.4 (454.5, 502.7)
-----Pic-----					
Oxnard	2002–2003	260.0 (251.9, 268.3)	398.3 (385.2, 413.1)	296.2 (285.5, 307.3)	507.1 (486.4, 530.9)
Oxnard	2003–2004	198.0 (187.5, 208.5)	428.4 (407.9, 451.9)	240.0 (231.7, 248.5)	391.0 (377.1, 406.8)
Watsonville	2002–2003	149.0 (143.3, 155.4)	201.7 (192.4, 212.9)	252.0 (240.8, 263.8)	437.4 (416.8, 461.4)
Watsonville	2003–2004	— ^y	—	126.9 (121.6, 134.0)	168.2 (156.8, 185.0)

^zValues in parentheses beside the GR₅₀ and GR₉₀ values indicate their lower and upper 95% fiducial limits in kg-ha⁻¹.

^yMissing data.

1,3-D = 1,3-dichloropropene; Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene.

Table 4. Effect of 1,3-D + Pic and Pic under VIF and HDPE tarps on knotweed viability at 15-cm depth near the edge of the bed, at Oxnard and Watsonville, CA.

		VIF		HDPE	
		GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)	GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)
Location	Season	(kg·ha ⁻¹)			
1,3-D + Pic					
Oxnard	2002–2003	234.2 (226.0, 242.6) ^z	380.9 (367.4, 396.3)	1004.2 (829.1, 1325.0)	1677.8 (1349.8, 2284.5)
Oxnard	2003–2004	243.4 (233.0, 254.2)	466.6 (445.9, 490.1)	410.2 (389.0, 434.8)	766.4 (714.7, 830.1)
Watsonville	2002–2003	11.0 (0.2, 20.4)	151.4 (137.9, 168.3)	130.1 (90.6, 164.8)	956.7 (805.8, 1197.1)
Watsonville	2003–2004	151.4 (141.4, 161.8)	282.5 (266.1, 301.9)	621.1 (561.4, 712.6)	908.5 (798.2, 1083.6)
Pic					
Oxnard	2002–2003	407.0 (390.8, 425.4)	673.8 (638.1, 716.8)	681.6 (618.5, 770.6)	1080.2 (958.0, 1256.0)
Oxnard	2003–2004	316.5 (303.5, 330.2)	580.5 (552.1, 613.4)	467.9 (445.6, 494.5)	766.0 (716.9, 826.7)
Watsonville	2002–2003	100.2 (84.9, 114.6)	432.5 (400.3, 472.1)	126.6 (87.9, 161.3)	933.6 (784.7, 1170.9)
Watsonville	2003–2004	294.0 (281.6, 306.8)	463.4 (442.6, 488.1)	484.9 (457.5, 519.8)	746.6 (689.0, 823.3)

^zValues in parentheses beside the GR₅₀ and GR₉₀ values indicate their lower and upper 95% fiducial limits in kg·ha⁻¹.

1,3-D = 1,3-dichloropropene; Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene.

Table 5. Effect of 1,3-D + Pic and Pic under VIF and HDPE tarps on yellow nutsedge viability at 15-cm depth near the edge of the bed, at Watsonville, CA, in 2002–2003.

Fumigant	VIF		HDPE	
	GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)	GR ₅₀ (fiducial limits)	GR ₉₀ (fiducial limits)
(kg·ha ⁻¹)				
1,3-D + Pic	164.3 (153.4, 175.2) ^z	382.4 (363.0, 404.8)	294.0 (264.2, 330.8)	934.0 (816.8, 1102.7)
Pic	143.8 (135.8, 151.9)	302.4 (287.8, 319.0)	244.7 (217.3, 276.5)	840.9 (738.9, 984.9)

^zValues in parentheses beside the GR₅₀ and GR₉₀ values indicate their lower and upper 95% fiducial limits in kg·ha⁻¹.

1,3-D = 1,3-dichloropropene; Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene.

were 40% to 77% less under VIF as compared with the HDPE tarp (Table 4). A greater reduction in the range of 69% to 92% of the GR₉₀ and GR₅₀ values under the VIF tarp were found in Watsonville over the two seasons. For Pic, at Oxnard, GR₉₀ values under VIF were 674 and 581 kg·ha⁻¹ in the two seasons, a reduction of 38% and 24%, respectively, from the HDPE tarp. For GR₅₀ values, a 40% and 32% reduction was observed in 2002–2003 and 2003–2004, respectively, from the use of VIF over the HDPE tarp. In Watsonville, for both seasons, the GR₉₀ and GR₅₀ values were reduced in the range of 21% to 54%. For knotweed, in both seasons, the GR₉₀ and GR₅₀ values under VIF were higher for Pic as compared with 1,3-D + Pic. For yellow nutsedge at Watsonville in 2002–2003, the GR₉₀s and GR₅₀s were reduced by 59% and 44%, respectively, for 1,3-D + Pic and by 64% and 41%, respectively, for Pic under VIF as compared with HDPE tarp (Table 5).

Results from the weed seed viability data suggest that the use of VIF can greatly reduce the rate for both 1,3-D + Pic and Pic as compared with the HDPE tarp to achieve the same level of weed control. Overall, GR₉₀ values for all weeds were reduced by 21% to 84% for 1,3-D + Pic and 5% to 64% for Pic, respectively, under VIF as compared with the HDPE tarp. This difference in relative benefits of VIF for Pic alone and 1,3-D + Pic is likely the result of the longer soil half-life of 1,3-D (2 to 17 d) than Pic alone (0.2 to 4 d). Pic trapped under VIF degrades more rapidly than 1,3-D and so lethal concentrations of 1,3-D under VIF are maintained for longer periods than for Pic.

Hand weeding time and weed biomass. Hand weeding times and weed biomass were inversely related to fumigant rate. Based on

Table 6. Fumigant rate under the two tarps for 1,3-D + Pic and Pic predicted to achieve the same hand weeding h·ha⁻¹ as the MBPic standard soil fumigation at 392 kg·ha⁻¹ under the HDPE tarp.

Fumigant	Season	Predicted fumigant rate (kg·ha ⁻¹)			
		Oxnard, CA		Watsonville, CA	
		VIF	HDPE	VIF	HDPE
1,3-D + Pic	2002–2003	370.4	463.0	224.0	428.8
1,3-D + Pic	2003–2004	<224.0 ^z	618.8	<224.0	1228.9
Pic	2002–2003	509.6	410.4	343.5	828.8
Pic	2003–2004	<224.0	786.1	396.3	723.3

^zA total of 224 kg·ha⁻¹ was considered the lowest feasible application rate for both alternative fumigants and predicted values less than 224 kg·ha⁻¹ were not calculated.

1,3-D = 1,3-dichloropropene; Pic = chloropicrin; MBPic = methyl bromide:chloropicrin; HDPE = high-density polyethylene.

the hand weeding times in both seasons at Oxnard, the 1,3-D + Pic rate under the HDPE tarp predicted to replace the MBPic standard fumigation exceeded the maximum rate of 448 kg·ha⁻¹ used in our study (Table 6; Fig. 1). Such predictions made beyond the range of studied data are generally not very accurate (Steel and Torrie, 1980). One reason for these high dose rates specifically in 2003–2004 at Oxnard is the high population of common mallow, which was hard to control by all fumigants, including the MBPic standard (Wilhelm and Paulus, 1980). At Oxnard in 2002–2003, the 1,3-D + Pic rates needed to equate MBPic were 20% less under VIF than HDPE tarp (Table 6). Similarly in 2003–2004 where VIF was used, less 1,3-D + Pic was needed to equate MBPic equivalent weeding times than where the HDPE tarp was used.

At Watsonville, an effective replacement rate of 1,3-D + Pic in the 2002–2003 season was 224 kg·ha⁻¹ under VIF and 429 kg·ha⁻¹ under the HDPE tarp (Table 6; Fig. 1). Hand weeding times at 56, 112, and 224 kg·ha⁻¹ of 1,3-D + Pic was significantly less under the VIF tarp than the HDPE tarp (Fig. 1). Notably,

the 1,3-D + Pic rate under the HDPE tarp needed to equate the MBPic standard soil fumigation in 2003–2004 at Watsonville exceeded the maximum rate used in the study. 1,3-D + Pic rates that would be needed to replace the MBPic standard at Watsonville were reduced 48% and 82% or greater, respectively, in the VIF-covered bed in 2002–2003 and 2003–2004 seasons (Table 6).

In 2002–2003, at Oxnard, the predicted Pic rate needed to replace MBPic increased under VIF by 24% and exceeded the maximum rate used in the study (Table 6). The improved predicted performance of the HDPE tarp over VIF was because the hand weeding time means recorded in our study at 224 and 336 kg·ha⁻¹ were numerically higher for VIF than the HDPE tarp (Fig. 2). A rate less than 224 kg·ha⁻¹ was estimated for Pic in 2003–2004 (Table 6). Hand weeding means were significantly lower under the VIF tarp than the HDPE tarp for Pic in 2003–2004 (Fig. 2).

In 2002–2003, at Watsonville, 829 kg·ha⁻¹ of Pic under the HDPE tarp was predicted as a replacement rate for the MBPic standard soil fumigation (Table 6; Fig. 2). For both trial runs

Fig. 1. Effect of 1,3-D + Pic fumigant rates with VIF and HDPE tarps on hand weeding time means ($\pm$ SE, N = 4) at Oxnard, CA, in 2002–2003 (A) and 2003–2004 (B) seasons and at Watsonville, CA, in 2002–2003 (C) and 2003–2004 (D) seasons. Reference line in A–D is of the MBPic standard applied at 392 kg·ha⁻¹ under an HDPE tarp. 1,3-D = 1,3-dichloropropene; Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene; MBPic = methyl bromide:chloropicrin.

at Watsonville, the Pic rates under the HDPE tarp needed to replace MBPic standard soil fumigation exceeded maximum rates tested (Table 6). However, under VIF for Pic, the predicted rates were within the range of the rates included in the study. Rates for Pic were reduced by 59% and 45% for the two seasons, respectively, under VIF compared with the HDPE

tarp. With the exception of Pic in 2002–2003 at Oxnard, fumigant rates needed for MB equivalence were less under VIF than the HDPE tarp.

For weed biomass, the rates of the alternative fumigants averaged over tarps and seasons were less than 448 kg·ha⁻¹ with the exception of Pic in 2003–2004 season. For 1,3-D + Pic and Pic in 2002–2003, the predicted

rates were 166 and 355 kg·ha⁻¹, respectively. In 2003–2004, the predicted rates were 416 and 483 kg·ha⁻¹ respectively.

Economic analysis. As a result of the need for prophylactic treatment of soil pathogens required for controlling pathogens throughout the soil rooting zone, 224 kg·ha⁻¹ is the minimum feasible rate for drip applications

Fig. 2. Effect of Pic fumigant rates with VIF and HDPE tarps on hand weeding time means ($\pm$ SE, $N = 4$) at Oxnard, CA, in 2002–2003 (A) and 2003–2004 (B) seasons and at Watsonville, CA, in 2002–2003 (C) and 2003–2004 (D) seasons. Reference line in A–D is of the MBPic standard applied at 392 kg·ha⁻¹ under an HDPE tarp. Pic = chloropicrin; VIF = virtually impermeable film; HDPE = high-density polyethylene; MBPic = methyl bromide:chloropicrin.

(Ajwa et al., 2002). We compare hand weeding plus fumigant material costs for application rates of 224 and 336 kg·ha⁻¹ under VIF and 336 kg·ha⁻¹ under the HDPE tarp for each fumigant, trial location, and season. This procedure allows us to assess the potential benefits of reduced application rates under VIF taking changes in the hand weeding times into account. Results are reported in Table 7, which uses the following cost specifications: 1,3-D + Pic cost at \$6.77/kg, Pic cost at \$8.62/kg, HDPE tarp cost at \$0.068/m², and VIF cost at \$0.129/m². Bed shares of field acreage and hand weeding wages and benefits per hour varied by location. Oxnard's bed share is

Table 7. Cost of tarp, fumigant, and hand weeding by fumigant, location, season, tarp, and application rate.

Fumigant	Season	Application rate (kg·ha ⁻¹)	Material + hand weeding cost			
			Oxnard, CA		Watsonville, CA	
			VIF	HDPE	VIF	HDPE
			(US \$/ha)			
1,3-D + Pic	2002–2003	224	2482	2032	2413	1999
1,3-D + Pic	2002–2003	336	3239	2789	3170	2756
1,3-D + Pic	2003–2004	224	2488	2039	2412	1994
1,3-D + Pic	2003–2004	336	3246	2797	3169	2751
Pic	2002–2003	224	2899	2447	2830	2415
Pic	2002–2003	336	3864	3413	2795	3380
Pic	2003–2004	224	2904	2455	2828	2404
Pic	2003–2004	336	3869	3420	3794	3366

VIF = virtually impermeable film; HDPE = high-density polyethylene; 1,3-D = 1,3-dichloropropene; Pic = chloropicrin; Pic = chloropicrin.

73.53% and its wage and benefits/h is \$9.38. Watsonville's bed share is 67.9% and its wage and benefits/h is \$9.72.

At a given application rate, when VIF reduces the hand weeding costs, it is unlikely to do so to the extent that the cost of VIF is offset by the reduction in weeding costs. However, the potential weed control benefit for growers of using VIF is the possibility of achieving equivalent efficacy at a lower application rate, which could reduce production costs. Additionally, reduction in emissions with the use of VIF can aid in sustaining production in townships where regulatory constraints may otherwise limit fumigant use (Nelson et al., 2001).

Given the wages, fumigant prices, and tarp prices used in the economic analysis, it was never less costly to use VIF than an HDPE tarp at any given application rate. Although a reduction in the price of VIF relative to the price of an HDPE tarp will narrow the cost difference, hand weeding costs are sufficiently small relative to other costs that even a substantial narrowing of the difference in tarp price will not result in VIF having lower overall costs. However, it was always less costly to apply 224 kg·ha⁻¹ of a fumigant under VIF than to apply 336 kg·ha⁻¹ under an HDPE tarp. These results are largely driven by the magnitude of fumigant costs, which are much larger than hand weeding and tarp costs per hectare. In fact, if the use of VIF rather than an HDPE tarp allowed the application rate of 1,3-D to be reduced by 60 to 70 kg·ha⁻¹, then costs would be equivalent. Any greater reduction in the application rate would result in lower costs using VIF. For Pic, a reduction of ≈50 kg·ha⁻¹ would result in equivalent costs. Larger reductions would result in lower costs under VIF.

Summary

With the exception of Pic in 2002–2003 in Oxnard, VIF allowed reduced use of rates as compared with an HDPE tarp for both fumigants and at both locations. The variability in the net benefit that VIF provides in terms of the reduction in the fumigant application rate for weed control comparable to that of the standard application rate under the HDPE tarp suggests that more work is needed to quantify these relationships and the production conditions under which VIF is most beneficial.

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