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Weed Control in Strawberry Runner Plant Nurseries with Methyl Bromide Alternative Fumigants

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Abstract. **Methyl bromide alternative fumigants were evaluated for weed control efficacy in low- and high-elevation strawberry (*Fragaria ×ananassa* L.) runner plant nurseries. Preplant soil fumigation treatments of methyl bromide plus chloropicrin (MBPic), iodomethane plus chloropicrin (IMPic), 1,3-dichloropropene plus chloropicrin mixture followed by (fb) dazomet, chloropicrin fb dazomet, and a nonfumigated control were evaluated at three California strawberry runner plant nurseries through two production cycles. Fumigant efficacy was measured by weed seed viability bioassays, weed density counts, and time of handweeding. Generally, all alternative fumigant treatments controlled weeds at levels comparable to MBPic. All fumigant treatments, including MBPic, killed more than 95% of common knotweed, common purslane, common chickweed, and strawberry seed. Iodomethane, chloropicrin fb dazomet, and 1,3-dichloropropene plus chloropicrin mixture fb dazomet controlled carpetweed, common lambsquarters, hairy nightshade, palmer amaranth, and prostrate spurge. Handweeding inputs for all fumigants were similar to MBPic at three of four locations. The exception was at the low-elevation nursery in 2000 where handweeding times with MBPic were lower than for IMPic. Treatment and handweeding costs were calculated. The handweeding costs for all treatments were approximately the same. However, the higher iodomethane material cost resulted in a substantially higher treatment cost.**

In the United States, 21,576 ha of strawberries were harvested for fruit in 2006 at a value of $1.5 billion. California leads the nation in strawberry production, where strawberry growers harvested 14,494 ha for fruit in 2006 with a value of $1.2 billion, accounting for 79% of the total U.S. gross sales (National Agricultural Statistics Service, 2007). California nurseries produce more than a billion strawberry runner plants annually with a total value of ≈$60 million (California Strawberry Commission, 1999). The diversity of climates in California along with the use of methyl bromide (MB) fumigation permits the production of high-quality runner plants. Strawberry runner plant production begins in virus-free rearing facilities, i.e., screenhouses. Plants are then vegetatively propagated in the field for two or three seasons. One or two 8-month-long propagation seasons at a low-elevation (less than 150 m) nursery (LEN) are followed by a 5-month-long propagation at a high-elevation (greater than 1000 m) nursery (HEN). Favorable warm climatic conditions at LEN allow rapid plant propagation, and cool late-summer HEN conditions ensure strawberry plants that are ready to transplant into fruit fields by early fall (Kabir et al., 2005; Larson, 1994; Larson and Shaw, 2000; Strand, 1994; Voth, 1989; Voth and Bringhurst, 1990).

Soil fumigation is used to manage soilborne pests, including weeds, and to ensure pest-free planting stock. Beginning approximately 1960, MB became the foundation of soilborne disease and weed control in California strawberries (Wilhelm, 1966). Methyl bromide in combination with chloropicrin (Pic) (Tri-Cal, Hollister, CA) controls weeds, soilborne pathogens, and nematodes (Wilhelm and Paulus, 1980). Virtually all runner plant nurseries fumigate soil with a mixture of MB and Pic to ensure pest-free planting stock. However, MB has been classified as a Class I stratospheric ozone-depleting chemical, and use of MB was phased out 1 Jan. 2005 under the Montreal Protocol (Anbar et al., 1996; U.S. Environmental Protection Agency, 1993) with exemptions for critical use [U.S. Department of State (USDS), 2007]. Approximately 4690 kg of MB was requested for preplant fumigation of California strawberry nurseries in 2009 under the critical use exemption (USDS, 2007).

This is the second article that describes research with MB alternative fumigants in California strawberry nurseries. The first paper, by Kabir et al. (2005), describes strawberry nursery runner plant yield results and this article describes weed control results in strawberry nurseries.

Some fumigant alternatives to MB currently under investigation are Pic (trichloronitromethane; Niklor Chemical Co., Long Beach, CA), iodomethane (IM, methyl iodide, Midas; Arysta LifeScience, Cary, NC), 1,3-dichloropropene (1,3-D, Telone; Dow AgroSciences, Redeck, NC), and dazomet (tetrahydro-3, 5-dimethyl-2*H*-1, 3, 5-thiadiazine-2-thione; Certis USA, Columbia, MD). Chloropicrin has been applied in combination with MB since the late 1950s for control of weeds and pests (Wilhelm, 1966). Application of Pic alone controls some weeds (Haar et al., 2003; Wilhelm and Paulus, 1980). However, because of the predominant use of Pic in combination with MB, little information is available regarding the effectiveness of Pic without MB for weed control in strawberry runner plant fields.

Iodomethane has an ozone depletion potential value of 0.016 (Ohr et al., 1996) compared with an ozone depletion potential of 0.4 for MB. Light rapidly degrades IM, and the stratospheric ozone-depleting potential of this fumigant is very low (National Oceanic and Atmospheric Administration, 2002; Solomon et al., 1994). Iodomethane alone is 1.5 times more effective than MB in controlling weeds such as purple nutsedge (*Cyperus rotundus* L.; Zhang et al., 1997) and is as effective as MB for control of common chickweed (*Stellaria media* L.), common knotweed (*Polygonum arenastrum* L.), and common purslane (*Portulaca oleracea* L.) seed in strawberry (Fennimore et al., 2002). In Florida, researchers found that control of nutsedge (*Cyperus* spp.) and winter annual weeds with 100% IM at 336 $kg \cdot ha^{-1}$ was comparable to MBPic 98:2 (98% MB and 2% Pic) at 560 $kg \cdot ha^{-1}$; however, control of *Ipomea* spp. weeds with IM was less than MBPic (Unruh et al., 2002). Iodomethane can be used in combination with other fumigants such as Pic to increase its spectrum of activity against soil pests

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such as yellow nutsedge (*C. esculentus* L.; Hutchinson et al., 2003).

The fumigant 1,3-D controls nematodes but not weeds (Noling and Becker, 1994; Roby and Melichar, 1997). To improve control of soilborne diseases and weeds, 1,3-D is often combined with 17% or 35% Pic, Telone C17, or Telone C35, respectively [Crop Data Management System (CDMS), 2007]. Telone C35 (TC35) at 355 L·ha^{-1} was as effective as fumigation with MBPic 67:33 at 364 kg·ha^{-1} for strawberry production in California (Duniway et al., 1998). Weed control with TC35 at 374 L·ha^{-1} controlled California burclover (*Medicago polymorpha* L.) and common chickweed comparable to MBPic 67:33 at 425 kg·ha^{-1} (Fennimore et al., 2003), and Unruh et al. (2002) found that 1,3-D at 140 L·ha^{-1} plus metam sodium at 748 L·ha^{-1} controlled carpetweed (*Mollugo verticillata* L.), winter annuals, and redroot pigweed (*Amaranthus retroflexus* L.) as well as MBPic 98:2 at 560 kg·ha^{-1}. Nutsedge control with Telone C17 at 327 L·ha^{-1} was not acceptable compared with MBPic 98:2 at 450 kg·ha^{-1} (Gilreath and Santos, 2004; Locascio et al., 1997). Dazomet (DZ) is a microgranular fumigant that controls soilborne fungi, bacteria, nematodes, and weeds (Fritsch and Huber, 1995; Harris, 1991; Mappes, 1995). When incorporated into moist soil, DZ breaks down into methylisothiocyanate, which kills many soilborne organisms and weeds. Dazomet is registered for use in strawberry nursery and fruiting fields (CDMS, 2006). Csinos et al. (1997) found that control of purple cudweed (*Gnaphalium purpureum* L. var. *purpureum*) with DZ at 387 kg·ha^{-1} alone was comparable to MBPic 98:2 at 489 kg·ha^{-1}. Unruh et al. (2002) found that Pic at 168 kg·ha^{-1} plus DZ at 392 kg·ha^{-1} controlled carpetweed and winter annual weeds comparable to MBPic 98:2 at 560 kg·ha^{-1}, but DZ at 440 kg·ha^{-1} did not control nutsedge either alone or in combination with 1,3-D at 140 L·ha^{-1} or Pic at 168 kg·ha^{-1}. Similarly, DZ at 440 kg·ha^{-1} resulted in poor control of nutsedge compared with MBPic 98:2 at 450 kg·ha^{-1} (Locascio et al., 1997).

Weed control in strawberry nurseries is more difficult than in fruiting fields. Differences between fruiting and nursery strawberries are: 1) nurseries require rapid growth of the mother plants and rooting of daughter runner plants and preclude use of herbicides such as napropamide that interfere with rooting of daughter plants (Weed Science Society of America, 2002); 2) dark plastic mulches used in fruiting fields for a variety of reasons, including weed control, cannot be used in nursery fields because they would prevent daughter plant rooting; 3) in nurseries, the row middles fill in with daughter plants limiting cultivation to the early season, whereas in fruiting fields, row middles are kept open and can be cultivated all season; 4) tolerance to risk of disease infection from weeds is near zero in nurseries as a result of potential for disease to pass from weed to strawberry runner plant and then carryover to infect fruiting fields. Fumigants are one of the most important weed control tools available for strawberry nursery fields, more critical than in fruiting fields where other weed control tools are available.

Soil fumigation is the cornerstone of the current strawberry production system; finding alternatives that effectively control a wide range of soilborne pests, including weeds, is necessary to maintain current levels of productivity and profitability. Because soil fumigation is used in several phases of the strawberry production system, MB alternative fumigants were evaluated at each production cycle. The objectives of the research described here were to evaluate the efficacy of alternative fumigants for weed control in LEN and HEN strawberry nurseries and to measure weed control costs when alternative fumigants are used.

Materials and Methods

Nursery site descriptions. Experiments were conducted at both LEN and HEN commercial fields to evaluate alternative preplant fumigation programs for production of strawberry runner plants. The LEN was located near Ballico, CA (lat. 37°4′N, long. 120°5′W, elev. ≈120 m) at a site previously cropped with almond (*Prunus dulcis* L.). The LEN fumigation experiment was conducted in the 2000 to 2001 season and repeated at the same location in 2001 to 2002 (Table 1). The soil at Ballico was a Tinnin loamy coarse sand (sandy, mixed, thermic, Entic Haploxeroll) (sand 90%, silt 7%) with a pH of 7.4 and an organic matter content of 0.4%. See Kabir et al. (2005) for details on cultural practices and runner plant production. Weather data collected during the strawberry growing seasons at Ballico are presented in Table 1.

High-elevation nursery experiments were conducted at two sites: near Susanville, CA (lat. 40°2′N, long. 120°3′W., elev. ≈1200 m) and near Macdoel, CA (lat. 41°5′N, long.122°W, elev. ≈1294 m). The Susanville evaluation was conducted in the 2000 season, and the experiment conducted at Macdoel during the 2001 season was repeated in the 2002 season (Table 1). Soil at the Susanville site was classified as Fordney loamy fine sand (brown and dark grayish brown loamy fine sand; sand 84%, silt 10%) with a pH of 7.6 and an organic matter content of 1.7%. The Susanville HEN site had never been fumigated or used to grow strawberry previously. At Macdoel, soil was classified as Poman loamy sand (sandy, mixed, mexic, Xerollic Durorthids; sand 90%, silt 6%) with a pH of 6.0 and organic matter content of 0.6%. The Macdoel 2001 site had been used previously for wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) production and had never been fumigated previously. The Macdoel 2002 site had been previously used for strawberry runner plant production and was in a 3-year cycle with 2 years in fallow and rye cover crops and 1 year in strawberry runner plant production on soils previously fumigated with MBPic. Weather data for the Macdoel and Susanville experiments are presented in Table 1. The nursery experiments all used sprinkler irrigation during the growing season.

Weed control practices at all sites included mechanical cultivation early in the season, before runner initiation. One to 2 months after transplanting, runners spreading out from the rows required that cultivation be discontinued to prevent runner damage. Handweeding was used as needed throughout the production season.

Fumigation treatments. At Ballico, treatments of: 1) MBPic (57% MB:43% Pic), 450 kg·ha^{-1}; 2) IMPic (50% IM:50% Pic), 392 kg·ha^{-1}; and 3) nonfumigated control (NF) each were applied to four replicate 10 m × 46-m plots before planting. The trial design for all experiments was a randomized complete block design with four replications. Planting and harvest dates at Ballico were 12 May 2000 and 15 Jan. 2001 (season 1) and 5 May 2001 and 15 Jan. 2002 (season 2).

At Susanville, the treatments were: 1) MBPic (67% MB:33% Pic) 400 kg·ha^{-1}; 2) IMPic (50% IM:50% Pic) 392 kg·ha^{-1}; and 3) NF. The plots were 6.7 m × 40 m with six

Table 1. Experimental locations, nursery location (low or high elevation), fumigation date, planting stock source, planting date, harvest date, precipitation, and air temperature during each strawberry growing period.

Trial no.	Location	Trial type	Fumigation date	Plant source	Planting date	Harvest date	Precip.[x] (mm)	Temp.[w] Minimum	Temp.[w] Maximum
1	Ballico	LEN[z]	25 Apr. 2000	MBPic stock	12 May 2000	15 Jan. 2001	153	8.9	24.3
2	Ballico	LEN	5 Apr. 2001	MBPic stock	5 May 2001	15 Jan. 2002	224	10.4	25.8
3	Susanville	HEN[y]	4 Apr. 2000	MBPic stock	20 Apr. 2000	20 Oct. 2000	272	1.5	17.8
4	Macdoel	HEN	26 Aug. 2000	Ballico trial 1	20 Apr. 2001	2 Oct. 2001	59	4.5	26.0
5	Macdoel	HEN	1 Aug. 2001	Ballico trial 2	24 Apr. 2002	30 Sept. 2002	61	3.9	25.5

[z]Low-elevation nursery (LEN)—runner plant production.
[y]High-elevation nursery (HEN)—runner plant production.
[x]Precipitation (mm) during strawberry growing seasons.
[w]Average air temperature (minimum and maximum °C) during strawberry growing seasons.

rows per plot and 100-cm spacing between rows. Planting and harvest dates at Susanville were 20 Apr. to 20 Oct. 2000. At the Macdoel HEN, the treatments in the 2001 and 2002 seasons were 1) MBPic (57% MB:43% Pic) 450 kg·ha^{-1}; 2) IMPic (50% IM:50% Pic) 392 kg·ha^{-1}; 3) 65% 1,3-D plus 35% Pic (TC35) mixture 300 L·ha^{-1} followed by (fb) DZ 280 kg·ha^{-1}; 4) Pic 336 kg·ha^{-1} fb DZ 280 kg·ha^{-1}; and 5) NF. All plots were 10 m × 45 m, and there were eight rows per plot. Planting and harvest dates for both seasons at Macdoel were 20 Apr. 2001 to 2 Oct. 2001 and 24 Apr. to 30 Sept. 2002.

Fumigant application. At all locations, fumigants, except DZ, were shank-injected, and the soil was covered with a polyethylene tarp as the fumigant was applied. In 2000 at Ballico, fumigants were shank-injected on 25 Apr. 2000 to a depth of ≈30 cm with six chisels spaced 35 cm apart when 15 to 45-cm soil temperatures were 17 to 18 °C. Soil was immediately covered with a black high-density polyethylene tarp (28 µm thickness). On 1 May 2000, the tarp was removed. Similarly, in 2001, fumigants were shank-injected on 5 Apr. 2001 when soil temperatures were 17 to 18 °C and the tarp was removed on 10 Apr. 2001. At Susanville, fumigants were shank-injected on 4 Apr. 2000, when soil temperatures were 12 to 14 °C, and the clear polyethylene tarp was removed on 10 Apr. 2000. At Macdoel, MBPic, IMPic, Pic, and TC35 were shank-injected on 26 Aug. 2000 for 2001 runner plant production and on 1 Aug. 2001 for 2002 runner plant production. The tarp was removed on 9 Sept. 2000 for the 2001 season and on 7 Aug. 2001 for the 2002 season. Dazomet was applied to the soil surface of the appropriate plots with a granular spreader the day after tarp removal and activated in the soil by sprinkler irrigation according to label directions (CDMS, 2006).

Weed control assessments. Weed control was assessed by three methods: 1) weed seed viability bioassays; 2) weed density counts; and 3) timing of handweeding inputs by commercial crews. For seed viability tests, 50 seeds of little mallow (*Malva parviflora* L.), prostrate knotweed, common purslane, common chickweed, and strawberry seed (included 2001 and 2002 only) were placed in 8 × 12-cm heat-sealed nylon mesh bags (Delnet, Middletown, DE). The little mallow and common chickweed seed was obtained from Valley Seed, Fresno, CA, and the prostrate knotweed and common purslane seed were gathered from agricultural fields near Salinas, CA. Strawberry seed was extracted from commercial fruit harvested near Watsonville, CA. Strawberry seed was included to determine the potential for strawberry seed to survive in fields treated with the alternative fumigants (H.C. Larsen, Sierra Cascade Nursery, Susanville, CA, personal communication). Four seed bags were buried per plot at depths of 5 and 15 cm deep (15 cm was included in 2001 and 2002 projects only). Each plot was divided into quarters and one seed bag was placed in the approximate center of each plot quarter, i.e., four weed seed bioassay points per plot were used. Seed bags were installed 1 to 2 d before fumigation to allow the seeds to equilibrate with the soil moisture. Seed bags were retrieved ≈14 d after fumigation, and seed viability was determined using the tetrazolium assay described in Peters (2000). Weed seed viability was converted to percentage weed control relative to the NF control. Weed density counts were measured before each cultivation. Weed densities by species were determined in four 0.25-m^2 quadrats sampled randomly within each quarter plot. Time for a worker to weed the length of each plot was measured twice per plot.

Statistical analyses. Data were analyzed using the SAS general linear model procedure (SAS Institute, Cary, NC). After testing for normality, data were log- or arcsine-transformed as necessary for statistical analysis, and untransformed data are presented. Fisher's protected least significant differences were used for mean comparisons.

Results and Discussion

Fumigant effect on weed seed viability. At Ballico and Susanville, weed seed, except little mallow, were similarly controlled by IMPic and MBPic (Table 2). IMPic and MBPic controlled over 94% of prostrate knotweed, common purslane, and common chickweed seed compared with the NF. At Macdoel, weed seed were similarly controlled by all alternative fumigants and MBPic (Table 3). Control of prostrate knotweed, common purslane, and common chickweed seed was greater than 97% . None of the fumigant treatments, including MBPic, controlled little mallow seed in any of the experiments (Tables 2 and 3).

Control of volunteer strawberry seed. Strawberry seed were controlled by all fumigant treatments (Tables 2 and 3). Any of the fumigant treatments tested here could be used to prevent the persistence of strawberry seed between strawberry runner plant production cycles.

Weed control. Principal weeds at Ballico were prostrate spurge [*Chamaesyce humistrata* (Engelm. ex Gray) Small], carpetweed, and redstem filaree [*Erodium cicutarium* (L.) L'Hér. ex Ait.] (Table 4). Both IMPic and MBPic controlled most carpetweed and prostrate spurge. Neither MBPic nor IMPic reduced redstem filaree densities compared with the NF control. Both MBPic and IMPic reduced total weed densities by greater than 88% relative to the NF. There were no differences in weed control between IMPic and MBPic with the exception of redstem filaree in 2000, in which densities in the plots previously fumigated with IMPic were lower than in plots previously fumigated with MBPic. At Susanville, the principal weeds

Table 2. Strawberry and weed seed relative control after fumigation at Ballico LEN in 2000 and 2001 and Susanville HEN in 2000[z].

	Strawberry seed[y]	Little mallow			Prostrate knotweed		Common purslane		Common chickweed
Fumigant	2001	2000[y]	2000[x]	2001	2000[w]	2001	2000[w]	2001	2001
	Control (%)								
IMPic	100.0	0.0	5.8	15.5	94.2	100.0	99.9	99.5	100.0
MBPic	100.0	0.0	7.6	12.7	99.6	100.0	99.9	100.0	100.0
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LSD[v]	21.6	16.8	6.0	17.3	14.7	1.0	11.9	2.0	0.6

[z]Control was calculated relative to the NF control.
[y]Ballico alone.
[x]Susanville alone.
[w]Ballico 2000 and Susanville pooled.
[v]Least significant differences (LSD) at $P = 0.05$.
LEN = low-elevation nursery; HEN = high-elevation nursery; IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

Table 3. Control of strawberry and weed seed with alternative fumigants at MacDoel HEN in 2001 and 2002[z].

	Strawberry seed[y]	Little mallow		Prostrate knotweed		Common purslane		Common chickweed	
Fumigant	2002	2001	2002	2001	2002	2001	2002	2001	2002
	Control (%)								
Pic fb DZ	100.0	10.1	0.0	99.9	100.0	99.8	99.7	99.7	100.0
TC35 fb DZ	99.7	5.7	14.0	99.7	99.2	98.9	100.0	100.0	99.6
IMPic	99.5	7.7	0.4	100.0	100.0	99.4	99.7	100.0	100.0
MBPic	100.0	19.4	0.0	97.6	100.0	99.9	100.0	100.0	100.0
NF	0.0	0.0	0.0	0.0	0.0	–[x]	0.0	0.0	0.0
LSD[w]	1.6	15.1	17.0	2.5	1.6	1.4	0.5	1.4	6.4

[z]Control was calculated relative to the NF control.
[y]Strawberry seed included in 2002 only.
[x]The viability of this sample of common purslane could not be determined as a result of excessive sprouting of the samples, which left empty seedcoats at the time of sample retrieval.
[w]Least significant differences (LSD) at $P = 0.05$.
HEN = high-elevation nursery; Pic = chloropicrin; fb = followed by; DZ = dazomet; IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

Table 4. The effect of IMPic and MBPic on weed densities at Ballico strawberry nursery in 2000 and 2001.

	Prostrate spurge^z		Carpetweed		Redstem filaree		Total weeds	
Fumigant	2000	2001	2000	2001	2000	2001	2000	2001
	no. m^{-2}							
IMPic	17.0	13.8	0.0	5.3	12.5	5.5	29.8	26.5
MBPic	35.8	5.5	0.5	4.0	25.5	2.3	61.8	13.8
NF	324.8	165.0	160.8	360.1	21.8	1.5	527.2	562.9
LSD^y	71.6^y	27.1	41.0	65.7	10.2	2.4	106.1	89.4

^zIn 2000, weed densities were measured 15 June, 18 July, and 3 Oct.; and in 2001 on 1 June, 23 July, and 31 Oct.

^yLeast significant differences (LSD) at $P = 0.05$.

IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

were common lambsquarters (*Chenopodium album* L.) and little mallow (Table 5). Common lambsquarters and total weed densities were reduced by greater than 68% compared with the NF control. Little mallow densities were lower in plots previously fumigated with IMPic compared with the NF control. However, MBPic did not reduce little mallow densities relative to the NF control. At Macdoel, the predominate weeds were palmer amaranth (*Amaranthus palmeri* S. Wats.), hairy nightshade (*Solanum physalifolium* Rusby), and common lambsquarters (Table 6). Weed densities were higher in 2001 than in 2002. All fumigant treatments reduced weed densities by greater than 70%. The alternative fumigants reduced palmer amaranth, hairy nightshade, and common lambsquarters densities to levels that were not different from MBPic.

Relative to the NF control, handweeding times at Ballico and Macdoel were reduced in all plots that had been fumigated (Table 7). Weeding inputs with the alternative fumigants were not different from MBPic, with the exception that at Ballico in 2000, MBPic weeding times were less than IMPic weeding times.

Economic analysis. Table 8 reports handweeding and treatment material costs per hectare for each treatment based on current prices. Handweeding times were very similar for all the fumigant treatments and, as a result, weeding costs were also similar. Treatment costs, i.e., fumigant costs, vary more. MBPic is less costly than the other treatments. Iodomethane is substantially more expensive than the other treatments and does not provide better weed control. Indeed, at Macdoel, the treatment cost differences are an order of magnitude larger than the weeding costs. At Ballico, the treatment cost difference between IMPic and MBPic is larger than the 2000 weeding costs and an order of magnitude larger than the 2001 weeding costs.

Although current prices were used to calculate handweeding and treatment costs, these prices will change over time. If relative prices change for the fumigant materials, the relative treatment costs will change. Methyl bromide prices have been increasing over time. If the price of MB increases more rapidly than the price of other fumigant materials, relative treatment costs may change. Another issue is that IM is being sold under an experimental use permit or is registered in a limited number of states, so there are limited price data. The price used for IM is an estimate provided by Arysta LifeSciences, the IMPic registrant (Neil Phillips, Arysta LifeSciences, personal communication). At this estimated price, IM is much more expensive than the alternative treatments. Finally, there is substantial uncertainty regarding the future cost of field labor in California as a result of the possibility that the state government will mandate health insurance coverage and other considerations.

We address the potential effects of relative fumigant price changes using sensitivity analysis. At Ballico, the price of MB would need to increase by 120% to 130% before the combined fumigation and handweeding costs of the MBPic treatment would be as high as those of the IMPic treatment (holding all other prices constant). At Macdoel, if the price of MB increases by 20%, then the combined fumigation and handweeding costs for MBPic will roughly equal those for TC35 fb DZ but will be lower than those for Pic fb DZ and IMPic (Fig. 1). If the price of MB increases by 40%, its combined costs will roughly equal those for Pic fb DZ. As a result of the much higher current price of IMPic, the price of MB would have to increase by roughly 120% before the MB costs would equal the IMPic costs. Figure 1 reports the results of the sensitivity analysis for Macdoel.

Because IM is a relatively new material, the economic viability of IMPic may change substantially for two reasons. First, the price of IM is high relative to alternative fumigants, namely Pic and 1-3-D, on a per-kilogram basis. For crops for which IMPic is demonstrated to be similarly efficacious at similar application rates, to induce growers to use IMPic, its price will have to decline substantially. Second, future research may find that it may be equally efficacious at lower application rates. If the price of MB increased by 25%, a 35% reduction in the IMPic application rate would result in the MBPic and IMPic treatments having roughly equal costs. The reduction in the application rate could be slightly smaller for it to have costs roughly equal to the other treatments.

Table 5. The effect of IMPic and MBPic on weed densities at Susanville strawberry nursery in 2000.

Fumigant	Common lambsquarters^z	Little mallow	Total weeds
	no. m^{-2}		
IMPic	6.8	35.0	48.3
MBPic	46.3	50.3	106.5
NF	226.3	63.8	335.5
LSD^y	58.1	22.3	74.0

^zWeed densities were measured 17 May, 20 June, 3 Aug. and 8 Sept. 2000.

^yLeast significant differences (LSD) at $P = 0.05$.

IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

Table 6. Weed densities at Macdoel strawberry nursery in 2001 and 2002 in plots previously fumigated with alternative fumigants.

	Palmer amaranth^z		Hairy nightshade	Common lambsquarters	Total weeds	
Fumigant	2001	2002	2001	2002	2001	2002
	no. 100 m^{-2}					
Pic fb DZ	0.0	0.3	0.0	2.0	50.0	8.7
TC35 fb DZ	0.0	0.2	0.0	0.8	75.0	7.7
IMPic	25.0	1.0	0.0	1.5	25.0	13.3
MBPic	0.0	1.9	0.0	0.8	75.0	13.0
NF	825.0	11.6	1075.0	19.7	2225.0	45.8
LSD^y	213.7	7.1	275.0	11.6	421.5	15.5

^zIn 2001, weed densities were measured 18 May, 21 June, 12 July, and 22 Aug.; and in 2002 on 9 July and 23 Aug.

^yLeast significant differences (LSD) at $P = 0.05$.

Pic = chloropicrin; fb = followed by; DZ = dazomet; IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

Table 7. The cumulative time (h·ha^{-1}) required to handweed fumigant treatments at Ballico and Macdoel.

	Ballico		Macdoel	
Fumigant	2000^z	2001^y	2001^x	2002^w
	h·ha^{-1}			
Pic fb DZ	—	—	9.4	7.8
TC35 fb DZ	—	—	9.8	8.3
IMPic	142.7	16.7	9.4	8.5
MBPic	111.8	18.0	9.2	9.7
NF	230.3	75.1	57.1	14.5
LSD^v	30.9	11.8	18.7	2.5

^zTimed 21 June 2000.

^yTimed 1 June 2001.

^xTimed 21 June, 12 July, and 22 Aug. 2001.

^wTimed 9 July and 23 Aug. 2002.

^vLeast significant differences (LSD) at $P = 0.05$.

Pic = chloropicrin; fb = followed by; DZ = dazomet; IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

Table 8. Treatment and weeding costs at Ballico and MacDoel.

			Weeding cost			
			Ballico		Macdoel	
Fumigant	Rate	Treatment cost[z]	2000	2001	2001	2002
	(kg·ha^{-1})	US\$/ha^{-1}				
Pic fb DZ	336 fb 280	4050	—	—	104	87
TC35 fb DZ	432 fb 280	3645	—	—	110	92
IMPic	392	5622	1584	185	104	94
MBPic	450	3247	1241	200	101	108
NF	0	0	2257	834	634	161

[z]Prices: Pic $6.61/kg, DZ 6.52/kg, TC35 $4.21/kg, IMPic $14.33/kg, MBPic $7.24/kg.

Pic = chloropicrin; fb = followed by; DZ = dazomet; IMPic = iodomethane plus chloropicrin; MBPic = methyl bromide plus chloropicrin; NF = nonfumigated control.

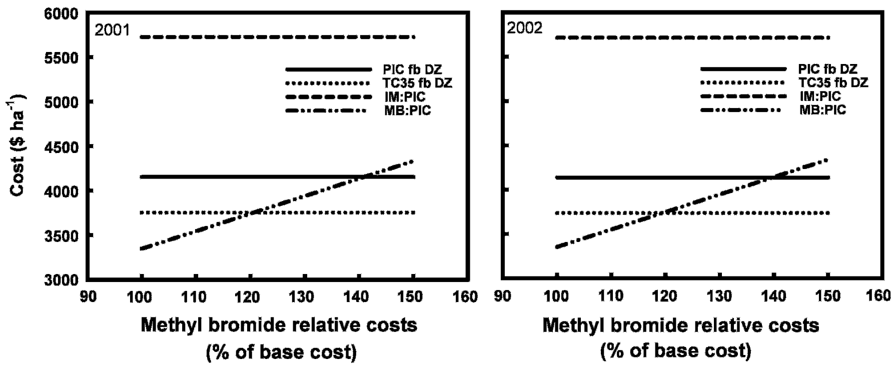

Fig. 1. Sensitivity analysis of fumigant plus handweeding costs relative to methyl bromide plus chloropicrin in the MacDoel strawberry nursery in 2001 and 2002.

These results indicate that IMPic, TC35 fb DZ, and Pic fb DZ provided weed control and required handweeding inputs similar to MBPic. The few published reports on weed control in strawberry nurseries indicate that alternative fumigant treatments do not provide weed control equivalent to MBPic. In California strawberry nurseries, Larson and Shaw (2000) reported visual observations that Pic at 140 to 336 kg·ha^{-1} and TC35 treatments had greater weed populations than the MBPic standard, but reported no data to support this observation. Furthermore, none of the treatments reported by Larson and Shaw (2000) included herbicide or fumigant treatments designed to control weeds. In research at Spanish strawberry nurseries, Melgarejo et al. (2003) tested several alternative fumigant treatments, including TC35 (reported as Telopic in the paper) and DZ each applied as single applications. Melgarejo et al. (2003) found that treatments of TC35 or DZ resulted in handweeding costs approximately the same as MBPic, very similar to our results. However, they concluded that weed control with alternative treatments was ''inconsistent,'' possibly as a result of the cool 7 °C soil conditions during fumigation at the sites (Garcia-Méndez et al., 2008). With the exception of the Susanville trial, we fumigated in August or September, as is the standard practice in California HENs, when soil temperatures were warm, 18 °C, and the weed control efficacy was consistently better (USDS, 2007).

Conclusions

In California strawberry nurseries, alternative fumigant treatments controlled weeds as effectively as MBPic. Handweeding costs were very similar among all fumigant treatments. On the basis of weed control, all of the alternative fumigant treatments were acceptable replacements for MB. The performance of IMPic was acceptable for weed control as reported here, and plant productivity reported in Kabir et al. (2005), but the cost of this product makes it much more expensive than MBPic. Producer decisions about the viability of these alternative treatments will likely be influenced by many factors such as treatment costs, pest control efficacy, runner plant yields, and profitability. Ultimately, grower profitability, phytosanitary certification of nursery plants by regulators, and acceptance of plants produced without MB by customers will be the deciding factors as to which fumigant treatments are chosen to replace MB.

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