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A Meta-analysis of Strawberry Yield Response to Preplant Soil Fumigation with Combinations of Methyl Bromide–chloropicrin and Four Alternative Systems

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***Abstract*. Yield for annual California strawberry (*Fragaria* ×*ananassa* Duch.) production systems in soils treated with combinations of methyl bromide–chloropicrin (MB:CP) were compared with four alternative soil treatment systems using meta-analysis. Studies represent 11 production seasons, and were conducted at three distinct locations in California. Fumigation with mixtures of methyl bromide (MB) and chloropicrin (CP) increased yield significantly compared with any and all alternatives lacking MB. In a combined analysis of 45 studies, fumigation with MB:CP compounds increased yield an average of 94.4% ($d_+ = 2.874 \pm 0.098$) compared with yields for plants in nonfumigated (NF) soils. Further, the effect of MB:CP fumigation increased over the first three strawberry cultivation cycles: MB:CP–fumigated soils provided a 59.2% ($d_+ = 2.166 \pm 0.146$) yield advantage when one cycle of fumigation was omitted, a 100.2% ($d_+ = 3.000 \pm 0.143$) advantage when two cycles were omitted, and a 148.4% ($d_+ = 6.201 \pm 0.348$) yield advantage when three or more cycles of MB:CP were omitted. In a combined analysis that included 34 studies, soil fumigation with MB:CP conferred a 9.6% ($d_+ = 0.751 \pm 0.087$) yield advantage over fumigation with CP alone. Soils treated with MB:CP yielded 6.8% ($d_+ = 0.437 \pm 0.114$) more fruit than those treated with very high rates of CP (336–396 kg·ha^{-1}), and 15.4% ($d_+ = 1.190 \pm 0.134$) more than soils treated with commercially realistic rates (168–224 kg·ha^{-1}). Similar to the comparison using NF soils, the efficacy of very high rates of CP appeared to diminish over cycles of strawberry cultivation; MB:CP increased yield 2.2% ($d_+ = 0.043 \pm 0.162$) in the first CP production cycle, 10.6% ($d_+ = 0.588 \pm 0.174$) and 13.7% ($d_+ = 2.054 \pm 0.401$) in the following two cycles. Combinations of dichloropropene (DP) and CP were no more effective than were lower rates of CP alone, and MB:CP conferred a 14.4% ($d_+ = 0.962 \pm 0.162$) yield advantage over mixtures of DP:CP. Mixtures of MB:CP increased yield 29.8% ($d_+ = 3.199 \pm 0.287$) compared with metam sodium (MS). The standardized effect was similar when comparing MB:CP combinations with either MS or NF soils, suggesting little effect of MS on the yield response. Chemical names used: trichloronitromethane (chloropicrin); 1,3-dichloropropene (dichloropropene); sodium *N*-methyldithiocarbamate (metam sodium).**

Preplant soil fumigation was originally investigated as a means for controlling *Verticillium dahliae* Koch (Wilhelm and Koch, 1956) in strawberry. Subsequent studies demonstrated advantages of preplant soil fumigation for at least three horticultural issues: weed control, control of lethal pathogens and nematodes, and a general growth and yield response that appears independent of specific host–pathogen interactions (Wilhelm et al., 1961, 1974). Studies of a range of other fumigation alternatives generally concluded that a synergistic effect of compounds containing methyl bromide (MB) and chloropicrin (CP) made mixtures of these fumigants the most effective (Wilhelm and Paulus, 1980).

As a consequence of fumigation research conducted during the past half-century, preplant soil fumigation with mixtures of 2 MB:1 CP (by weight) at ≈390 kg·ha^{-1} was standard for the California strawberry industry by the mid-1970s, and continues to be at present (Larson and Shaw, 1995a). However, concerns about the role of the halogen compound MB in ozone depletion emerged in 1990, and international regulatory restrictions may preclude future use of soil fumigants that include this chemical. Anticipating a future regulatory phaseout of MB, researchers in California have engaged in a decade-long effort to evaluate and quantify the benefits of soil fumigation, and determine the efficacy of other available chemical and nonchemical alternatives for current cultivars and production systems.

The objective of the research synthesis that follows was to compare strawberry productivity across a range of soil treatments, essentially from minimal treatment such as repeated use of nonfumigated (NF) soils (with or without crop rotation) to application of alternative chemicals at high rates, in an effort to quantify the consequences of a ban on MB. This synthesis is limited in scope in that it does not consider the consequences of lethal pathogens that are likely to be a greater problem with some of the available alternatives. Further, this analysis does not quantify reductions in fruit quality, economic losses due to the cost of alternative chemicals or fruit quality reduction, or capital costs and/or yield reductions that might accrue as a result of any changes in cultural practice changes required by alternatives to MB:CP. This synthesis also considers only yield effects for soil treatments applied in the fruiting field. Strawberry production systems depend on preplant soil fumigation in a number of nursery propagation steps, and preliminary indications suggest that problems may arise for both plant productivity and quality using available alternatives (Larson and Shaw, 1995b). The effects of eliminating MB on nursery production, plant quality, and eventual yield reduction due to reduced nursery plant quality will be considered separately. This synthesis begins by defining strawberry performance in the NF control. Thereafter, the choice of comparison treatments was limited to those that had demonstrated some promise in prior experiments, and to chemical alternatives currently registered and thus available for use in California. As a consequence, several chemical and nonchemical alternatives that had either shown little effect in prior trials or are not currently registered in California were not included. Lastly, several of the chemical alternatives were tested at rates too high to be legally, economically, or socially feasible in operational production systems; these trials were included to provide boundaries for efficacy estimates.

Materials and Methods

The individual studies used for this research synthesis were conducted at three macro-locations within California: Irvine, at the south edge of the Los Angeles basin (33°40´, 117°43´); Oxnard, ≈97 km north of Los Angeles (34°13´, 119°11´); and Watsonville, ≈130 km south of San Francisco (36°56´, 121°46´). These locations are representative of the environments that produce >97% of the strawberries grown in California, or ≈80% of those produced in North America (Faxon, 1997). Results were obtained from trials conducted on three subsites in the Irvine region, two in the Oxnard region, and three in the Watsonville region.

The trials included in this synthesis extend from 1987 to 1997; most were conducted after 1992, as a consequence of increasing concerns about future availability of MB. Fumigation trials prior to 1987 frequently used germplasm no longer considered commercially viable, a potentially confounding factor eliminated in this synthesis.

Most of the trials were conducted using commercial cultivars adapted to the specific

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test region chosen, although a few comparisons included advanced selection materials from the Univ. of California (UC) strawberry improvement program, and two of the NF trials used cultivars of other North American origin. Likewise, several of the studies included runner plants from nurseries treated with different fumigants. Where multiple cultivars were used or where several nursery fumigation treatments were applied, the standard deviations used for weighting in combined analysis were calculated using pooled within-genotype or within-nursery-treatment sums of squares.

The results presented in this synthesis represent a reasonably complete array of those studies conducted to test fumigation alternatives by public sector researchers in California between 1987 and 1997. Original results requested from two authors for four studies were no longer available, and because the published results lacked the necessary parameters (means, SDS, sample numbers) for inclusion in a meta-analysis, these were omitted. Also, results for six studies were judged proprietary by their originators and not made available for this synthesis. The vast majority of research results synthesized here were reported in symposia, industry bulletins, or are unpublished at present because of recent completion; these publications rarely included the necessary parameters for inclusion in a meta-analysis. In these cases, parameters were obtained from raw data provided by the original authors and reanalyzed for this synthesis. Typically, individual studies contained an industry standard control (fumigated with MB:CP), a NF control, and one or more chemical alternatives. Individual comparisons were made between the industry standard treatment (MB:CP) and each of several different alternatives within a single trial. Thus, results from the MB:CP treatment were used in multiple comparisons. As a consequence, comparisons of the different alternatives are not independent, but their covariance is expected to be large only when very small numbers of studies are evaluated, and thus will be of little importance here.

Study results were combined 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 many independent studies. These techniques adjust for differences in error rate among studies and weight individual results based on both intrinsic error and sample size. In our synthesis, yield differences for treated and control groups in individual studies were converted to standardized effects, d, as:

$$d = \frac{\overline{X}_T - \overline{X}_C}{s} \quad [1]$$

$\overline{X}_T$ and $\overline{X}_C$ are means for the treated and control groups, respectively, and s is the pooled standard deviation for both groups. To obtain a composite estimate for the magnitude of a given treatment effect, the d_i's from individual studies were weighted according to individual study error rates, $\hat{\sigma}^2(d_i)$, where:

$$\sigma^2(d_i) = \frac{n_i^T + n_i^C}{n_i^T n_i^C} + \frac{d_i^2}{2(n_i^T + n_i^C)} \quad [2]$$

In Eq. 2, n_i^T and n_i^C are the numbers of replications for treated and control groups, respectively, and d_i is the estimated treatment effect for the i^{th} study, i = 1, . . . , k. The weight, w_i, assigned to each effect size estimate is inversely proportional to its variance and was computed as:

$$w_i = \frac{1/\hat{\sigma}^2(d_i)}{\Sigma\left[1/\hat{\sigma}^2(d_j)\right]} \quad [3]$$

and the combined estimate, d_+, of effect size was calculated as:

$$d_+ = w_1 d_1 + w_2 d_2 + \ldots + w_k d_k = \Sigma w_i d_i \quad [4]$$

Statistical comparisons were made using 95% confidence intervals constructed from the estimated variance of the combined effect size, $\hat{\sigma}(d_+)$, calculated as:

$$\hat{\sigma}^2(d_+) = \frac{1}{\Sigma\left[1/\hat{\sigma}^2(d_j)\right]} \quad [5]$$

A confidence interval for the combined effect size was determined as $d_+ \pm c_{\alpha/2}\hat{\sigma}(d_+)$, with $c_{\alpha/2}$ being the appropriate coefficient obtained from the normal distribution for the chosen confidence interval; for example, 1.96 for a 95% confidence interval.

Sufficient numbers of studies were obtained to compare four alternatives with the MB:CP industry standard: a NF control, CP alone at high and moderate rates, mixtures of dichloropropene (DP) and CP, and metam sodium (MS). In all cases, the critical comparison was between the current industry standard and an alternative, with MB:CP designated as the treated group and one of the alternatives listed above as the control. Thus, the standardized effect sizes provided by meta-analysis, statistical comparisons based on their confidence limits, and the unweighted percentage increase in yield provide a direct comparison between efficacy of fumigation using MB:CP and that of each of the designated alternatives. Figures are expressed in standardized effect size or percentage advantage for the current fumigation system, but could be expressed as relative losses for the alternatives by simple transformation.

Because most trials included both an industry standard and a NF control, comparison between fumigation with MB:CP mixtures and the absence of fumigation is the best tested of the treatment effects evaluated here; 45 studies were available for this comparison (Table 1, study set "N" in the far right column). Trials with NF included both those that followed strawberry cultivation directly with another strawberry crop and those that include a crop rotation other than strawberry. Prior work showed little difference in fumigation response with either 1 or 20 years rotation out of strawberry (Larson and Shaw, 1995a). Similarly, no mean difference was apparent among sets of studies established with and without crop rotations consisting of alternate years of strawberry and a barley (*Hordeum vulgare* L.)/fava bean (*Vicia faba* L.) cover crop that was incorporated into the soil every other spring, thus any rotation effect was ignored. Trials differed in the number of strawberry production cycles since the last fumigation cycle, and we subdivided our NF studies into sets with one, two, or more than two strawberry cycles to evaluate the changes in relative productivity over time.

Direct comparison of yield for plants in soils fumigated with MB:CP mixtures and those grown in soils fumigated with CP alone were possible using 34 studies (Table 1, study set "C" in the far right column). Twenty-three of these studies were conducted using CP at rates of 336 $kg \cdot ha^{-1}$ or greater; due to the cost of materials and the social consequences of emissions of this compound, such rates are not likely to be commercially realistic. Eleven studies were conducted using moderate, and more realistic, rates (121–224 $kg \cdot ha^{-1}$). Rate differences were compared in a subdivided meta-analysis. The effect of high rates of CP on yield was also evaluated by subdividing the 23 high-rate studies over the number of cycles since the last fumigation with MB:CP combinations; a similar subdivision was not possible for CP at moderate rates due to an insufficient number of studies.

Ten studies were available for comparing yields of plants grown in soils treated with MB:CP vs. DP:CP mixtures (Table 1, study set "D" in the far right column). These 10 studies are a heterogeneous mix with substantial differences in the total quantity of product applied (336–666 $kg \cdot ha^{-1}$) and, importantly, from 94–235 $kg \cdot ha^{-1}$ of CP as part of the mixture. Several of the studies used DP at rates that exceed the maximum currently allowed by regulatory agencies.

Eight studies were included in yield comparisons for MB:CP vs. MS (Table 1, study set "M" in the far right column). Seven of the eight studies were conducted using the recommended rates of 275–305 $L \cdot ha^{-1}$ a.i of MS, the other used 153 $L \cdot ha^{-1}$ a.i. The treatment differences were somewhat larger for this comparison, and comparisons were rather precise despite inclusion of relatively few studies. Fewer studies were available for evaluating the effect of MS on strawberry yield during the past 11 seasons, probably because a large number of prior studies had routinely demonstrated this to be a less effective soil treatment (Himelrick and Dozier, 1991). Three studies not included because they lacked appropriate statistical information will be discussed to support these comparisons.

Results

Yields were larger following fumigation with MB:CP than for NF treatments in all studies, and these differences were statistically significant or highly significant in 41 of the 45 individual studies evaluated (Table 2). Over all studies the weighted standardized effect was $d_+ = 2.874 \pm 0.098$ (95% confidence: 2.672, 3.056), indicating a significant

Table 1. Descriptive information for comparing strawberry genotypes on methyl bromide : chloropicrin (MB:CP) fumigated soils vs. nonfumigated (NF) soils or on soils treated with chloropicrin (CP), dichloropropene: chloropicrin (DP:CP), or metam sodium.

Study no.	Test year	Location	Cultivars/ selections	Crop	Treatment[z]	Rate/ha	Reference	Study set[y]
1	1987	Watsonville	Chandler	First NF	NF	---	Welch, unpublished	N
2	1988	Watsonville	Chandler	First DP:CP[x] and NF	NF 83 DP:17 CP	--- 666 kg	Welch, unpublished	N,D
3	1989	Watsonville	Chandler	Second NF	NF	---	Welch et al., 1990	N
4	1989	Watsonville	Chandler	Second NF	NF	---	Welch et al., 1990	N
5	1990	Watsonville	Chandler	Third DP:CP[x] and NF	NF 83 DP:17 CP	--- 666 kg	Welch et al., 1991	N,D
6	1990	Watsonville	Chandler	Third NF	NF	---	Welch et al., 1991	N
7	1991	Watsonville	Selva	First DP:CP[x] and NF	NF 83 DP:17 CP	--- 554 kg[2]	Welch, unpublished	N,D
8	1992	Watsonville	Selva	First MS[x]	MS	842 L	Welch, unpublished	M
9	1993	Watsonville	12 UC cultivars/ selections	First NF	NF	---	Larson and Shaw, 1994	
10	1993	Irvine	12 UC cultivars/ selections	First NF	NF	---	Larson and Shaw, 1994	N
11	1993	Irvine	Chandler	First CP and NF crop, 20-yr rotation	NF CP	--- 112 kg	Larson and Sterrett, 1994	N,C
12	1993	Irvine	Oso Grande	First CP and NF, 20-yr rotation	NF CP	--- 112 kg	Larson and Sterrett, 1994	N,C
13	1993	Watsonville	four UC cultivars	Second NF	NF	---	Walsh et al., 1996	N
14	1994	Irvine	Camarosa	Second NF	NF	---	Larson, unpublished	N
15	1994	Irvine	six UC cultivars	Second CP and NF CP	NF 336 kg	---	Larson, unpublished	N,C
16	1994	Irvine	Chandler	Second CP and NF CP	NF 336 kg	---	Larson et al., 1996	N,C
17	1994	Watsonville	Selva	First CP and NF CP	NF 336 kg	---	Larson, unpublished	N,C
18	1994	Watsonville	Selva	First CP and NF CP	NF 336 kg	---	Larson, unpublished	N,C
19	1994	Watsonville	Selva	First CP and NF CP	NF 336 kg	---	Larson, unpublished	N,C
20	1994	Watsonville	Selva	First CP and NF CP	NF 336 kg	---	Larson, unpublished	N,C
21	1994	Oxnard	Chandler MS	First DP:CP[x], CP[x], MS[x] and NF 917 L	NF CP 7 DP:3 CP	--- 396 kg 556 kg	Paulus, unpublished	N,C, D,M
22	1994	Watsonville	12 UC cultivars/ selections	First NF	NF	---	Shaw, unpublished	N
23	1994	Watsonville	Selva	First CP[x] and NF	NF CP	--- 231 kg	Welch et al., 1995	N,C
24	1995	Irvine	Chandler	Second CP and NF crop	NF CP	--- 336 kg	Larson, unpublished	N,C
25	1995	Irvine	Chandler	Second NF	NF	---	Larson, unpublished	N
26	1995	Irvine	Chandler	Second CP	CP	336 kg	Larson, unpublished	C
27	1995	Irvine	Camarosa	Second NF	NF	---	Larson, unpublished	N
28	1995	Watsonville	Selva	Second CP and NF	NF CP	--- 336 kg	Larson, unpublished	N,C
29	1995	Watsonville	Selva	Second CP and NF	NF CP	--- 336 kg	Larson, unpublished	N,C
30	1995	Watsonville	Sunset	Second CP and NF	NF CP	--- 336 kg	Larson, unpublished	N,C
31	1995	Oxnard	Chandler	First DP:CP[x], CP[x] and NF	NF CP 7 DP:3 CP	--- 336 kg 539 kg	Paulus, unpublished	N,C, D
32	1995	Watsonville	nine UC cultivars	Second NF	NF	---	Shaw and Larson, 1996	N
33	1995	Watsonville	nine non-UC cultivars	Second NF	NF	---	Shaw and Larson, 1996	N
34	1995	Watsonville	12 UC cultivars/ selections	Second NF	NF	---	Shaw, unpublished	N
35	1996	Irvine	Camarosa	Third CP	CP	336 kg	Larson, unpublished	C
36	1996	Irvine	Chandler, Nur. trt.[w] = low CP	Third CP	CP	336 kg	Larson, unpublished	C
37	1996	Irvine	Chandler, Nur. trt.[w] = low CP	Third CP	CP	336 kg	Larson, unpublished	C

continued on next page

Table 1. Continued.

Study no.	Test year	Location	Cultivars/ selections	Crop	Treatment[z]	Rate/ha	Reference	Study set[y]
38	1996	Irvine	Chandler, Nur. trt.[w] = NF	Third CP	CP	336 kg	Larson, unpublished	C
39	1996	Irvine	Camarosa	First CP crop after NF	CP	168 kg	Larson, unpublished	C
40	1996	Irvine	Chandler, Nur. trt.[w] = low CP	First CP crop after NF	CP	168 kg	Larson, unpublished	C
41	1996	Irvine	Chandler, Nur. trt.[w] = high CP	First CP crop after NF	CP	168 kg	Larson, unpublished	C
42	1996	Irvine	Chandler, Nur. trt.[w] = NF	First CP crop after NF	CP	168 kg	Larson, unpublished	C
43	1996	Irvine	Camarosa	Third NF	NF	---	Larson, unpublished	N
44	1996	Irvine	Chandler, Nur. trt.[y] = low CP	Third NF	NF	---	Larson, unpublished	N
45	1996	Irvine	Chandler, Nur. trt.[y] = high CP	Third NF	NF	---	Larson, unpublished	N
46	1996	Irvine	Chandler, Nur. trt.[w] = NF	Third NF	NF	---	Larson, unpublished	N
47	1996	Irvine	Camarosa	First MS[x] crop after NF	MS	935 L	Larson, unpublished	M
48	1996	Irvine	Chandler, Nur. trt.[w] = low CP	First MS[x] crop after NF	MS	935 L	Larson, unpublished	M
49	1996	Irvine	Chandler, Nur. trt.[w] = high CP	First MS[x] crop after NF	MS	935 L	Larson, unpublished	M
50	1996	Irvine	Chandler, Nur. trt.[w] = NF	First MS[x] crop after NF	MS	935 L	Larson, unpublished	M
51	1996	Watsonville	Selva	Second NF	NF	---	Larson, unpublished	N
52	1996	Watsonville	Selva	Second NF	NF	---	Larson, unpublished	N
53	1996	Watsonville	Selva	First CP	CP	336 kg	Larson, unpublished	C
54	1996	Watsonville	Selva	First CP	CP	168 kg	Larson, unpublished	C
55	1996	Watsonville	Selva	First CP	CP	336 kg	Larson, unpublished	C
56	1996	Watsonville	Selva	First CP and Second NF	NF CP	--- 224 kg	Larson, unpublished	C
57	1996	Watsonville	Selva	First CP	CP	168 kg	Larson, unpublished	C
58	1996	Oxnard	Chandler	First DP:CP, CP and NF crop	NF CP 7 DP:3 CP	--- 358 kg 389 kg	Paulus, unpublished	N,C,D
59	1996	Watsonville	12 UC cultivars/ selections	Second NF	NF	---	Shaw, unpublished	N
60	1996	Watsonville	8 UC cultivars/ selections	First CP	CP	336 kg	Shaw, unpublished	C
61	1996	Watsonville	8 UC cultivars/ selections	First CP	CP	168 kg	Shaw, unpublished	C
62	1996	Watsonville	Selva	First MS[x]	MS	468 L	Larson, unpublished	M
63	1996	Watsonville	Selva	First MS[x]	MS	935 L	Larson, unpublished	M
64	1997	Watsonville	Selva	First DP:CP, Third NF	NF 65 DP:35 CP	--- 448 kg	Larson, unpublished	N,D
65	1997	Watsonville	5 UC cultivars/ selections	First DP:CP, Third NF	NF 65 DP:35 CP	--- 448 kg	Shaw, unpublished	N,D
66	1997	Irvine	Chandler	First DP:CP[x] and CP[x], fourth NF	NF CP 65 DP:35 CP	--- 336 kg 386 kg	Larson, unpublished	N,C,D
67	1997	Irvine	Camarosa	First DP:CP[x], CP[x] and NF	NF CP 4 DP:6 CP	--- 224 kg 392 kg	Paulus et al., 1998	N,C,D

[z]Mixtures of dichloropropene:chloropicrin were used at four rates. All trials were established using one of the treatments listed and 2 MB : 1 CP (wt:wt) with a rate of 392 $kg\cdot ha^{-1}$; MB:CP rates differed for cases 21 (427 $kg\cdot ha^{-1}$), 31 (405 $kg\cdot ha^{-1}$), 58 (383 $kg\cdot ha^{-1}$), 67 (57 MB : 43 CP @ 420 $kg\cdot ha^{-1}$). All MS applications were performed using a formulation with 33.4% a.i.

[y]Studies labeled N, C, D, and M were used in comparisons between MB:CP and NF (N), CP(C), DP:CP (D), and MS (M) alternatives.

[x]Fumigants applied using bed application methods. MB treatments were applied using bed application methods to studies 1–8, 21, 23, 31, 66, and 67.

[w]Nur. trt. = nursery fumigation treatment; low CP is 168–224 $kg\cdot ha^{-1}$, high CP is 336–396 $kg\cdot ha^{-1}$; NF is nonfumigated.

fumigation response for yield, and the overall unweighted increase in yield due to fumigation was 94.4%.

The difference between yields for plants in fumigated and NF soils increased over the first three strawberry cultivation cycles. Fumigation with MB:CP provided a standardized effects of $d_+ = 2.166 \pm 0.146$ (59.2% yield advantage) for 17 studies where one cycle of fumigation was skipped or soil not recently cropped in strawberry was used, $d_+ = 3.000 \pm 0.143$ (100.2% advantage) for 19 studies where strawberries were cultivated for two cycles without MB:CP fumigation, and $d_+ = 6.201 \pm 0.348$ (148.4% yield advantage) in nine cases where strawberries were grown without soil fumigation for three or more cycles. Direct comparison of yields over cycles was not possible because the subsets of studies used different genotypes, harvest periods, etc. However, because nearly all the studies were conducted on ground that had been fumigated with MB:CP and cropped in strawberry for several prior cycles, the increase in d_+, or the change in relative yield advantage reported here over cycles, can be attributed to the reduction of yield with repeated cultivation in NF soils, rather than increases in yield due to serial fumigation with MB:CP. Because the 95% confidence limits for these three effect size estimates do not overlap, these results indicate significant yield reduction at each of the first three NF cultivation cycles, and the minimum productivity expected without soil fumigation has likely not been reached in the NF soil environments evaluated to date.

Results for the 34 individual studies comparing MB:CP fumigation with CP alone are summarized in Table 3. Yields following fumigation with MB:CP were larger than for CP fumigation in 28 of the 34 studies, and these differences were significant or highly significant in 12 of the 34 individual studies evaluated. Over all studies, the standardized effect was $d_+ = 0.751 \pm 0.087$ (95% confidence: 0.581, 0.921), indicating a significant yield advantage for combinations of MB:CP over CP alone, and the overall unweighted increase in yield due to fumigation was 9.6%.

As a second step in evaluation of the CP alternative, the 34 studies were subdivided into a set of 23 studies where the rate of application was equal to or greater than 336 $kg \cdot ha^{-1}$ CP, and a set of 11 studies with rates between 121 and 224 $kg \cdot ha^{-1}$. At the higher application rate, the standardized effect was $d_+ = 0.437 \pm 0.114$ (unweighted increase = 6.8%) whereas the lower application rate gave $d_+ = 1.190 \pm 0.134$ (unweighted increase = 15.4%); 95% confidence limits for these subset effect sizes did not overlap, demonstrating a statistically significant dependence on application rate.

As a final step in comparing these two alternatives, the 23 studies in the high application rate subset were further subdivided based on the number of strawberry cultivation cycles between the last MB:CP treatment and the current evaluation. Similar to the case comparing MB:CP with NF, the difference between yields for plants in soils fumigated with a MB:CP mixture and soils treated with CP alone increased over the first three cultivation cycles: MB:CP fumigated soils provided a standardized effect of $d_+ = 0.043 \pm 0.162$ (2.2% yield advantage for MB:CP) for 12 studies where one cycle of MB:CP fumigation was replaced by CP alone, $d_+ = 0.588 \pm 0.174$ (10.6% advantage for MB:CP) for seven studies where strawberries were cultivated for two cycles with high rates of CP, and $d_+ = 2.054 \pm 0.401$ (13.7% yield advantage for MB:CP) in four cases in which CP was used for three cycles. Although the initial yield decline after fumigation with high rates of CP was small, this appears largely the consequence of a carry-over effect of MB:CP fumigation for a single cycle; even on soils fumigated with high rates of CP yield declined as a new equilibrium was approached after more than one strawberry production cycle.

Yields for MB:CP-treated soils exceeded those for DP:CP treated soils in nine of the ten individual studies reported here (Table 4), and individual differences were statistically significant in four of these nine cases. Over all 10 studies, the standardized effect was $d_+ = 0.962 \pm 0.162$ (95% confidence: 0.645, 1.279), indicating a significant yield advantage for combinations of MB:CP over DP:CP combinations; the overall unweighted increase in yield due to fumigation with MB:CP was 14.4%. Performance of plants was statistically indistinguishable in soils fumigated with DP:CP mixtures and low rates of CP alone. Mixtures of DP:CP mixtures that use higher rates of CP might perform better on average, but there is no strong indication for this in the present set of studies.

Soil treatment with MS proved the least productive of the chemical alternatives tested, with yields for MB:CP treatments exceeding those for MS treated soils significantly in all eight individual studies (Table 5). Over all

Table 2. Effects of soil fumigation with methyl bromide : chloropicrin (MB:CP) vs. nonfumigated (NF) control studies on yields (grams/plant) of strawberry in 45 studies.

		Treated		Nontreated					
Study	No. reps	Mean yield	SD	Mean yield	SD	Increase[z] (%)	t^y	p^y	d^y
1	5	1007	74	502	63	100.6	11.62	<0.001	7.35
2	6	992	177	390	104	154.4	7.18	<0.001	4.15
3	6	916	136	384	167	138.5	6.05	<0.001	3.49
4	5	1720	82	710	135	142.3	14.30	<0.001	9.04
5	6	1331	40	463	112	187.4	17.87	<0.001	10.32
6	6	1734	212	713	117	143.2	10.32	<0.001	5.96
7	5	1069	110	619	122	72.7	6.12	<0.001	3.87
9	24	1480	359	752	173	96.8	8.95	<0.001	2.58
10	24	833	218	476	154	75.0	6.55	<0.001	1.895
11	18	763	80	557	116	37.0	3.58	0.003	2.07
12	18	772	64	535	95	44.3	5.07	<0.001	2.92
13	16	1239	62	529	46	134.2	36.79	<0.001	13.01
14	6	1704	44	1227	37	38.9	20.23	<0.001	11.73
15	24	1365	219	992	183	37.6	4.53	0.001	1.84
16	6	1423	106	1112	101	28.0	5.20	<0.001	3.00
17	4	1493	177	1149	332	30.0	1.83	0.055	1.29
18	4	1580	122	1328	233	19.0	1.92	0.048	1.36
19	5	1343	169	1118	148	20.0	2.24	0.026	1.42
20	5	1351	144	1227	390	10.1	0.67	0.259	0.42
21	6	886	71	503	50	76.0	10.82	<0.001	6.25
22	24	1346	252	1017	227	32.4	4.84	<0.001	1.40
23	5	1643	78	1012	81	62.4	12.55	<0.001	7.93
24	12	1369	191	891	102	53.6	7.65	<0.001	3.12
26	12	1415	158	989	113	43.1	6.12	<0.001	3.87
27	16	1449	172	651	94	122.5	11.52	<0.001	5.76
28	4	1397	192	400	70	249.3	9.76	<0.001	6.90
29	4	1553	135	571	137	172.0	10.21	<0.001	7.22
30	8	1352	286	595	140	127.2	6.72	<0.001	3.36
31	4	655	65	353	42	85.4	7.75	<0.001	5.48
32	18	1296	355	733	345	76.8	4.83	<0.001	1.61
33	18	578	310	263	207	119.8	3.59	<0.001	1.20
34	24	1602	276	792	157	102.3	11.70	<0.001	3.38
35	12	1460	59	521	77	180.2	33.53	<0.001	13.69
46	12	1282	55	511	56	150.9	34.02	<0.001	13.89
51	18	1357	114	760	90	78.5	17.43	<0.001	5.81
52	18	1503	241	708	166	112.2	11.53	<0.001	3.84
55	12	1648	66	547	116	201.3	28.58	<0.001	11.67
56	8	1540	89	887	136	73.6	11.36	<0.001	5.68
57	4	1401	80	528	127	165.3	11.63	<0.001	8.23
58	6	871	56	546	36	59.6	11.89	<0.001	6.86
59	24	1627	125	1058	112	53.8	16.61	<0.001	4.79
64	36	1381	146	759	118	81.9	19.88	<0.001	4.69
65	10	1742	131	955	152	82.4	12.40	<0.001	5.55
66	12	994	88	409	47	143.0	20.3	<0.001	8.29
67	4	610	46	465	46	31.2	4.46	<0.001	3.15

[z]Unweighted percent increase in yield resulting from MB:CP treatment.
[y]*t* is Student's *t* test value, *p* is a one-tailed probability (requires $P < 0.025$ for conventional significance), and d is the standardized effect size.

eight studies the standardized effect was $d_+ = 3.199 \pm 0.287$ (95% confidence: 2.637, 3.761), indicating a significant yield advantage for combinations of MB:CP over MS, and the overall unweighted increase in yield due to fumigation with the current industry standard was 29.8%. These results are consistent with the three studies eliminated because of insufficient data, where the average increase for MB:CP over MS was 29.0%. In fact, the standardized effect for this comparison did not differ significantly from the overall comparison of MB:CP mixtures with NF ($d_+ = 2.874 \pm 0.098$), suggesting very little yield response following treatment with MS.

Table 3. Effects of soil fumigation with methyl bromide:chloropicrin (MB:CP) vs. chloropicrin (CP) on yields (grams/plant) of strawberry in 34 studies.

		MB:CP treated		CP treated					
Study	No. reps	Mean yield	SD	Mean yield	SD	Increase[z] (%)	*t*[y]	*p*[y]	d[y]
11	18	763	80	768	84	–0.0	–0.10	0.538	–0.06
12	18	772	64	780	83	–1.0	–0.18	0.569	–0.11
15	24	1365	219	1283	286	6.4	0.79	0.219	0.32
16	6	1423	106	1233	252	15.4	1.70	0.060	0.98
17	4	1493	177	1477	162	1.2	0.13	0.451	0.09
18	4	1580	122	1528	76	3.4	0.72	0.248	0.51
19	5	1343	169	1371	390	–2.0	–0.15	0.558	–0.09
20	5	1351	144	1470	206	–8.1	–1.06	0.842	–0.67
23	5	1643	78	1502	141	9.4	1.96	0.043	1.24
24	12	1369	191	1227	110	11.6	2.23	0.018	0.91
26	12	1415	158	1316	125	7.5	1.70	0.052	0.69
27	6	886	71	823	70	7.7	1.56	0.075	0.90
28	4	1397	192	1303	77	7.2	0.91	0.197	0.64
29	4	1553	135	1270	234	22.3	2.10	0.040	1.48
30	8	1352	286	1304	381	3.7	0.28	0.392	0.14
31	4	655	65	598	96	9.3	0.95	0.190	0.67
35	12,6	1648	66	1409	99	17.0	4.92	<0.001	2.84
36	4,2	1401	80	1267	205	10.6	0.86	0.250	0.86
37	12,6	1460	59	1228	96	18.9	5.04	<0.001	2.91
38	12,6	1282	55	1185	74	8.2	2.58	0.011	1.49
39	12	1648	66	1235	100	33.4	11.94	<0.001	4.87
40	4	1401	80	1209	303	15.9	1.23	0.143	0.87
41	12	1460	59	1243	63	17.5	8.71	<0.001	3.56
42	12	1282	55	1068	52	20.0	9.79	<0.001	4.00
53	18	1358	114	1479	140	–8.2	–2.84	0.999	–0.95
54	18	1358	114	1168	125	16.3	4.76	<0.001	1.59
55	10	1540	90	1568	158	–1.7	–0.48	0.820	–0.22
57	10	1540	90	1316	138	17.0	4.29	<0.001	1.92
58	6	871	56	848	63	2.7	0.67	0.259	0.39
59	8	1627	125	1454	262	11.9	1.69	0.057	0.84
60	8	1627	125	1340	151	21.4	4.14	<0.001	2.07
64	36	1381	146	1204	176	14.7	4.64	<0.001	1.09
66	6	994	88	982	67	1.2	0.27	0.397	0.15
67	4	610	46	531	46	14.9	2.43	0.025	1.72

[z]Unweighted percent increase in yield for the MB:CP treatment over the CP treatment group.
[y]*t* is Student's *t* test value, *p* is a one-tailed probability (requires $P < 0.025$ for conventional significance), and d is the standardized effect size.

Table 4. Effects of soil fumigation with methyl bromide:chloropicrin (MB:CP) vs. dichloropropene-chloropicrin (DP:CP) on yields (grams/plant) of strawberry in 10 studies.

		MB:CP treated		DP:CP treated					
Study	No. reps	Mean yield	SD	Mean yield	SD	Percent increase[z]	t[y]	p[y]	d[y]
2	6	992	177	856	109	15.9	1.60	0.070	0.93
5	6	1331	40	1046	55	27.2	10.27	<0.001	5.93
7	5	1096	110	687	62	59.5	6.76	<0.001	4.28
21	6	886	71	914	48	–2.9	–0.78	0.727	–0.45
31	4	655	65	647	54	1.0	0.15	0.443	0.11
58	6	871	56	836	11	4.3	1.52	0.077	0.88
64	36	1381	146	1180	185	17.0	5.12	<0.001	1.21
65	10	1742	131	1489	141	17.0	4.16	<0.001	1.86
66	6	994	88	981	97	1.3	0.37	0.355	0.15
67	4	610	46	591	46	3.2	0.58	0.291	0.41

[z]Unweighted percent increase in yield for the MB:CP treatment over the DP:CP treatment group.
[y]*t* is Student's *t* test value, *p* is a one-tailed probability (requires $P < 0.025$ for conventional significance), and d is the standardized effect size.

Discussion

The results of all meta-analyses are summarized in Table 6. For these studies, fumigation with a mixture of MB and CP increased yield significantly in comparison with any and all alternatives lacking MB. Mixtures of DP:CP that include a greater proportion of CP may provide a superior alternative to those tested here, although the deterioration of soil conditions for systems treated with high rates of CP alone over multiple cycles suggests that this likelihood is small. We conclude from this synthesis that there is no direct substitute for the current industry standard of preplant soil fumigation with mixtures of MB:CP. Furthermore, strawberry growers in California and other strawberry production locations with similar climate, using similar cultural tools, can expect yield reductions in excess of 10.5% because of changes in fruiting field fumigation practices alone if MB is eventually banned.

Yield reduction in the strawberry fruiting field is just one of many potential results of a regulatory elimination of MB. Of immediate and quantifiable consequence is the use of fumigation alternatives in runner propagation nurseries. Fumigation with MB:CP is practiced in such nurseries to enhance both plant production and quality (Larson and Shaw, 1995b) and to ensure a source of pest and disease free planting stock. Preliminary indications here are that use of planting stock from strawberry nurseries fumigated with realistic alternatives may reduce cumulative fruit yield substantially (Larson and Shaw, 1995b), even in the absence of lethal pathogens. Use of alternate fumigants will eventually impact the incidence of lethal pathogens in nursery and fruiting fields, and disease incidence may increase toward those levels experienced prior to widespread use of MB:CP (Wilhelm and Paulus, 1980).

Present-day cultural systems have evolved substantially during the past 50 years (Shaw, 1990; Voth and Bringhurst, 1990), and the trend has been toward an optimization relative to the superior soil environment provided by fumigation with MB:CP. Changes in fumigation practices that affect plant vigor and weed control can be expected to mandate changes in horticultural systems that in themselves will modify the magnitude and timing of strawberry fruit production. For example, alternatives deficient in weed control may require use of colored plastic mulches which will delay fruiting and reduce total yield. Furthermore, changes in both soil fumigation environment and cultural practice affect fruit quality (Larson and Shaw, 1995a), which will ultimately determine the value of the crop produced. The consequences of these secondary effects must be quantified and their outcomes considered in evaluating the ultimate impact of MB regulatory policies on strawberry productivity.

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Table 5. Effects of soil fumigation with methyl bromide:chloropicrin (MB:CP) vs. metam sodium (MS) 153–305 L·ha^{-1} a.i. on yields (grams/plant) of strawberry in eight studies.

		MB:CP treated		MS treated					
Study	No. reps	Mean yield	SD	Mean yield	SD	Percent increase[z]	t^y	p^y	d[y]
8	3	2126	47	1641	130	29.6	6.08	0.002	4.96
21	6	886	71	667	94	32.8	4.55	0.001	2.63
47	12	1648	66	1241	67	32.8	14.99	<0.001	6.12
48	4	1401	80	1184	119	18.3	3.03	0.012	2.14
49	12	1460	59	1270	51	15.0	8.44	<0.001	3.44
50	12	1282	55	1136	62	12.9	6.10	<0.001	2.49
62	8,5	1540	89	982	182	56.8	6.16	<0.001	3.90
63	8,5	1540	89	1100	190	40.0	4.69	<0.001	2.97

[z]Unweighted percent increase in yield for the MB:CP treatment over the MS control group.
[y]t is Student's t test value, p is a one-tailed probability (requires $P < 0.025$ for conventional significance), and d is the standardized effect size.

Table 6. Summary of meta-analysis comparisons presented in the text.

Comparison	No. studies	d_+ (±SE)	Increase with MB:CP (%)
Methyl bromide:chloropicrin vs. nonfumigated	45	2.874 ± 0.098	94.4
First nonfumigated cycle	17	2.166 ± 0.146	59.2
Second nonfumigated cycle	19	3.000 ± 0.143	100.2
Third nonfumigated cycle	9	6.201 ± 0.348	148.4
Methyl bromide:chloropicrin vs. chloropicrin	34	0.751 ± 0.087	9.6
High rate	23	0.437 ± 0.114	6.8
Moderate rate	11	1.190 ± 0.134	15.4
First chloropicrin cycle (high rate)	12	0.043 ± 0.162	2.2
Second chloropirin cycle (high rate)	7	0.588 ± 0.174	10.6
Third chloropicrin cycle (high rate)	4	2.054 ± 0.401	13.7
Methyl bromide:chloropicrin vs. dichloropropene:chloropicrin	10	0.962 ± 0.162	14.4
Methyl bromide:chloropicrin vs. metam sodium	8	3.199 ± 0.287	29.8

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