Chemical Alternatives to Methyl Bromide for Weed Control and Runner Plant Production in Strawberry Nurseries

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Abstract. The phase out of methyl bromide (MB) requires effective alternatives for soil disinfection, particularly in high-elevation strawberry (*Fragaria* × *ananassa* Duch.) nurseries. Methyl bromide alternative fumigants were evaluated over a 3-year period for weed control and runner plant yields at strawberry nurseries in Spain. Two types of field trials were carried out: replicated experiments and commercial-scale field demonstrations. In the replicated experiments, eight fumigant treatments were evaluated each year, including the nonfumigated control and commercial standard methyl bromide plus chloropicrin mixture (MB : Pic) (50 : 50 w/w). Among the treatments evaluated were dazomet, chloropicrin (Pic) alone, metam sodium plus chloropicrin (MS + Pic), 1,3-dichloropropene:chloropicrin (1,3-D : Pic) (61 : 35 w/w), DMDS plus chloropicrin (DMDS + Pic), and propylene oxide. The best alternative fumigant treatments from the replicated experiments were carried forward to the demonstration phase of the project. Treatments such as 1,3-D : Pic (300 kg·ha⁻¹), the combination of metam sodium plus chloropicrin (Pic) (400 to 500 + 150 to 250 kg·ha⁻¹), Pic alone (300 kg·ha⁻¹) as well as dazomet (400 kg·ha⁻¹) controlled weeds at the level of MB : Pic (400 kg·ha⁻¹). Runner plant yields, in soils previously fumigated with alternative fumigants varied, among years, locations, and trial scale, i.e., commercial scale, or small plot. By comparison, runner plant yields in MB : Pic-fumigated soils were consistently high among years, location, and trial scale. Chemical names used are: 1,3-D, 1,3-dichloropropene; MB, methyl bromide; Pic, trichloronitromethane; MS, sodium N-methyldithiocarbamate; DMDS, dimethyl disulphide; dazomet, tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione; PO, propylene oxide

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For years, strawberry (*Fragaria* × *ananassa* L.) runner plant nurseries have relied on methyl bromide (MB) or mixtures of MB and chloropicrin (Pic) fumigation of soil to produce healthy transplants (Ajwa et al., 2003; Kabir et al., 2005). Most strawberry nursery plants throughout the world are produced in disinfested soils under phytosanitary control and certification programs (Porter

et al., 2004); e.g., Spanish Technical Regulations on Control and Certification of Fruit Trees Production (strawberry nursery section). However, MB has been classified as an ozone-depleting substance (Anonymous, 2000) and it was banned in European Union countries in 2005 with the exception of critical use exemptions.

The majority of MB used in Spain is for preplant fumigation in strawberry (López-Aranda et al., 2002a). In 2005 and 2006, 230 t of MB was applied to 1300 ha in Castilla-León strawberry nurseries. More than 600 million strawberry runner plants per year were harvested and shipped to the coastal fruit production area of Huelva, Spain, and for export. The high-elevation nurseries are located at 800 to 1000 m in arid areas with light soils, relatively level terrain, hot summers, and cold winters. The mother plants are transplanted in the nurseries during April and May and daughter runner plants are harvested during October (De Cal et al., 2004). Approximately 95% of strawberry mother plants used in Spanish nurseries were produced in California (López-Aranda et al., 2002b). Rotations with cereal, sugar beet, and vegetable crops are common and the production field is moved periodically.

Variable weather conditions, soil moisture, soil texture, and uneven soil pest pressure may contribute to inconsistent fumigant performance among years. Soilborne pathogens (such as *Phytophthora cactorum*, *Verticillium* spp., *Rhizoctonia* spp., *Pythium* spp., and *Fusarium* spp.) and weeds are common pests of Spanish strawberry nurseries (De Cal et al., 2005a). Alternative fumigants must control weeds in strawberry nurseries because strawberry runner plant yields are sensitive to weed competition and because weeds can host many diseases (Wilhelm and Paulus, 1980). Most weeds that infest Spanish strawberry nurseries are annual weeds, although perennial weeds such as yellow nutsedge (*Cyperus esculentus* L.) and field bindweed (*Convolvulus arvensis* L.) are found. Generally, MB:Pic preplant fumigation controls most of these weeds. Another challenge is that a replacement fumigant must maintain runner plant yields and quality at the level of MB. The introduction of MB as a soil fumigant in Spain in the 1980s led to increased runner plants yields (Palacios-Vazquez, 2002). Duniway (2002a) and Porter et al. (2004) suggested that chemical and nonchemical alternatives to MB have not been developed for strawberry runner plant production to the extent that they have been for strawberry fruit production. Little research has been conducted on weed control and yield in strawberry nurseries either in Spain or elsewhere.

In Spain, commercially available alternatives to MB are Pic alone, metam sodium (MS), dazomet, 1,3 dichloropropene (1,3-D), and 1,3-D : Pic (61 : 35) mixture. Pic has always been applied in combination with MB as a soil fumigant and limited information is available for the weed control efficacy of Pic alone in strawberry runner plant nurseries.

The efficacy of Pic alone on soilborne pathogenic fungi is well documented (Wilhelm, 1999), although it is less effective on nematodes and weeds than MB (Himelrick and Dozier, 1991; Noling and Becker, 1994). MS in its active form, methylisothiocyanate (MITC), controls a broad spectrum of soilborne pests, including weeds (Teasdale and Taylorson, 1986). In previous work, we concluded that MS alone was not a stand-alone product because it was less effective than MB : Pic and 1,3-D : Pic for runner plant production (López-Aranda et al., 2002a). Recent studies have demonstrated that the combination of MS and propylene oxide (PO) (Rodríguez-Kabana and Simmons, 2004a) and dimethyl disulphide (DMDS) (Rodríguez-Kabana and Simmons, 2004b) controlled weeds.

Dazomet, a MITC generator, controls soilborne fungi, bacteria, nematodes, and weeds (Fritsch and Huber, 1995; Mappes, 1995); dazomet requires optimum soil moisture so that it dissolves and is fully activated after application to avoid residual activity and crop injury (Duniway, 2002b). In California strawberry nursery experiments, dazomet activated with sprinkler irrigation did not injure strawberry (Kabir et al., 2005).

The fumigant 1,3-D controls nematodes and is known to be active on certain plant pathogenic fungi and bacteria but does not control weeds (Noling and Becker, 1994). To expand the activity of 1,3-D, it is often used in combination with Pic and the results from 1,3-D : Pic fumigation are often comparable to MB : Pic (Carrera et al., 2004; Duniway et al., 1997). Although there is some information on strawberry runner plant production with Pic alone and 1,3-D : Pic (Larson and Shaw, 2000), little is known about the potential risks of pathogen damage and contamination of nursery materials grown without MB (Duniway, 2002a).

As a result of pending European Union regulations, it is possible that the use of 1,3-D and Pic alone or their mixtures with other fumigants will be prohibited in the near future. Appropriate viable alternatives to MB must be found for strawberry nurseries in Spain. Our objectives were: 1) to identify alternative soil disinfestation treatments that

control weeds and produce strawberry runner plant yields approximately equal to MB; and 2) to carry forward the most promising treatments from objective 1 to commercial-scale evaluations.

Materials and Methods

Fumigation trials were conducted in 2003 to 2005 at high-elevation nurseries located in Castilla-Leon (north-central Spain). Trials were conducted in both small replicated experiments and large commercial-scale demonstration fields. Mother plants of cultivar 'Camarosa', imported from California, were planted in each trial on soil that had not been fumigated with MB for at least 3 years. 'Camarosa' was used because it has been the most important variety in Spain since 1997. Standard cultural practices for runner plant production were followed (De Cal et al., 2004). Replicated plots and demonstration fields were located in Avila and Segovia provinces. Locations, elevations, and previous crops are listed in Table 1.

Small replicated plots. The plots in Avila province were at Vinaderos in 2003 and 2004 and at Palacios Rubios in 2005, whereas the plots in Segovia province were at Navalmanzano in 2003 to 2005. Soils at the sites were sandy loams with pH of 5.5 to 7.5 and organic matter content of 0.4%. Fumigation treatments, rates, and methods of application used at each site are listed in Table 2. Each treatment was applied in late March in 2003 and early April in 2004 and 2005, which was ≈ 3 weeks before planting each year. Treatments were arranged in a randomized complete block design with four replicates per treatment. Each replicate consisted of two 50-m long rows of mother plants (2.75 m wide). Plants were planted 0.32 m apart in 1.37-m wide rows and irrigated as needed by sprinkler irrigation on 9×9 -m spacing. Soil temperatures during fumigation were slightly higher than 7 °C and soil water content was 55% of field capacity. All fumigants except dazomet were applied 0.20 to 0.25 m deep using eight injection chisels spaced 0.33 m apart. Dazomet was applied to the soil surface and incorporated 0.14 to 0.15 m deep with a rototiller. Transparent low-density

polyethylene (PE) plastic film was used to cover commercial standard MB : Pic mix (50:50 w/w) treatments. Transparent, coextruded, three-layer, virtually impermeable plastic film (VIF) was used to cover the soil of all other treatments immediately after fumigation. Mixed treatments, i.e., MS + Pic, DMDS + Pic, and PO + Pic (in 2005) were simultaneously injected using two separate pressurized cylinders connected with the injection chisels. In the case of dazomet + 1,3-D : Pic (2005), dazomet was applied first followed by 1,3-D : Pic application later the same day.

To monitor weed populations at each location, areas of 3.5-m² sample quadrats were monitored in each plot throughout the duration of each study. Weeds in the sample quadrats were collected on five or six dates each season (year), from mid-June until early October. At each sample date, weed species present, total weed density, and total fresh weight were measured for each treatment. Strawberry runner plants were harvested by hand from three randomly selected 1-m² areas in the central part of each plot on 9 to 14 Oct. 2003, 5 to 6 Oct. 2004, and 10 to 11 Oct. 2005. Daughter plants harvested inside these three areas were classified as either marketable or unmarketable (i.e., less than 9- to 10-mm diameter crown) and counts of each plant category were recorded. In 2005, to monitor phytotoxicity phenomena induced by fumigant applications, a quick test was carried out in the Avila location (Palacios Rubios). The total number of mother plants per plot was observed on 1 July, just before runner activity, and the percentage of plant mortality resulting from phytotoxicity symptoms by visible inspection was recorded.

Demonstration fields. Field demonstrations were conducted in Segovia at Navalmanzano in 2003 and 2004 and at Mudrian in 2005 and in Cabezas de Alambre at Avila in 2003 to 2005. Soils at the sites were classified as sandy loams with similar characteristics as the experimental field plots. Fumigation treatments and rates used at each site are listed in Table 3. The MB:Pic mix (50 : 50 w/w), broadcast shank-applied at 400 kg/ha and covered with PE plastic film, was included as the commercial standard. All other treatments

Table 1. Locations of replicated plots and demonstration in Castilla-Leon, Spain, geographic coordinates, elevations, and previous crops.

Yr		Avila province		Segovia province	
		Small replicated plots	Demonstration fields	Small replicated plots	Demonstration fields
2003	Location	Vinaderos-1 ²	Cabezas de Alambre-1 ²	Navalmanzano-1 ²	Navalmanzano-1bis ²
	Geographic location	lat. 41°0'N, long. 4°7'W	lat. 40°9'N, long. 4°8'W	lat. 41°2'N, long. 4°3'W	
	Elevation (m)	840	900	837	
	Previous crop	Irrigated carrots	Nonirrigated cereals (wheat)	Irrigated potatoes	Nonirrigated cereals (wheat)
2004	Location	Vinaderos-2	Cabezas de Alambre-2	Navalmanzano-2	Navalmanzano-2 bis
	Geographic location	lat. 41°0'N, long. 4°7'W	lat. 40°9'N, long. 4°8'W	lat. 41°2'N, long. 4°3'W	
	Elevation (m)	840	900	837	
	Previous crop	Nonirrigated cereals (wheat)		Irrigated potatoes and carrots	Irrigated potatoes
2005	Location	Palacios Rubios	Cabezas de Alambre-3	Navalmanzano-3	Mudrián
	Geographic location	lat. 41°0'N, long. 4°8'W	lat. 40°9'N, long. 4°8'W	lat. 41°2'N, long. 4°3'W	
	Elevation (m)	850	900	837	830
	Previous crop	Nonirrigated cereals (wheat)			

²Same location name on different rotational parcels of the same nursery each year.

Table 2. Fumigation treatments applied to replicated plots planted with Camarosa strawberry in Castilla-Leon, Spain, during 2003 to 2005.

Treatment	Active ingredient ^z	Application rate (kg·ha ⁻¹)	Type of plastic ^y	Method of application	Formulated product, supplier
Nonfumigated	Untreated control				
MB:Pic	Methylbromide:chloropicrin (50:50 w/w)	400	PE	Shank, 8 chisels broadcast	Bromofifty, Eurobrom, Spain
Dazomet	Tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione	400 ^x	VIF	Incorporated, rototilled	Basamid, BASF, Spain
1,3-D:Pic (61:35)	1,3-Dichloropropene:chloropicrin (61:35 w/w)	300	VIF	Shank, 8 chisels broadcast	Telopic, Dow AgroSciences Iberica, Spain
Pic	Chloropicrin (trichloronitromethane)	300	VIF	Shank, 8 chisels broadcast	Chloropicrin, Mebron, Belgium
MS + Pic	Sodium N-methyldithiocarbamate + chloropicrin	400 + 250 ^w	VIF	Shank, 8 chisels broadcast	Arapam-50, Aragonesas Agro, Spain + chloropicrin
DMDS + Pic	Dimethyl disulphide + chloropicrin	250 + 250 ^v	VIF	Shank, 8 chisels broadcast	DMDS + chloropicrin mixture
PO	Propylene oxide	500 ^u	VIF	Shank, 8 chisels broadcast	Propozone, Aberco, USA

^zNumbers in parentheses indicate w/w mixture of the two chemicals listed.

^yFilm PE = transparent polyethylene; Film VIF = transparent virtually impermeable.

^xDazomet: rate of 250 kg·ha⁻¹ mixed with 200 kg·ha⁻¹ of 1,3-D:Pic (61:35) in 2005.

^wMS + Pic: rate of 500 kg·ha⁻¹ + 150 kg·ha⁻¹ in 2005.

^vDMDS + Pic: rate of 400 kg·ha⁻¹ + 150 kg·ha⁻¹ in 2005.

^uPO: rate of 450 kg·ha⁻¹ mixed with 350 kg·ha⁻¹ of MS in 2005.

Table 3. Fumigation treatments applied to demonstration nursery fields planted with Camarosa strawberry in Castilla-Leon, Spain, during 2003 to 2005.

Yr	Fumigation treatment ^z	Application rate (kg·ha ⁻¹)	Type of plastic ^y	Field area (ha)
2003	MB:Pic (50:50)	400	PE	0.33
	MB:Pic (50:50)	300	VIF	0.33
	1,3-D:Pic	600	PE	0.33
	1,3-D:Pic	300	VIF	0.33
2004	MB:Pic (50:50)	400	PE	0.25
	MB:Pic (33:67)	300	VIF	0.25
	1,3-D:Pic	300	VIF	0.25
	Pic	300	VIF	0.25
	Dazomet	400	VIF	0.25
2005	MB:Pic (50:50)	400	PE	0.10
	1,3-D:Pic	600	PE	0.10
	1,3-D:Pic	350	VIF	0.10
	Pic	350	VIF	0.10

^zNumbers in parentheses indicate w/w mixture of the two chemicals listed.

^yFilm PE = transparent polyethylene; Film VIF = transparent virtually impermeable.

See Table 1 for a list of a.i., rate and method of application, formulated product, and supplier of each fumigant.

were chosen based on results from the replicated plots. Fumigants were applied using the same practices and on the same dates as those used in the replicated plots. Mother plants were planted 0.45 m apart in 1.5-m wide rows and irrigated as needed by overhead sprinklers.

Two 15-m² plots were randomly selected in each field and left unweeded to monitor weed populations. Weed density and fresh weed weight were measured on five or six sampling dates from mid-June to early October each year. Strawberry runner plants were machine-harvested from the whole demonstration field, and trained crews sorted and counted the total number of marketable plants (i.e., greater than 9- to 10-mm diameter crown) in late October each year.

Statistical analysis. Weed densities and fresh weed weights were subjected to analysis of variance using the SAS general linear model procedure (SAS Institute, Cary, NC). Effects of treatments and locations and their interaction on the study variables were assessed by a two-way analysis of variance.

When significant differences were found, a multiple comparison test was used for mean separation. All data were tested for normality and transformed as needed and backtransformed when necessary for data presentation. Significant mean differences among fumigant treatments in weed density, weed fresh weight, and number of runner plants harvested were separated using Duncan's multiple range test ($P < 0.05$).

Results

Weed control in small replicated plots. The most common weeds in the experimental plots were *Amaranthus retroflexus*, *A. albus*, *Chenopodium album*, *C. murale*, *Solanum nigrum*, and *S. villosum*. These species represented 65.7% of the total weeds observed and were primarily found in the nonfumigated control (NF). Other weeds included *Senecio vulgaris*, *Polygonum aviculare*, *Digitaria sanguinalis*, *Convolvulus arvensis*, *Anacyclus* spp., *Portulaca oleracea*, *Cynodon dactylon*, *Malva* spp., *Echinochloa crus-*

gali, *Raphanus* spp., and *Eragrostis* spp. *Malva* spp. (mallow) were the most difficult weeds to control by fumigation and, in fact, were more numerous in plots fumigated with MB : Pic (400 kg·ha⁻¹) and dazomet (400 kg·ha⁻¹) than in the untreated control.

Fumigation treatment had a significant effect ($P < 0.001$) on both weed density and weed fresh weight during each year of the study. More weeds were found in NF plots than in those treated with any fumigant (Table 4). Higher weed populations also occurred in plots fumigated with PO (500 kg·ha⁻¹) (at Avila) than in those fumigated with other chemicals in 2003. Significant interactions ($P \leq 0.05$) between fumigation treatment and location on weed density indicated that weed production was higher in NF plots at Segovia than at Avila in 2004 and 2005. Dazomet (400 kg·ha⁻¹), 1,3-D : Pic (300 kg·ha⁻¹), Pic alone (300 kg·ha⁻¹), MS + Pic (400 + 250 or 500 + 150 kg·ha⁻¹), and DMDS + Pic (250 + 250 or 400 + 150 kg·ha⁻¹) provided control of weeds that was not statistically different from the MB : Pic standard.

Runner plant production in small replicated plots. With the exception of the commercial standard in the nursery area [i.e., MB : Pic (50:50) with PE film], fumigation treatment effects on runner plant production varied among sites and years (Table 4). In general, runner plant production with MB : Pic was higher than other fumigation treatments. In all cases, the number of marketable runner plants produced by the NF control was lower than in all chemical fumigant treatments and in 2005, NF control relative yield was 48% and 29% of standard MB : Pic (50:50) in Avila and Segovia, respectively (Table 4). However, in some locations, the runner yield produced with dazomet, dazomet + 1,3-D : Pic, Pic alone (300 kg·ha⁻¹), DMDS + Pic, and PO (500 kg·ha⁻¹) did not differ significantly from NF control. 1,3-D : Pic, DMDS + Pic, Pic alone, and MS + Pic runner plant yields were numerically lower than for the MB:Pic standard in most cases;

Table 4. Fumigation treatments effects on weed density, fresh weed weight, and total and relative marketable runner plant production in replicated plots of Camarosa strawberry in Castilla-Leon, Spain, during 2003 to 2005.

Yr	Fumigation treatment ^z	Weed density (number/m ²)		Fresh weed wt. (g·m ⁻²)		Runner plant production in Avila		Runner plant production in Segovia	
		Avila	Segovia	Avila	Segovia	Plants/m ²	Relative ^x	Plants/m ²	Relative ^x
2003	MB:Pic (50:50) PE	1.04 c ^y	0.39 b	16.7 b	5.1 b	69.8 a	100	57.5 a	100
	Dazomet	0.78 c	0.91 b	11.5 b	23.7 b	58.0 bc	83	48.5 a	84
	1,3-D:Pic (61:35)	0.40 c	0.71 b	4.1 b	15.2 b	61.8 abc	89	44.0 a	77
	Pic	1.13 c	1.22 b	48.3 b	19.3 b	57.8 bc	83	40.5 a	70
	MS + Pic	0.53 c	0.51 b	16.0 b	3.7 b	68.0 ab	97	43.5 a	76
	DMDS + Pic	0.81 c	0.93 b	23.1 b	35.5 b	58.3 bc	84	51.3 a	89
	Propylene oxide	4.41 b	0.70 b	19.5 b	14.0 b	64.3 ab	92	42.8 a	74
	Nonfumigated	7.20 a	14.74 a	306.2 a	236.9 a	51.3 c	73	35.5 a	62
	MB:Pic (50:50) PE	0.05 b	3.26 b	0.27 b	34.3 b	44.8 a	100	50.8 ab	100
2004	Dazomet	0.08 b	0.94 b	0.41 b	14.7 b	41.3 a	92	44.0 ab	87
	1,3-D:Pic (61:35)	0.33 b	8.48 b	2.41 b	89.9 b	43.5 a	97	54.8 a	108
	Pic	0.92 b	8.51 b	5.37 b	75.5 b	41.3 a	92	57.3 a	113
	MS + Pic	0.54 b	3.76 b	2.57 b	53.9 b	40.3 a	90	56.5 a	111
	DMDS + Pic	0.21 b	1.49 b	0.51 b	15.4 b	38.3 ab	85	52.3 a	103
	Propylene oxide	1.73 b	3.37 b	5.13 b	30.5 b	37.5 ab	84	42.3 ab	83
	Nonfumigated	18.36 a	186.48 a	68.70 a	365.1 a	31.5 b	70	35.3 b	69
	MB:Pic (50:50) PE	0.91 b	0.41 b	0.59 b	3.09 b	46.8 a	100	59.5 a	100
	Dazomet + 1,3-D:Pic	0.26 b	0.53 b	1.03 b	4.33 b	24.3 c	52	32.5 c	54
2005	1,3-D:Pic (61:35)	0.41 b	1.14 b	1.82 b	10.9 b	40.5 ab	87	44.5 bc	75
	Pic	1.04 b	1.73 b	2.64 b	9.35 b	47.0 a	100	44.3 bc	74
	MS + Pic	0.10 b	0.84 b	0.41 b	4.17 b	39.3 ab	85	44.3 bc	74
	DMDS + Pic	0.19 b	1.84 b	0.64 b	9.06 b	43.8 ab	94	44.3 bc	74
	Propylene oxide + MS	0.49 b	2.16 b	2.72 b	13.2 b	36.0 b	77	47.0 b	79
	Nonfumigated	24.33 a	36.84 a	53.00 a	117.0 a	22.3 c	48	17.5 d	29

^yNumbers in parentheses indicate w/w mixture of the two chemicals listed. See Table 1 for a list of a.i., rate and method of application, formulated product, and supplier of each fumigant.

^zMeans followed by the same letter within a column each year are not significantly different according to Duncan's multiple range test ($P \leq 0.05$).

^xRelative plant production to standard MB:Pic (50:50) under transparent PE.

however, these treatments yielded numerically more runner plants than the MB:Pic standard in Segovia during 2004.

Weed control in demonstration fields. The most common weeds in the demonstration fields were *Amaranthus retroflexus*, *A. albus*, *Chenopodium album*, *C. murale*, *Solanum nigrum*, *S. villosum*, *Spergula* spp., and *Eragrostis* spp. These species represented 82% of the total weeds collected. However, unlike the small replicated plots, weed species composition varied among years. For example, *Senecio vulgaris*, *Convolvulus arvensis*, *Malva* spp., and *C. album* were the most common weeds in 2003, *Amaranthus* spp., *Eragrostis* spp., *Spergula* spp., and *C. album*

in 2004, whereas *C. murale*, *Linaria* spp. and *Trifolium* spp. were the most common species in 2005. None of the fumigant treatments had a tendency to control any one weed species better than another species with the exception of MB : Pic (50 : 50) standard and MB : Pic applied at 300 kg·ha⁻¹ under VIF film, which controlled most weeds except *S. vulgaris*, *C. arvensis*, *Malva* spp., and *Trifolium* spp.

Analysis of 2003 data for both locations indicated no significant differences in weed densities or weed fresh weight among treatments or the locations. However, considering the mean of weed density (Table 5) and total weed weight at both locations (data not shown) in 2003, the MB standard provided

the best weed control. The variance analyses carried out for the variable weed density and weed fresh weight in 2004 and 2005 (Table 5) indicated significant differences among the treatments ($P \leq 0.01$ in 2004 and $P \leq 0.05$ in 2005); it also showed significant effect of treatment $\times$ location ($P \leq 0.01$ in 2004 and $P \leq 0.05$ in 2005).

Comparisons among fumigation treatments (Table 5) indicated that except at Segovia in 2004, the treatments did not significantly differ in efficacy on weed control compared with standard MB : Pic. However, at Segovia in 2004, the fresh weight was significantly lower for the standard MB:Pic than other treatments; in addition,

Table 5. Fumigation treatments effects on weed density, fresh weed weight, total and relative marketable runner plant production in demonstration nursery fields of Camarosa strawberry in Castilla-Leon, Spain, during 2003 to 2005.

Yr	Fumigation treatment ^z	Weed density (number/m ²)		Fresh weed (g·m ⁻²)		Runner plant production in Avila		Runner plant production in Segovia	
		Avila	Segovia	Avila	Segovia	Plants/m ²	Relative ^x	Plants/m ²	Relative ^x
2003	MB:Pic (50:50) PE	0.10 a ^y	0.75 a	—	—	44.7	100	49.3	100
	MB:Pic (50:50)VIF	8.62 a	2.63 a	—	—	43.7	98	48.1	98
	1,3-D:Pic PE	0.42 a	5.82 a	—	—	38.2	85	42.7	87
	1,3-D:Pic VIF	2.01 a	1.22 a	—	—	37.3	83	34.7	70
	MB:Pic (50:50) PE	0.09 a	0.79 b	0.43 a	23.39 b	66.5	100	63.7	100
2004	MB:Pic (33:67)VIF	0.09 a	38.32 a	0.65 a	229.45 a	70.7	106	49.1	77
	1,3-D:Pic VIF	0.17 a	30.37 ab	1.80 a	345.90 a	62.3	94	59.8	94
	Pic VIF	0.49 a	25.20 ab	5.72 a	323.47 a	47.6	72	43.9	69
	Dazomet VIF	0.14 a	15.57 ab	0.49 a	121.80 a	28.7	43	45.0	71
	MB:Pic (50:50) PE	0.04 a	0.97 ab	0.16 a	3.64 a	61.5	100	50.7	100
2005	1,3-D:Pic PE	0.05 a	1.84 ab	0.42 a	6.85 a	48.2	78	34.7	68
	1,3-D:Pic VIF	0.12 a	0.33 b	0.79 a	1.53 a	50.5	82	36.5	72
	Pic VIF	0.14 a	5.24 a	0.62 a	62.79 a	56.3	92	30.7	61

^yNumbers in parentheses indicate w/w mixture of the two chemicals listed. See Table 2 for a list of application rates used in each treatment.

^zMeans followed by the same letter within a column each year are not significantly different according to Duncan's multiple range test ($P \leq 0.05$).

^xRelative plant production to standard MB:Pic (50:50) under transparent PE.

this treatment reduced the total weed densities. 1,3-D : Pic provided additional weed control in comparison with Pic alone. Weed density recorded in Segovia (2005) in the demonstration field with Pic alone was significantly higher ($P \leq 0.05$) than the 1,3-D : Pic mixture.

Runner plant production in demonstration fields. Runner plant yields were not consistent among years and locations (Table 5). With the exception of MB : Pic (33 : 67) under VIF film at Avila in 2004, standard MB : Pic (50 : 50) under PE treatment had a tendency to yield more marketable runner plants than other treatments. Plant yields from 1,3-D : Pic, Pic alone, and dazomet were inconsistent (Table 5).

Discussion

Small replicated plots. In the small plots studies, dazomet, 1,3-D : Pic, Pic alone, MS + Pic, and DMDS + Pic controlled weeds at a level not different from the MB : Pic standard (Table 4). Results obtained at Segovia in 2004 suggest that for experiments after a nonirrigated cereal crop, weed control resulting from alternative treatments was similar to the standard MB : Pic, but for experiments that followed irrigated vegetable crops (carrots, potatoes, and so on), weed control was inconsistent (De Cal et al., 2005b). Presumably this is because the weed seedbanks were lower after the cereals than the vegetable crops, and so weed control with all fumigants was better after cereals. This suggests that a more integrated approach to weed control will be necessary if we are to successfully use alternative fumigants in strawberry nurseries. In other words, it will be necessary to better manage weeds and prevent them from setting seed and infesting seedbanks in irrigated rotational crops grown before strawberry runner plant production.

The poor yields from dazomet + 1,3-D : Pic ($250 + 200 \text{ kg} \cdot \text{ha}^{-1}$) in 2005 could be the result of residual phytotoxicity observed after planting. In the Avila replicated plots (2005), plant mortality was 26.25% in dazomet + 1,3-D : Pic and was higher ($P < 0.05$) than other fumigation treatments. In contrast, plant mortality was 4.25% in DMDS + Pic ($400 + 150 \text{ kg} \cdot \text{ha}^{-1}$) and near zero in all other treatments. Runner plant production with the 1,3-D : Pic mixture was similar to those obtained previously in Spanish nurseries with MB : Pic (50–50) (López-Aranda et al., 2002a). In California strawberry nurseries, 1,3-D : Pic (Telone C-35) followed by dazomet produced runner plant yields similar to MB : Pic (Kabir et al., 2005). However, the California treatments were applied in late summer when the soil temperatures were 17°C , much warmer than soil temperatures at time of treatment in the studies described here. Australian nursery researchers found that although 1,3-D : Pic (61 : 35) produced runner yields equivalent to MB, this treatment did not control weeds. Moreover, 1,3-D : Pic failed to adequately control *Chenopodium album*, *C. murale*, and *Raphanus*

raphanistrum. The sequential combination of MS + Pic provided better weed control than 1,3-D : Pic (61–35) (Donohoe et al., 2001).

The low vapor pressures of chloropicrin and 1,3-D relative to MB would suggest that warmer, more ideal soil temperatures may improve the performance of the alternative treatments. However, these ideal conditions are difficult to achieve in Spanish high-elevation nurseries because the land is unavailable in the fall and so soil fumigation must be conducted during late winter when soil conditions are cool. Porter et al. (2004) suggested that cool soil conditions would favor MB because of its excellent soil dispersion characteristics in a wide range of soil temperatures.

Demonstrations. Our results suggest that after irrigated vegetable crops and the resulting high weed populations that the only satisfactory weed control treatment for strawberry nurseries is MB : Pic. Crops such as carrots, leeks, potatoes, and so on, allow high weed densities to accumulate during several cultivation cycles of irrigated vegetables that are difficult for alternative fumigants to control. This suggests that an integrated approach to weed management such as use of herbicides (e.g., napropamide or pendimethalin) in the nursery crop together with alternative fumigants and rotational crops, mainly cereals, would be a good solution. On the other hand, runner plant yield trends in our demonstration fields are similar to those reported for Spanish strawberry nurseries in previous years (López-Aranda et al., 2002a; Melgarejo et al., 2003).

Conclusions

Many of the alternative treatments evaluated here such as 1,3-D : Pic, Pic alone, MS + Pic, DMDS + Pic, and dazomet controlled weeds as well as MB : Pic, but for runner plant yields, all treatments were less consistent than MB : Pic. MB in combination with Pic (50 : 50) continues to be the reference standard for weed control, providing the best results in all trials and years. However, the available alternatives are likely to be used in simultaneous combinations, either as mixtures (e.g., 1,3-D : Pic) or sequentially (e.g., Pic alone followed by MS). They may also be supplemented with other more specific pesticides (like specific herbicides) and cultural controls.

Many factors such as weather, soils, and rotational crops contribute to inconsistencies in weed control and runner yields at high-elevation nurseries. Methyl bromide is the only single treatment that provided consistent weed control and crop yield. Replacements for MB will require more than one fumigant component as well as a higher level of management of pest populations in the fields during rotational crop production.

The use of VIF barrier films may be a way to increase the performance and consistency of alternative fumigants in comparison with PE films. VIF film technology, although still in need of improvement, may allow the use

of lower fumigant rates, including MB, and reduce fumigant emissions.

The importance of soil fumigation for nursery production must be given sufficient consideration in the future development and regulation of soil fumigants (Duniway, 2002a) as a result of the disproportionate impact of limited numbers of strawberry nursery fields on large numbers of fruiting fields. For example, the relationship between production of pathogen-free runner strawberry plants on a relative small area of fumigated soils in California and Castilla-Leon has very large and long-term benefits, including reductions of pesticide use, for production on very important strawberry fruit production regions in California and Southern Spain (Huelva), nearly 20,000 ha in the United States, Spain, and elsewhere. Furthermore, a large portion of these runner plants are for export to other countries and must meet strict phytosanitary requirements. Although many factors require consideration before any alternative fumigation treatment can replace MB as the standard treatment for strawberry nurseries, in Spain and other European countries (France, Italy, Poland, and so on). It is necessary to continue evaluation of alternative fumigants for strawberry nurseries, to focus on improved methods of application, to evaluate new alternatives treatments, to estimate the potential economic viability of these alternatives treatments, and to evaluate the most promising alternative fumigant treatments in commercial field-scale demonstrations. Moreover, despite the increased risk with nonchemical options, European Union regulatory restrictions may require in the near future the use of nonchemical MB alternatives for soil disinfection in strawberry nurseries. Therefore, the need for evaluations of chemical and nonchemical soil disinfection methods in strawberry nurseries is urgent.

Literature Cited

- Ajwa, H.A., S. Klose, S.D. Nelson, A. Minuto, A.L. Gullino, F. Lamberti, and J.M. López-Aranda. 2003. Alternatives to methyl bromide in strawberry production in the United States of America and the Mediterranean region. *Phytopathol. Mediterr.* 42:220–244.
- Anonymous. 2000. Regulation EC2037/00 of the European Parliament and of the council of 29 June 2000 on substances that deplete the ozone layer. *Off. J. Eur. Communities* L244:1–24.
- Carrera, T., A. Carrera, and V. Pedros. 2004. Use of 1,3-dichloropropene/chloropicrin for the production of strawberries in Spain, p. 53–56. *Proc. of Fifth Int. Conf. on Alternatives to Methyl Bromide*, Lisbon, 27–30 September.
- De Cal, A., A. Martínez-Trecheño, J.M. López-Aranda, and P. Melgarejo. 2004. Chemical alternatives to methyl bromide in Spanish strawberry nurseries. *Plant Dis.* 88:210–214.
- De Cal, A., A. Martínez-Trecheño, T. Salto, J.M. López-Aranda, and P. Melgarejo. 2005a. Effect of chemical fumigation on soil fungal communities in Spanish strawberry nurseries. *Appl. Soil Ecol.* 28:47–56.
- De Cal, A., P. Melgarejo, A. Martínez-Trecheño, T. Salto, M.L. Martínez-Beringola, I. Santin, J.M. García-Baudin, D. García-Sinovas, E. García-Méndez, M. Becerril, J.J. Medina, and J.M.

- López-Aranda. 2005b. Alternatives to MB for strawberry nurseries in Spain. 2004 results. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 57.
- Donohoe, H., S. Mattner, R. Brett, V. Bianco, A. Shanks, R. Gounder, and I. Porter. 2001. Status of methyl bromide phase-out in the temperate Australian strawberry industry. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 44.
- Duniway, J.M. 2002a. Status of chemical alternatives to methyl bromide for pre-plant fumigation of soil. *Phytopathology* 92:1337–1343.
- Duniway, J.M. 2002b. Chemical alternatives to methyl bromide for soil treatment particularly in strawberry production, p. 47–50. Proc. Int. Conf. Alternatives to Methyl Bromide. The Remaining Challenges, Seville, 5–8 March.
- Duniway, J.M., W.D. Gubler, and C.L. Xiao. 1997. Response of strawberry to some chemical and cultural alternatives to methyl bromide fumigation of soil under California production conditions. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 6.
- Fritsch, H.J. and R. Huber. 1995. Basamid granular—A halogen-free soil disinfestant. *Acta Hort.* 382:76–85.
- Himelrick, D.G. and W.A. Dozier, Jr. 1991. Soil fumigation and soil solarization in strawberry production. *Adv. Straw. Prod.* 10:12–28.
- Kabir, Z., S.A. Fennimore, J.M. Duniway, F.N. Martin, G.T. Browne, C.Q. Winterbottom, H.A. Ajwa, B.B. Westerdahl, R.E. Goodhue, and M.J. Haar. 2005. Alternatives to methyl bromide for strawberry runner plant production. *HortScience* 40:1709–1715.
- Larson, K.D. and D.V. Shaw. 2000. Soil fumigation and runner plant production: A synthesis of four years of strawberry nursery field trials. *HortScience* 35:642–646.
- López-Aranda, J.M., J.J. Medina, L. Miranda, F. Montes, F. Romero, J.M. Vega, J.I. Paez, B. Santos, F. Dominguez, J. López-Medina, F. Flores, I. Clavero, J. Galvez, M. Becerril, J. Palacios, E. Bardon, M.L. Martínez-Beringola, T. Salto, A. De Cal, A. Martínez-Trecheño, and P. Melgarejo. 2002a. Alternatives to methyl bromide for use in strawberry production and nurseries in Spain, p. 51–55. Proc. Int. Conf. Alternatives to Methyl Bromide. The Remaining Challenges, Seville, 5–8 March.
- López-Aranda, J.M., J.J. Medina, J.I. Marsal, and R. Bartual. 2002b. Strawberry production in Spain, p. 230–237. In: N.F. Childers (ed.). *The strawberry. A book for growers, others.* University of Florida, Horticultural Sciences Department, Gainesville, FL, Section VIII.
- Mappes, D. 1995. Spectrum of activity of dazomet. *Acta Hort.* 382:96–103.
- Melgarejo, P., A. Martínez-Trecheño, A. De Cal, T. Salto, M.L. Martínez-Beringola, J.M. García-Baudin, I. Santin, E. Bardon, J. Palacios, M. Becerril, J.J. Medina, and J.M. López-Aranda. 2003. Chemical alternatives to MB for strawberry nurseries in Spain. 2002 results. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 15.
- Noling, J.W. and J.O. Becker. 1994. The challenge of research and extension to define and implement alternatives to methyl bromide. *J. Nematol.* 26:573–586.
- Palacios-Vazquez, J. 2002. Spanish strawberry plant nurseries and the use of methyl bromide as a soil disinfestant, p. 137–139. Proc. Int. Conf. Alternatives to Methyl Bromide. The Remaining Challenges, Seville, 5–8 March.
- Porter, I., S. Mattner, R. Mann, and R. Gounder. 2004. Strawberry nurseries: Summaries of alternatives to methyl bromide fumigation and trials in different geographic regions, p. 67–70. Proc. International Conference on Alternatives to Methyl Bromide. Lisbon, Portugal, 20–30 Sept.
- Rodríguez-Kabana, R. and L. Simmons. 2004a. Combinations of metam sodium and propylene oxide for weed control. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 12.
- Rodríguez-Kabana, R. and L. Simmons. 2004b. Potential of combination treatments of methyl disulfide and metam sodium for weed control. Annu. Intl. Res. Conf. Methyl Bromide Alternatives and Emissions Reductions. Abstr. 14.
- Teasdale, J.R. and R.B. Taylorson. 1986. Weed seed response to methyl isothiocyanate and metham. *Weed Sci.* 34:520–524.
- Wilhelm, S. 1999. The California strawberry industry and soil fumigation. A review. Published by the California Strawberry Commission, Watsonville, CA.
- Wilhelm, S. and A.O. Paulus. 1980. How soil fumigation benefits the California strawberry industries. *Plant Dis.* 64:264–270.