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Soil Fumigation and Runner Plant Production: A Synthesis of Four Years of Strawberry Nursery Field Trials

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Abstract. **Strawberry (*Fragaria ×ananassa* L.) runner plant production during a 4-year period was compared on nursery soils treated with methyl bromide (MB) and chloropicrin (CP) mixtures (MB:CP) and three alternative soil treatments: CP, mixtures of 1,3-dichloropropene (Telone®) and CP (DP:CP), and no fumigation (NF). The effect of soil treatment on runner plant production for a single nursery propagation cycle was determined in all 4 years. In 2 years, runner production in a final propagation cycle was also determined as a function of soil treatment in previous cycles. A single propagation cycle in NF soil decreased runner production relative to all other treatments. Treatments with CP at rates of 140 to 191 kg·ha^{-1} generally decreased runner production significantly ($P \leq 0.05$) in comparison with treatment with MB:CP; use of CP at rates ≥303 kg·ha^{-1} resulted in statistically equivalent runner production. In one trial, use of two DP:CP formulations (516 kg·ha^{-1} of a 7:3 DP:CP mixture, and 448 kg·ha^{-1} of a 3:7 DP:CP mixture) significantly reduced and did not affect runner production, respectively, relative to the use of MB:CP. Use of MB:CP in the previous propagation cycle also increased runner productivity in comparison with NF. Runner productivity of planting stock produced with 314 kg·ha^{-1} of CP did not differ statistically from that of stock produced with MB:CP, but productivity of planting stock on soil treated with 157 kg·ha^{-1} of CP was intermediate between that on NF and MB:CP-treated soil. Planting stock grown on nontreated soil in two previous propagation cycles produced 25% fewer runner plants than did similar stock grown on MB:CP-treated soil. Productivity of planting stock produced with CP at rates of 280 to 314 kg·ha^{-1} in two previous propagation cycles did not differ statistically from that of stock produced with MB:CP. Results of meta-analyses indicated that fumigation with MB:CP was more effective in increasing runner production than was CP or NF, regardless of the propagation cycle or rate of application. For mixtures of 1,3-dichloropropene and CP, nursery productivity was maximized by using at least 280 kg·ha^{-1} of CP.**

California strawberry nurseries produce ≈1 billion runner (stolon) plants each year, with an annual farm value estimated at $60 million (C. Gaines, Lassen Canyon Nursery, Redding, Calif., personal communication, 1999). As a result of climate, geography, production and handling systems, and the Strawberry Certification Program administered by the California Dept. of Food and Agriculture, California nurseries produce high-quality strawberry plants that are marketed worldwide to nursery and fruit growers.

Commercial strawberry propagation is a multiyear process in which vegetative runner plants produced in one nursery propagation cycle are used as planting stock for the next cycle. In California, the first runner generation is produced in a screenhouse, and at least three additional runner generations are produced in field nurseries. Two or more field propagation cycles are conducted in low-elevation (LE, <150-m elevation) nurseries in the state's interior valleys, where climatic conditions result in prolific runner production during a long growing season. A final field propagation cycle is conducted in high-elevation nurseries (HE, >1000-m elevation) in northeastern California. In this region, temperature and photoperiod limit runner production, but increase transplant vigor and productivity, as well as fruit quality after transplanting to fruiting fields (Larson, 1994; Voth, 1989; Voth and Bringhurst, 1970).

Preplant soil fumigation with methyl bromide (MB) and chloropicrin (CP) mixtures (MB:CP) is a standard practice in California strawberry field nurseries; this treatment controls weeds, nematodes, and soilborne plant pathogens (Wilhelm and Paulus, 1980; Wilhelm et al., 1974; Yuen et al., 1991), and ensures the production of pest- and pathogen-free planting stock. Even in the absence of identifiable pests or pathogens, soil fumigation improves runner plant production and quality (Larson and Shaw, 1995b) because it suppresses a highly variable complex of sublethal or competitive soil microorganisms (Wilhelm and Paulus, 1980; Wilhelm et al., 1974; Yuen et al., 1991).

Methyl bromide has been classified as an ozone-depleting compound (Watson et al., 1992), and U.S. legislation currently requires a phaseout of MB production and use by 2005. Alternatives to MB soil fumigation have been evaluated extensively for strawberry fruit production (Himelrick and Dozier, 1991; Larson and Shaw, 1995a, 1996; Shaw and Larson, 1996, 1999), but little information exists regarding strawberry nursery management in the absence of MB in soil fumigation mixtures. In one study involving a single propagation cycle on new strawberry nursery ground, 140 kg·ha^{-1} of CP was less effective than MB:CP in enhancing nursery productivity and runner plant size (Larson and Shaw, 1995b). Nevertheless, preplant fumigation with high rates (≥336 kg·ha^{-1}) of CP alone effectively controls lethal soilborne fungal pathogens (Wilhelm, 1961). Chloropicrin is registered as a preplant soil fumigant for strawberry, and is frequently considered as an alternative to MB:CP for fumigation (U.S. Environmental Protection Agency, 1996). Mixtures of CP and 1,3-dichloropropene (Telone®) (DP:CP) are also considered alternatives to MB:CP for soil fumigation (U.S. Environmental Protection Agency, 1997), and while DP is currently registered as a soil fumigant for strawberry, its use is highly restricted in California because of environmental concerns.

From 1993 through 1996, we conducted trials to compare the effects of nursery soil treatments with MB:CP, CP, DP:CP, and NF (no fumigation) on strawberry runner plant production. The objective of this research was to quantify the extent to which productivity would be affected by using treatments other than the current standard MB:CP. As commercial strawberry plant propagation consists of multiple nursery cycles, these trials determined runner productivity: 1) following treatment in the final nursery propagation cycle after conducting the previous cycles in ground treated with MB:CP; and 2) in the final cycle using stock generated with alternative soil treatments in previous propagation cycles.

Materials and Methods

Experimental nursery sites. Soil fumigation experiments were conducted at four different HE nursery sites near Macdoel, Calif. (lat. 41.8°N, elev. ≈1300 m) in 1993–96. Individual sites differed as to cropping history, soil treatments, plot dimensions, and planting stock origin (Table 1). All sites had histories of production of various agronomic crops, including wheat (*Triticum aestivum* L.), annual rye (*Secale cereale* L.), sugar beets (*Beta vulgaris* L.), alfalfa (*Medicago sativa* L.), and potatoes (*Solanum tuberosum* L.). All trials except the 1994 HE trial were conducted on ground that had never been fumigated or used for strawberry fruit or nursery production; the one exception was a field that had been used to produce a single strawberry nursery crop in 1991.

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Soil fumigation trials were also conducted at two LE nursery sites near Manteca, Calif. (lat. 37.5°N, elev. ≈15 m) in 1994 and 1995. Both LE sites had been used for perennial crop production for many years, but were maintained fallow for at least 2 years prior to use as experimental nurseries.

Normal nursery practices were employed through the growing season at all nursery sites, and all plots were weeded by hand at about monthly intervals.

Plant material. All trials were established using cold-stored planting stock of 'Chandler' and 'Selva', the two principal strawberry cultivars grown in California during the period of this study. We used California Dept. of Food and Agriculture (CDFA)-certified, pathogen-free (produced with MBCP soil fumigation) planting stock to establish the 1993 and 1994 HE trials, as well as the 1994 LE trial (Table 1). Thereafter, runner plants produced with the various treatments in the 1994 LE trial were used to establish the 1995 LE and HE trials, and, similarly, plants produced in the 1995 LE trial were used to establish the 1996 HE trial.

General experimental details. In all trials, fumigants were applied by a commercial applicator. Materials were injected into the soil to a 36-cm depth and plots were covered with a polyethylene tarp that was removed 7 d after fumigant application.

Alternative soil treatments were applied at different rates and combinations in the various trials; NF and CP were included as alternatives to MB:CP soil fumigation in all six nursery trials, although CP application rates differed for each trial (Table 1). Four of the six trials included high (303–336 kg·ha^{-1}) and low (157–191 kg·ha^{-1}) application rates of CP, but only one rate of CP was used in the 1993 HE and 1995 LE trials. For the 1996 trial, CP was applied alone at high and low rates, and also was applied at high (314 kg·ha^{-1} of CP) and low (155 kg·ha^{-1} of CP) rates in combination with DP at 3:7 and 7:3 DP:CP ratios.

For both LE trials, mother plants were established in late May using double rows 182 cm apart with 90-cm in-row plant spacing. A 1.5 × 12.2-m section of runner plants was machine-harvested in January from the center of each of two replicate plots for each treatment × cultivar combination. Runner plants were immediately trimmed and graded to commercial standards, but runner production was not determined; rather, our objective was to produce planting stock for subsequent nursery propagation cycles. Plants were stored at –2 °C until planting.

For all HE trials, mother plants were established in double rows 91 cm apart using a 30-cm in-row plant spacing. Entire plots were machine-harvested in October, after which plants were graded to commercial standards, and the numbers of marketable runners produced per plot and per mother plant were determined.

Site-specific details. Three soil treatments were applied in the 1993 HE trial on 5 Apr. 1993: 1) MB:CP (2:1), 2) CP, and 3) NF (Table 1) with three replications per treatment. Prior cropping history, plot dimensions, and experimental methodology have been described previously for this trial (Larson and Shaw, 1995b). The original trial tested runner production at two spacings; no significant differences were detected for the number of runners produced per mother plant, and these spacing results were combined and reanalyzed in a simplified design here.

The experimental site of the 1994 HE trial was maintained in rye for 2 years following a single strawberry nursery crop produced with MB:CP preplant soil fumigation in 1991. Prior to 1991, the site had been used for many years for production of wheat, rye, alfalfa, and potato. Four soil treatments were applied on 31 Mar. 1994: 1) MB:CP (4:1), 2 and 3) CP at 2 rates, and 4) NF (Table 1). There were two replications per soil treatment. On 20 Apr. 1994, CDFA-certified 'Chandler' and 'Selva' mother plants were planted in separate plots measuring 5.5 × 9.1 m in all treatments. For all treatments, entire plots of 'Chandler' and 'Selva' were machine-harvested on 7 and 17 Oct. 1994, respectively.

The experimental site for the 1994 LE trial had a long history of almond (*Prunus dulcis* L.) production and had been fallow for 2 years prior to conducting the trial. Four soil treatments were applied on 4 May 1994 (rates are shown in Table 1): 1) MB:CP; 2 and 3) CP at high and low rates; and 4) NF. There were two replicate plots per soil treatment. The CDFA-certified 'Chandler' and 'Selva' mother plants were planted in separate plots measuring 5.5 × 9.1 m in all treatments on 27 May 1994. Center strips of all plots were machine-harvested on 10 Jan. 1995.

The experimental site of the 1995 LE trial had a long history of grape (*Vitis vinifera* L.) production and had been fallow for 3 years prior to conducting the trial. Three soil treatments were applied on 28 Apr. 1995: MB:CP, CP, and NF (Table 1). There were two replicate plots per soil treatment. On 27 May 1994, 'Chandler' and 'Selva' mother plants produced using treatments 1, 2, and 4 (MB:CP, CP291, and NF, respectively) in the 1994 LE trial were established in separate subplots measuring 1.5 × 6.7 m in all treatments (Table 1). Center portions of all plots were machine-harvested on 14 Jan. 1996.

The experimental site of the 1995 HE trial had been maintained in winter rye for 2 years prior to the trial. The site had a history of mixed agronomic cropping, but had not been fumigated previously or used as a strawberry nursery. Four soil treatments were applied on 7 Sept. 1994: 1) MB:CP (2:1); 2 and 3) CP at 2 rates; and 4) NF (Table 1). There were 3 replicate plots per treatment. On 27 April, 'Chandler' and 'Selva' mother plants were established in separate plots, each 3.35 × 22.9 m, in all treatments. For each cultivar, mother plants produced with the four 1994 LE treatments (MB:CP, CP291, CP157, and NF) were established in separate subplots, each 3.05 × 3.35 m, within each soil treatment plot (Table

Table 1. Nursery sites, plots per treatment, plot dimensions, source of mother plants used, and soil treatments and rates used in nursery soil fumigation trials, 1993–96.

Trial no.	Year	Site[z]	Plots per trt.	Plot size (m)	Planting stock source	Trt. no.	Soil trt.[y]	Rate (kg·ha^{-1})
1	1993	HE	3	3.4 × 30.5	Certified[x]	1	MB:CP, 2:1	392
						2	CP	140
						3	NF	
2	1994	HE	2	6.7 × 30.5	Certified[x]	1	MB:CP, 4:1	392
						2	CP	303
						3		191
						4	NF	
3	1994	LE	2	6.7 × 30.5	Certified[x]	1	MB:CP, 2:1	381
						2	CP	291
						3		157
						4	NF	
4	1995	HE	3	6.7 × 22.9	Trial 3, trts. 1–4	1	MB:CP, 2:1	392
						2	CP	314
						3		157
						4	NF	
5	1995	LE	2	6.7 × 30.5	Trial 3, trt. 1	1	MB:CP, 2:1	392
					Trial 3, trt. 2	2	CP	280
					Trial 3, trt. 4	3	NF	
6	1996	HE	3	6.7 × 22.9	Trial 5, trts. 1–3	1	MB:CP, 2:1	392
						2	CP	336
						3		168
						4	DP:CP, 3:7	448
						5	DP:CP, 7:3	516
						6	NF	

[z]HE = high-elevation (1300 m) nursery site near Macdoel, Calif. (lat. 41.8°N); LE = low-elevation (15 m) nursery site near Manteca, Calif. (lat. 37.5°N).
[y]Trt. = treatment; MB:CP (2:1 and 4:1) = 2:1 or 4:1 (weight : weight) mixtures, respectively, of methyl bromide and chloropicrin; CP = chloropicrin; DP:CP (3:7) = a 3:7 (weight : weight) mixture of 1,3-dichloropropene and chloropicrin; DP:CP (7:3) = a 7:3 (weight : weight) mixture of 1,3-dichloropropene and chloropicrin.
[x]Plants produced in accordance with the California Dept. of Food and Agriculture Strawberry Certification Program and grown with MBCP preplant soil fumigation.

Table 2. Analysis of variance of high-elevation nursery treatment effects on strawberry runner plant yield per mother plant in 1993 and 1994.

	1993 Runner yield		1994 Runner yield	
Source	df	Mean square	df	Mean square
Block (B)	2	5.63	1	0.25
Fumigation (H)	2	180.40**	3	316.30**
Error (a)	4	4.43	3	2.86
Cultivar (C)	1	0.43	1	164.67**
H × C	2	0.98	3	5.18
Error (b)	6	3.91	4	1.23

Table 3. Analysis of variance of low-elevation (LE) and high-elevation (HE) nursery treatment effects on runner plant yield per mother plant[z] in 1995 and 1996.

	1995 runner yield		1996 runner yield	
Source	df	Mean square[y]	df	Mean square[y]
Block (B)	2	2.45	1	130.6
HE fumigation (H)	3	332.46**	5	4372.3**
Error (a)	6	3.02	5	74.6
LE fumigation (L)	3	9.92**	2	3290.6**
Cultivar (C)	1	164.89**	1	253.2
L × H	9	0.83	10	89.0
L × C	3	0.70	2	3.1
H × C	3	0.72	5	235.8
L × H × C	9	0.51	10	79.1
Error (b)	58	0.79	29	110.9

[z]Original data were power transformed to remove significant regression between treatment mean and SD.
[y]Mean squares multiplied by 100 for ease of presentation.
**Significant at $P \leq 0.01$.

1). All plots of both cultivars were machine-harvested on 12 Oct. 1995.

The experimental site of the 1996 HE trial had been maintained in alfalfa for 4 years prior to the trial, and had not been fumigated previously or used as a strawberry nursery. Six soil treatments were applied on 7 Sept. 1994: MB:CP (2:1), CP at 2 rates, two mixtures of CP and DP (DP:CP 3:7 and 7:3), and NF (Table 1), with three replications per treatment. On 27 Apr. 1996, 'Chandler' and 'Selva' mother plants were established in separate plots, each 3.35 × 22.9 m, in all soil treatments; these plants had been produced using MB:CP, high rates of CP, and NF soil treatments throughout the 1994 and 1995 LE nursery propagation cycles. For each cultivar, plants produced with these three LE treatments were established in separate subplots (3.35 × 4.6 m) within the six nursery field treatments (Table 1). 'Chandler' and 'Selva' plots were machine-harvested on 4 and 16 Oct. 1996, respectively.

In summary, the 1993 and 1994 trials quantified the effect on runner production of soil treatments applied in a single HE nursery propagation cycle, the 1995 HE trial quantified their effects in two consecutive (one LE and one HE) cycles, and the 1996 trial quantified their effect in three consecutive (two LE and one HE) cycles.

Statistical analyses. Analyses of variance (ANOVAs) were conducted for runner production using split-plot designs. For 1993 and 1994 trials, HE fumigation treatments were treated as whole plots with fumigation × block interaction used as the whole plot error term (error a); cultivars were treated as minor plots. For 1995 and 1996 trials, HE fumigation treatments were treated as whole plots, and LE nursery source and cultivars were randomized within main plots and considered as minor plots. In all trials, the minor plot error included pooled sums of squares and degrees of freedom due to all block interactions, except the fumigation × block component used for whole-plot error.

Results of individual studies were further synthesized into combined results following the meta-analysis procedures of Hedges and Olkin (1985), as summarized in Olkin and Shaw (1995). Meta-analysis refers to a set of statistical techniques developed to provide a quantitative comparison of research results obtained from independent studies. In our synthesis, runners per mother plant for treated and control groups in individual studies were converted to standardized effects, d, and a composite estimate for the magnitude of a given treatment effect, d+, using the weighting procedure demonstrated in Olkin and Shaw (1995) and Shaw and Larson (1999). Statistical comparisons were made using 95% confidence intervals constructed from the estimated variance of the combined effect size, $\sigma^2(d_+)$, and Fisher's χ^2 procedure (Olkin and Shaw, 1995).

Results

Cultivar effects for runner plant yield were highly significant ($P \leq 0.01$) in two of the four HE trials (Tables 2, 3). Runner production differs among cultivar types (Darrow, 1966); in California, short-day (June-bearing) cultivars, such as 'Chandler', do not flower in summer and tend to be more prolific runner producers than day-neutral cultivars, such as 'Selva', that produce fruit throughout the summer. Importantly, all soil treatment × cultivar interactions were nonsignificant, suggesting that soil treatments affect runner production similarly in important cultivars.

Effects of nursery soil treatments were highly significant for runner plant production in all HE trials, but no interactions between HE treatment and either cultivar or LE nursery source were observed (Tables 2, 3). Application of any soil fumigant significantly increased runner production relative to NF, but nursery productivity varied with fumigant material and application rate (Tables 4, 5). Production following soil treatments that included high rates (>300 kg·ha^{-1}) of CP (i.e., CP and DP:CP, 3:7) ranged from 86% to 100% of the MB:CP control; no significant differences between these alternative treatments and the MB:CP control were detected in individual ANOVAs (Table 4). For alternative soil treatments with low rates (≤191 kg·ha^{-1}) of CP (i.e.,

Table 4. Descriptive statistics [replicate numbers (N), means, and standard deviations (SD)] for effects of fumigation treatments in high-elevation nurseries on strawberry nursery runner production in four test years.

Test	Nursery treatment			Runners/	
year	Chemical[z]	Rate (kg·ha^{-1})	N	mother plant[y]	SD[x]
1993	MB:CP, 2:1	392	12	18.0 a	2.50
	CP	140	12	15.7 b	3.00
	NF	---	12	7.9 c	1.53
1994	MB:CP, 4:1	392	4	29.7 a	0.87
	CP	191	4	27.0 a	0.98
	CP	303	4	29.7 a	1.89
	NF	---	4	11.2 b	1.17
1995	MB:CP, 2:1	392	24	18.8 a	1.03
	CP	157	24	16.7 b	0.82
	CP	314	24	18.9 a	1.47
	NF	---	24	10.3 c	0.69
1996	MB:CP, 2:1	392	11	39.2 a	3.30
	CP	168	12	28.6 bc	3.18
	CP	336	12	33.8 abc	4.07
	DP:CP, 3:7	448	12	35.8 ab	2.97
	DP:CP, 7:3	516	12	33.0 bc	5.39
	NF	---	12	15.8 d	1.08

[z]MB:CP, 2:1 and 4:1 = 2:1 or 4:1 (weight : weight) mixtures, respectively, of methyl bromide and chloropicrin. DB:CP = a mixture of 1,3-dichloropropene and chloropicrin.
[y]Means were pooled over cultivars. Mean separation by Bonferroni's adjusted post-hoc comparison ($P \leq 0.05$).
[x]SDs were pooled within cultivars and/or low-elevation treatments to eliminate main effects.

CP and DP:CP, 7:3), production ranged from 73% to 92% of the MB:CP control and significant differences were detected in three of the four comparisons.

Highly significant effects of LE nursery treatment on subsequent runner production at HE were detected in both trials (Table 3). Establishing the 1995 HE trial with planting stock produced with NF in 1994 reduced ($P \leq 0.05$) runner production compared with use of planting stock produced with MB:CP. Runner production at HE for planting stock produced with 157 kg·ha^{-1} of CP in the 1994 LE trial was greater than that of stock produced with NF but less than that produced with MB:CP or a high rate (314 kg·ha^{-1}) of CP. In the 1996 HE trial, productivity of stock produced with NF (no soil fumigation in the two previous LE propagation cycles) yielded only 71% as many runner plants as stock grown for two propagation cycles in MB:CP-treated soil ($P \leq 0.05$) (Table 5). Stock produced with high rates of CP (314 and 280 kg·ha^{-1} in 1994 and 1995, respectively) in consecutive LE propagation cycles produced 95% as many runner plants as did stock produced with MB:CP (differences nonsignificant at $P \leq 0.05$).

Meta-analysis demonstrated that MB:CP soil fumigation at HE nurseries was more effective in increasing runner production ($P \leq 0.05$) than was either CP at 140–336 kg·ha^{-1} or NF (Table 6). At HE, fumigation with MB:CP increased runner production 5.1% more than did high rates of CP (303–336 kg·ha^{-1}), whereas fumigation with MB:CP increased production 18.6% over low rates of CP (140–191 kg·ha^{-1}). Combined results of the four studies at HE demonstrate a 130.9% increase in runner production for MB:CP compared with NF.

Use of MB:CP for LE nursery stock resulted in a small (5.2%), but highly significant, increase in subsequent HE nursery productivity in comparison with use of CP (Table 6). Here, the comparison was made across two LE trials and with CP applied at both low (157 kg·ha^{-1}, 1994 LE trial) and high rates (280 and 291 kg·ha^{-1} for the 1994 and 1995 LE trials, respectively). Two studies were available for comparing nursery productivity using MB:CP and NF in LE nurseries (Table 6). In these two studies, planting stock grown on soil treated with MB:CP produced 25.9% more runners than did stock grown on NF soils ($P \leq 0.01$).

There were no visual symptoms of plant disease in any LE treatment plot, and no plant mortality.

Table 5. Descriptive statistics [replicate numbers (N), means, and standard deviations (SD)] for effects of using planting stock produced with low-elevation nursery treatments on high-elevation nursery runner production in 2 test years.

Test year	Nursery treatment: Chemical^z	Rate (kg·ha^{-1})	N	Runners/ mother plant^y	SD^x
1995	MB:CP, 2:1	381	24	16.9 a	0.92
	CP	157	24	16.1 b	1.25
	CP	314	24	16.6 a	0.90
	NF	---	24	15.2 c	0.94
1996	MB:CP	392	24	35.3 a	4.16
	CP	280	23	32.4 a	2.01
	NF	---	24	25.1 b	3.82

^{z}MB:CP = a 2:1 (weight : weight) mixture of methyl bromide and chloropicrin.
^{y}Means were pooled over cultivars. Mean separation by Bonferroni's adjusted post-hoc comparison ($P \leq 0.05$).
^{x}SDs were pooled within cultivars and/or high-elevation treatments to eliminate main effects.

Table 6. Results from meta-analysis of effects of high- (HE) and low-elevation (LE) soil fumigation treatments on strawberry runner plant production in high elevation nurseries.

Nursery source	Comparison treatment	No. of studies	d_+^{z} (±SE)	95% Confidence interval	$\sigma^2_{(2k)}$^{y}	% Increase^x
LE	Chloropicrin	3	0.638 (±0.173)	0.30–0.98	25.74**	5.2
	NF	2	2.146 (±0.258)	1.64–2.65	27.63**	25.9
HE	Chloropicrin	7	1.074 (±0.170)	0.74–1.41	56.62**	12.8
	High rate	3	0.294 (±0.235)	–0.16–0.75	14.75*	5.1
	Low rate	4	1.957 (±0.249)	1.47–2.44	41.87**	18.6
	NF	4	7.331 (±0.582)	6.19–8.47	54.60**	130.9

^{z}Composite estimate for the magnitude of a given treatment effect obtained using a weighting procedure (Okin and Shaw, 1995).
^{y}Estimated variance of the combined effect size.
^{x}Unweighted percentage increase in runner plant number from using a combination of methyl bromide-chloropicrin rather than the treatment listed (comparison treatment).

Discussion

The results of the present study confirm our previous report of strawberry growth and yield responses to soil fumigation in a runner plant nursery (Larson and Shaw, 1995b). Syntheses provided by meta-analysis demonstrated that mixtures containing MB and CP provided superior nursery stock and greater runner plant productivity than the alternatives tested.

For all studies and statistical comparisons, NF resulted in significant reductions in nursery runner productivity and plant vigor relative to any other soil fumigation treatment, despite the use of nursery ground not previously planted to strawberry. For all treatments and trials, plant roots were visually inspected for signs of root decay or discoloration immediately after nursery harvest; no symptoms were observed in any soil treatment or nursery trial. There were no visual symptoms of soilborne pathogens or pests in any plots in the LE trials, and few visual symptoms of soilborne pathogens for plants in any HE trials. However, stunting of aboveground vegetative tissues and desiccation of older leaves were observed in some mother plants in NF plots in the 1995 and 1996 HE trials, and the presence of *Verticillium dahliae* Kleb. in tissues of symptomatic plants was confirmed by laboratory analyses. Although plant infection with Verticillium probably contributed to reductions in nursery productivity in NF plots in these trials, plant mortality was not observed in any trial, and only a small percentage of runner plants from NF plots developed Verticillium wilt symptoms after transplanting to fruit production fields.

Although plants from CP treatments were symptomless for soilborne pathogens such as Verticillium, use of CP reduced nursery productivity relative to use of MB:CP, regardless of CP rate or propagation cycle (Table 6), suggesting that nonspecific, competitive, or sublethal microorganisms were also responsible for observed yield reductions. Use of DP:CP mixtures in only 1 year of trials prevented inclusion of these treatments in the meta-analyses. Use of a DP:CP mixture containing a high rate of CP (DP:CP 3:7) resulted in 8.6% fewer runners than did use of MB:CP, but this difference was not statistically significant (Table 4). The use of the DP:CP mixture containing a low rate of CP (DP:CP 7:3) significantly reduced production compared to MB:CP, despite a very high application rate (Table 4). The effects of the two DP:CP treatments were similar to those obtained using high and low rates of CP (Tables 4, 5, 6), suggesting that the use of CP at high rates (>280 kg·ha^{-1}), possibly in combination with other materials such as DP, will be an important component of future nursery management programs. However, DP, even when used at extremely high rates, appears to be less effective than CP in enhancing runner production.

Weed control was not determined for soil treatments in any trial. However, weed control is one of the main benefits of MB soil fumigation, and is a major issue in strawberry nurseries. Despite the lack of quantitative data on weed suppression, visual observations indicated that all alternative treatments had significantly greater weed populations than did the MB:CP standard, but that use of any fumigant material reduced weed populations compared with NF.

When the NF and MB:CP treatments were compared, soil fumigation in the final runner propagation cycle had a greater effect on productivity than did fumigation in prior propagation cycles (Table 6). However, the absence of LE × HE interactions in either the 1995 or 1996 trial (Table 3) indicates that the effects of nursery treatments applied throughout a multiple-year propagation cycle are additive, and that the consequences of using less effective soil fumigants in strawberry propagation are cumulative over propagation cycles. Our previous observation that serial application of less effective soil fumigants leads to increasingly greater reductions in fruit yield during three consecutive years (Shaw and Larson, 1999) also suggests that nursery productivity will be adversely affected by such treatments. These results indicate that, to determine the full impact of the loss of MB on strawberry production, studies need to be conducted on the effects of MB alternatives in fruit production fields, as well as on the cumulative effects of alternative soil treatments on the productivity of the nursery stock itself.

In addition to enhancing nursery productivity, soil fumigation reduces the risk of disseminating soilborne pathogens and pests to other nurseries and fruiting fields. As effective nursery soil fumigants are banned or restricted because of environmental concerns and regulatory action, the dissemination of soilborne pathogens and pests will probably become an increasingly important issue.

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