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Strawberry production from transplants fumigated with methyl bromide alternatives

J. López-Medina[1]*, J. M. López-Aranda[2], J. J. Medina[2], L. Miranda[2], C. Soria[2], F. Domínguez[3], E. Vázquez-Ortiz[1] and F. Flores[1]

[1] Departamento de Ciencias Agroforestales. Universidad de Huelva. 2819 Palos de la Frontera (Huelva). Spain
[2] Instituto Andaluz de Investigación y Formación Agraria (IFAPA). Consejería de Innovación,Ciencia y Empresa. Junta de Andalucía. 29140 Churriana (Málaga) y 21800 Moguer (Huelva). Spain
[3] Oficina Comarcal Agraria (OCA). Costa Occidental Huelva. Consejería de Agricultura y Pesca. 21450 Cartaya (Huelva). Spain

Abstract

Research aimed at finding alternatives to methyl bromide has tended to focus on strawberries, since this crop is the largest methyl bromide consumer in Spain, pre-plant soil fumigation with methyl bromide, or with mixtures of methyl bromide and chloropicrin, are standard practices for controlling soil-borne diseases. Methyl bromide, however, has been phased out due to its environmental risks except for critical use exemptions. Soil fumigants were evaluated as alternatives for methyl bromide soil fumigation at two high-elevation strawberry nurseries in Spain. Strawberry plants produced at high elevation nurseries were evaluated for fruit yield at two commercial fruit production sites. All fumigation treatments had higher stolon production than plants grown in non-fumigated soil. The results indicate that pre-plant soil treatment with chloropicrin alone or 1,3-dichloropropene plus 35% chloropicrin could be potential alternatives to methyl bromide for soil treatment at high-elevation strawberry nurseries in Spain.

Additional key words: AMMI, chloropicrin, dichloropropene, *Fragaria × ananassa*, high-elevation nurseries, methyl bromide, strawberry.

Resumen

Evaluación de plantas de fresón multiplicadas en vivero con distintas alternativas al bromuro de metilo

El cultivo del fresón es un gran consumidor de bromuro de metilo para el control de los agentes telúricos de suelo. La fumigación del suelo en preplantación con bromuro de metilo o con mezclas de bromuro de metilo y de cloropicrina es una costumbre habitual en los campos de fresón. Sin embargo, su utilización ha sido prohibida, excepto para usos críticos, debido a los riesgos ambientales que conlleva. Se ensayaron varias alternativas al bromuro de metilo en dos viveros de altura del norte de España y las plantas producidas en estos viveros fueron evaluadas en dos localidades productoras de fresón. Los resultados indican que todas las parcelas fumigadas registraron un mayor número de plantas hijas que aquellas no fumigadas, y que el tratamiento en preplantación con cloropicrina, sola o combinada al 35% con 1,3 D, podría considerarse una alternativa potencial al bromuro de metilo en los viveros de altura.

Palabras clave adicionales: análisis AMMI, bromuro de metilo, cloropicrina, dicloropropeno, *Fragaria × ananassa,* fresón, viveros de altura.

Introduction

Spain is the world's second-largest strawberry producer after the USA. Huelva is Spain's leading agricultural region, with about 7,047 ha of strawberry production, yielding 237,773 t of strawberries per year, of these 80% are exported (MAPA, 2003). Strawberry stolons produced in nurseries in Castile-Leon in central-northern Spain are shipped every year for transplanting into fruit-producing fields throughout Spain and other European Union (EU) and Mediterranean countries. Spain is the leading strawberry-stolon producer in the EU (De Cal *et al.,* 2004).

* Corresponding author: medina@uhu.es
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J. López-Medina, J. M. López-Aranda, J. J. Medina and F. Flores are members of the SECH.

Strawberry production is the largest single use of methyl bromide (MB) in Spain. Soil fumigation with MB plus chloropicrin (Pic) (MB:Pic, 50:50 w/w), at 40 g m^{-2}, is a standard practice for the control of soil borne diseases, nematodes and weeds both in nurseries and (at 20 g m^{-2}) in fruit production fields. This fumigation is considered critical in current production practices. However, MB has been classified as a class I stratospheric ozone-depleting chemical, and use of MB is scheduled to be phased out under the Montreal Protocol (Duniway, 2002). Except for critical use exemptions, the use manufacture and import of MB was banned on 1 January 2005 in EU countries (Batchelor, 2002). Phasing-out of MB could have serious negative economic consequences for the EU's strawberry industry. The strawberry industry faces an urgent need to find effective alternatives to MB for soil fumigation in both strawberry nurseries and in fruit production fields.

Numerous chemical and non-chemical alternatives to MB have been evaluated for strawberry production (Carpenter *et al.,* 2001; Rieger *et al.,* 2001; López-Medina *et al.,* 2003). Indeed, research into MB alternatives is the main area of strawberry research in Spain, the United States and other Montreal Protocol (MP) Article 2 countries (Ajwa *et al.*, 2003). Studies on MB alternatives for strawberry nurseries have investigated fumigant effects on fungal soil population. De Cal *et al.* (2004) tested the effect of various MB+Pic combinations, 1,3-dichloropropene + chloropicrin combinations (1,3-D + Pic) (Telone C-17®, Telopic®), chloropicrin (Pic alone), Dazomet (Basamid®), metam sodium (Vapam®), and metam potassium (K-pam), on soil fungal populations in high-elevation strawberry nurseries in north central Spain. In addition, the effect of MB and some alternatives to MB, together with different plastic tarp covers were evaluated on beneficial and detrimental soil fungal communities in Spanish strawberry nurseries (De Cal *et al.,* 2005).

Other studies evaluated the effect of soil treatment with fumigants that have been proposed as alternatives to MB on nursery stolon production and subsequent performance in production fields. Shaw and Larson (1999) reviewed studies conducted to test fumigation alternatives by public sector researchers in California between 1987 and 1997. Several of the studies included stolons from nurseries which had been treated with different fumigants. Four alternative soil treatment systems —a non-fumigated control, Pic alone at high and moderate rates, mixtures of 1,3-dichloropropene (Telone) and Pic, and metam sodium— were compared to a standard mixture of MB and Pic. They observed that fumigation with mixtures of MB and Pic significantly increased yield compared to any alternative lacking MB. In a study, over 4 years, that compared nursery soils treated with MB and Pic mixtures to three alternative soil treatments —Pic, mixtures of Telone and Pic, and no fumigation— Larson and Shaw (2000) found stolon production at a high elevation nursery with MBPic was similar to that with Pic alone at application rates > 303 kg ha^{-1}.

Zahangir *et al.* (2005) conducted several experiments at both low and high elevation nurseries to evaluate alternative pre-plant fumigation programs for production of strawberry stolons. The treatments were: MBPic, iodomethane plus Pic, non-fumigated control, 1,3 dichloropropene plus Pic mixture (TC35) followed by Dazomet and Pic followed by Dazomet. Plants produced from stolons from high elevation nurseries were evaluated for fruit yield at commercial fruit production sites. The results indicated that combinations of TC35 or iodomethane with Pic showed promise as alternatives to methyl bromide in nursery production. However, additional investigations are needed to confirm their efficacy. López-Aranda *et al.* (2004) reported that the assessment of MB alternatives for strawberry nurseries might usefully address three key issues: a) soil-borne pathogen control; b) weed control; and c) consistent yield of commercial stolons at harvest.

After a six year national research project on MB alternatives for strawberry nurseries in Spain, these workers have not found a successful solution for weed control. Moreover, yields obtained using alternative treatments to MB vary widely among location and year; however, MB:Pic, 50:50, seems to give fairly consistent yields.

This paper reports on a study of the agronomic response of the strawberry cv. 'Camarosa' in production fields in Huelva (south-western Spain), using transplanted stolons obtained during a national research project which was designed to test MB alternatives in high-elevation strawberry nurseries in Castilla-León in central, northern Spain. The pest management results of this work, at high elevation nurseries have been published by De Cal *et al.* (2004, 2005), and are not discussed here.

Materials and Methods

The field trials reported here were part of a RAEA program (Andalusian Network for Experimental Agriculture) and supplemented an official research project

(National Project INIA SC 97-130) on MB alternatives in a range of crops.

Ten experiments (two per year) were carried out at two experimental farms El Cebollar, at Moguer (37º15'N 6º52'W) and at Los Reventones, Cartaya (37º18'N 7º09'W), located in the eastern and western coastal areas of Huelva, between 1999 and 2003.

Planting material of cv. Camarosa was obtained every year from experimental plots which had been used for testing MB alternatives from two participating high-elevation nurseries: Viveros California SL and Viveros Rio Eresma SA, located in Arevalo (41º05'N 4º45'W, Avila) and Navalmanzano (41º13'N 4º15'W, Segovia), respectively. High-elevation nursery stock produced on soil treated with alternative fumigants was transplanted into commercial strawberry fruit production fields on the Huelva coast (Moguer and Cartaya). The design of each experiment was a randomized complete block with three replicates. There were 200 plants/replicate. At both Huelva sites, the same standard, fresh-plant, winter-cultivation system was implemented every year: stolons were planted between 27 and 31 October, under small plastic tunnels, mulched with black polyethylene (LDPE) and drip-irrigated. Apart from the different agro-environments of the two locations (Moguer and Cartaya), located 50 km apart, the main differences were the soil fumigation system used. At El Cebollar experimental farm, Moguer, solarization and biofumigation were applied each summer, between mid-July and mid-August, using transparent polyethylene (PE) sheets and the simultaneous incorporation of 5 kg m^{-2} of chicken manure (Medina-Mínguez, 2002). At Los Reventones injected applications of MB-Pic (50-50) were applied each summer at rates of 20 to 25 g m^{-2} under preformed beds.

Treatments applied in strawberry nurseries

At Viveros California SL nursery, Arévalo and Viveros Rio Eresma SA nursery, Navalmanzano, six treatments were applied in 1998, 1999, 2000, 2001 and 2002 (Table 1). Different experimental plots were used each year and no plots used had been fumigated with MB for at least three years prior to the experiment. A randomized complete block design with three replicates was used. The area of each treatment was 400 m^2. Treatment applications were broadcast, applied and sealed with transparent film 3.30 m wide and 35 microns thick for 1 week for MB-Pic (MB:Pic, 50:50 w/w under LDPE film), MB-VIF (MB:Pic, 50:50 w/w under virtually impermeable film, VIF), TC35 (1,3-D+Pic 61:35 w/w Telopic®), and Pic-alone treatments, and for 2 weeks for Daz (Dazomet, Basamid®) from the start of April to mid-April. All fumigants except Daz were applied at a depth of 20 to 25 cm, using eight injection chisels spaced 33 cm apart. Daz was applied to the soil surface and incorporated to 15 cm with a rota tiller.

Table 1. Chemical alternatives to methyl bromide in Spanish strawberry nurseries

Treatment	Description	Dose
Control	Untreated	
Pic[a]	Chloropicrin	40 g m^{-2}
MB-Pic[a]	Methyl bromide (MB) plus Pic (50/50)	40 g m^{-2}
MB-VIF[b]	Methyl bromide (MB) plus Pic (50/50)	20 g m^{-2}
Daz[a]	Dazomet	50 g m^{-2}
TC35[a]	1,3-dichloropropene (1,3-D) plus Pic (65/35)	35-40 cm^3 m^{-2}

[a] Sealed with transparent PE film. [b] Sealed with virtually impermeable film (VIF).

Statistical methods

The following crop traits were recorded weekly in production fields:

— Early strawberry production, in g per plant, was split into three classes: extra class, second-class and total yield (from January until March 31) (EYIELD1, EYIELD2, and EYIELDT).

— Total production, in g per plant, was also split into three classes: extra class, second-class and total yield, until the end of the season (TYIELD1, TYIELD2, TYIELD).

— Average early fruit weight, in g per fruit, from January to March 31 (AEFW).

— Percent of second quality fruit in both Early Extra (PSEYIELD) and total Extra yield (PSTYIELD).

— Percent plant survival (PPSUR).

Prior to statistical analysis, percentage data were arcsine transformed to improve homogeneity of variances. Traits were recorded weekly for each plot for 23 consecutive weeks, beginning in the last week of January and ending in late May. The number of strawberry plants per hectare for each MB alternative at each high-elevation nursery (PLHA) was also recorded.

A preliminary analysis of variance (ANOVA) was carried out on the measured traits in the ten agro-environments. Each specific year-location combination was treated as a separate agro-environment: Cartaya-1999 (Ca99), Cartaya-2000 (Ca00), Cartaya-2001 (Ca01), Cartaya-2002 (Ca02), Cartaya-2003 (Ca03), Moguer-1999 (Mo99), Moguer-2000 (Mo00), Moguer-2001 (Mo01), Moguer-2002 (Mo02) and Moguer-2003 (Mo03).

Within each agro-environment a randomized complete block design with three replications was used. To test effects F-ratios on the source of variation were determined (McIntosh 1983). When the MB alternative in the strawberry nursery × agro-environment interaction was significant, an additive main effects and multiplicative interaction (AMMI) analysis was performed.

The AMMI model (Zobel *et al.,* 1988) can be stated as follows:

$$Y_{ij} = \mu + g_i + e_j + \sum\nolimits_1^N \lambda_k \, \gamma_{ik} \, \delta_{jk} + \varepsilon_{ij}$$

where Y_{ij} is the average value of i^{th} MB alternative in the j^{th} agro-environment for each measured trait; μ is the grand mean; g_i and e_j are the MB alternative and agro-environment deviations from the grand mean, respectively; λ_k is the Eigen value of the principal component analysis (PCA) axis k; γ_{ik} and δ_{jk} are the MB alternative and agro-environment principal component scores for axis k, respectively; N is the number of principal components retained in the model; and ε_{ij} is the error term. Agro-environment and MB alternative PCA scores are expressed as unit vector times the square root of λ_k (i.e., agro-environment PCA score = $\lambda_k^{0.5}\,\delta_{jk}$; MB alternative PCA score = $\lambda_k^{0.5}\,\gamma_{ik}$).

Gauch and Zobel (1988) created the term «postdictive» in order to measure the level of success of prediction. Postdictive success was measured by comparing the mean square of each principal component with the pooled within-agro-environment error mean square. The PCA axes that were not significant were pooled into a residual term.

All statistical analyses were performed using the SAS Inst. (1996) statistical software package.

Results

Strawberry nurseries

Results of analyses of variance for *plants per hectare* traits showed that the MB alternatives were significant in the strawberry nursery × year interaction (data not shown).

In an attempt to understand the nature of these interactions, the AMMI model was used. The postdictive success criterion for AMMI recommended including the first PCA interaction (IPCA1) axis because only the IPCA1 was significant (data not shown). The model that considered a single PCA axis accounted for a large proportion of the interaction; IPCA1 accounted for 49% of MB alternative by year variation for the number of plants ha^{-1}. Figure 1 is a biplot of the number of plants ha^{-1} against year in both nurseries, which shows main effect means (MB alternatives and years) and the grand mean on the abscissa and the IPCA1 values of both effects on the ordinate simultaneously. Displacement along the abscissa reflects differences in main effects, whereas displacement along the ordinate illustrates differences in interaction effects. The MB alternatives with IPCA1 values close to zero showed similar behavior in all years. The MB alternative × year combinations with IPCA1 scores of the same sign produced positive specific interactions, whereas combinations with opposing signs had a negative specific interaction.

For any combination of MB alternative and year, the main effects is the MB alternative mean + year mean – the grand mean (505,878 plants ha^{-1}) while the interaction is the MB alternative IPCA score × the year IPCA score. For example, Pic-1 (545,333 plants ha^{-1}) in 2000 (577,500 runner plants ha^{-1}) has a main effect

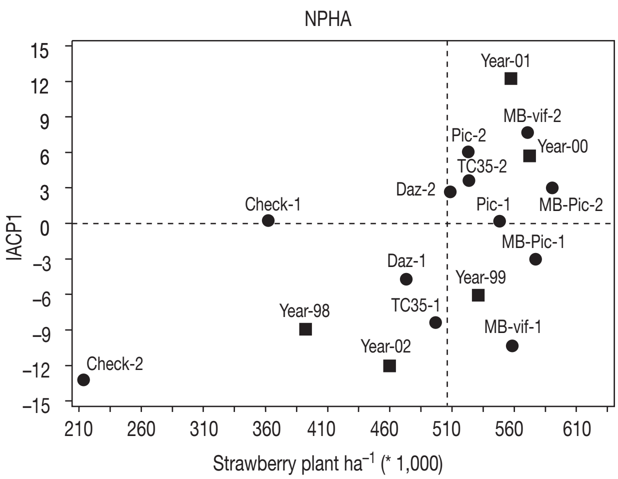

Figure 1. Biplot of principal component analysis (IPCA1) axis 1 against strawberry plant ha-1 for (●) methyl bromide alternatives in strawberry nurseries at (■) five years. The vertical line is the grand mean of the experiment. Treatment-1: «Viveros California» nursery. Treatment-2: «Viveros Rio Eresma» nursery.

Table 2. Total strawberry plant production at «Rio Eresma» and «California» nurseries 1998 to 2002

Fumigant[a]	Production (* 1,000 plants ha^{-1})										
	«Rio Eresma»					Mean per nursery[b]	«California»				
	1998	1999	2000	2001	2002		1998	1999	2000	2001	2002
MB-VIF	439ab	532ab	827a	693a	430b	584-573	554a	542a	633ab	503b	637a
MB-Pic	475a	513b	670ab	780a	567a	601-580	529a	522a	670a	626a	557ab
Pic	354b	593ab	660ab	700a	420b	545-545	383b	527a	623ab	646a	547ab
Daz	413ab	561ab	583b	660a	367b	517-481	461ab	482a	550ab	496b	420bc
TC35	380ab	690a	530b	717a	370b	537-508	385b	508a	526ab	503b	617a
Check	184c	445b	170c	117b	193c	221-373	131c	423a	486b	446b	380c
Mean	374.2	555.6	573.3	611.2	391.2		407.2	500.6	581.3	536.6	526.3

[a] Fumigant column indicates the fumigant used for runner plant production at the high elevation nursery. [b] First number is the runner plants ha^{-1} at «Rio Eresma» nursery and, second number at «California» nursery. Means sharing the same letters within a column are not different according to the Duncan's multiple range test (P = 0.05).

of (545,333 + 577, 500) – 505,878 = 616, 955 plants ha^{-1} and an interaction of (0.9 × 5.8) = 5,220 plants ha^{-1}. Thus, the AMMI model estimated that the number of plants ha^{-1} was 622,175 for Pic-1 in 2000. This was close to the observed number of plant ha^{-1} at 623,333. The biplot for strawberry plants ha^{-1} against year in both nurseries (Fig. 1) and Table 2 show that MB alternatives at «Viveros Rio Eresma» had a mean response above the grand mean, except for the control, which had the smallest mean response. They showed a positive interaction except for the control, which had the highest negative interaction (Fig. 1). The greatest variability was among main effects for MB alternatives from «Viveros California» where the MB alternatives Pic and MB-Pic with IPCA1 values close to zero were the most stable MB alternatives across years with a mean response above the grand mean. The remaining MB alternatives Daz, TC35 and MB-VIF had a negative interaction, and the control had the lowest main effect at this nursery. Methyl bromide treatments had the greatest additive effects, and TC35 and Pic gave a plant ha^{-1} production rate very similar to that of the MB treatments (Fig. 1 and Table 2).

Production fields

The results of the analysis of variance for measured traits are shown in Table 3. This gives an overall picture of the relative magnitude of MB alternatives in the strawberry nursery (A), agro-environments in the production fields (E), and the A × E interaction variance terms. The agro-environment was always the most important source of variation, accounted for 94 to 99% of A + E + AE, except for percent plant survival, where it accounted for 77%. A large sum of squares for the agro-environments indicated that they were diverse. The large differences among agro-environmental means caused most of the variation in strawberry fruit yield. The A × E interaction was a significant source of variation for all characters except the AEFW. The magnitude of the A × E interaction sum of squares was from 36 times larger than that for MB alternatives for EYIELD1 to 4.5 times larger for TYIELD2 and PSTYIELD, indicating that there were substantial differences in the response to MB alternatives across the agro-environments.

The postdictive success criterion for AMMI recommended including the first PCA interaction (IPCA1)

Table 3. Methyl bromide (MB) alternatives in strawberry nurseries (A), Agro-environment (E) and MB Alternative × Agro-environment (AE) mean squares terms for all observed traits on 1999-2003 MB alternative performance trial data for strawberry

Source	df	EYIELDT	EYIELD1	EYIELD2	PSEYIELD	AEFW	PPSUR	df[a]	TYIELD	TYIELD1	TYIELD2	PSTYIELD
E	9	122,986***	93,758***	10,010***	0.23918***	260***	0.107385***	8	2,803,644***	2,360,273***	53,830***	0.132467***
A	11	976	673	156*	0.00502**	3.13	0.014178***	11	5,200	5,511	1,177**	0.002806***
AE	99	1,844***	2,247***	155***	0.00863***	4.15	0.016955***	99	9,952***	7,616***	868***	0.001542***

[a] Missing TYIELD, TYILED1, TYIELD2 and PSTYIELD for Ca00. *, **, ***: significant at the 0.05, 0.01 and 0.001 probability level, respectively.

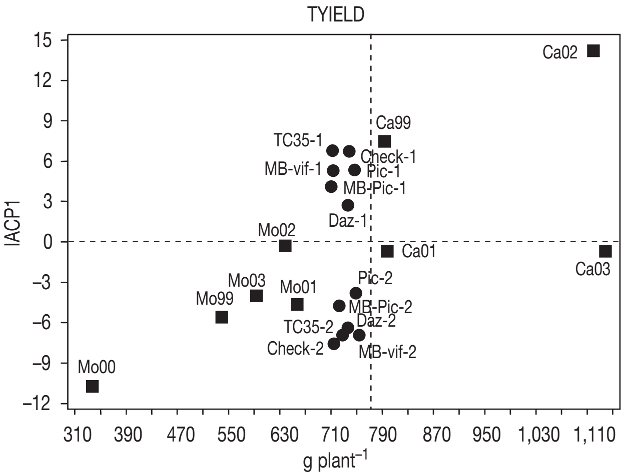

Figure 2. Biplot of principal component analysis (IPCA1) axis 1 against total yield for (●) MB alternatives in strawberry nurseries in (■) nine agro-environments (not including Ca00). The vertical line is the grand mean of the experiment. Treatment-1: «Viveros California» nursery. Treatment-2: «Viveros Rio Eresma» nursery.

axis in all models because only the IPCA1 was significant (data not shown). Simple AMMI analyses accounted for most of the interaction sum of squares for all characters measured. The model that considered a single PCA axis accounted for a large proportion of the interactions; IPCA1 accounted for 50% of the MB alternative-agro-environment variability for EYIELDT. This rose to 68% of the MB alternative-agro-environment variability for PSEYIELD.

Biplots for the MB alternative × agro-environment interaction, for all characters, showed a similar overall pattern. Rather than include a larger number of figures, the behavior patterns of the MB alternatives are described in the text and only two figures are presented.

Biplots for *Early* (EYIELD1, EYIELD2, and EYIELDT) and *Total yield* (TYIELD1, TYIELD2, and TYIELD) showed a similar pattern (Fig. 2, only the biplot for TYIELD is shown). Figure 2 is a biplot of the MB alternative × agro-environment interaction for TYIELD. All biplots shown as agro-environments differed in both main effects and interactions whereas the MB alternatives showed similar additive effects for both nurseries but their interactions with the agro-environments were quite different.

Figure 2 clearly shows two groupings of MB alternatives. The first group includes MB alternatives from the «Viveros California» strawberry nursery, with a similar mean and positive IPCA1 scores, and the second group consists of MB alternatives from the «Rio Eresma» nursery, with negative interaction scores and a similar mean to the overall mean. Two agro-environment groupings are also evident in Figure 2. The first group includes Cartaya-year combination agro-environments and shows the highest mean response and a positive interaction (except for Ca01 and Car03 which had the smallest negative interaction). The second group includes Moguer-year combination agro-environments with a mean response below the grand mean and a negative interaction (except for Mo02 which had the smallest positive interaction).

The AMMI1 model (when only the first PCA interaction axis is included) predicted large yields in Moguer with MB alternatives from «Viveros Rio Eresma» nursery and large yields in Cartaya with MB alternatives from

Table 4. Total strawberry fruit yield at Moguer from 1999 to 2003 from strawberry plants produced at «Rio Eresma» and «California» nurseries from 1998 to 2002

	Total yield (g plant^{-1})									
Fumigant[a]	«Rio Eresma»					«California»				
	1999[b]	2000	2001	2002	2003	1999	2000	2001	2002	2003
MB-VIF	590.1a	380.2a	825.1a	700.1a	640.1a	535.1a	266.8a	692.3a	655.6a	638.7a
MB-Pic	571.8a	366.9a	704.7a	690.3a	667.1a	551.9a	204.6a	688.2a	692.5a	614.4a
Pic	525.6a	354.7a	751.4a	683.9a	647.7a	540.0a	295.7a	707.9a	698.8a	598.6a
Daz	552.7a	359.4a	715.1a	705.3a	720.9a	538.6a	282.6a	689.7a	655.6a	691.6a
TC35	611.5a	376.1a	673.1b	658.8a	668.1a	431.4a	306.2a	633.3a	694.6a	618.1a
Check	496.8a	390.6a	775.4a	688.0a	692.9a	485.8a	223.5a	750.0a	701.8a	646.9a
Mean	558.0	371.3	740.8	687.7	672.8	513.8	263.2	693.5	683.1	634.7

[a] Fumigant column indicates the fumigant used for plant production at the high elevation nursery. [b] 1999 column indicates the total yield (g plant^{-1}) in the fruit production field (Moguer) in 1999. Means sharing the same letters within a column are not different according to the Duncan's multiple range test (P = 0.05).

Table 5. Early strawberry fruit yield at Moguer from 1999 to 2003 from strawberry plants produced at «Rio Eresma» and «California» nurseries from 1998 to 2002

Fumigant[a]	Early yield (g plant^{-1})									
	«Rio Eresma»					«California»				
	1999[b]	2000	2001	2002	2003	1999	2000	2001	2002	2003
MB-VIF	231.7ab	173.9a	149.1a	270.6a	238.2a	224.6a	145.3a	124.6a	230.0a	286.9a
MB-Pic	232.1ab	177.4a	146.3a	264.9a	254.3a	224.8a	127.3a	129.2a	289.3a	262.3a
Pic	208.4b	165.4a	148.3a	283.1a	267.3a	217.1a	157.2a	139.1a	274.6a	241.1a
Daz	231.3ab	181.5a	129.7a	281.5a	288.3a	217.6a	172.6a	129.7a	255.8a	294.5a
TC35	247.9a	190.7a	135.8a	274.2a	263.1a	171.6a	162.7a	124.8a	270.9a	244.3a
Check	205.7b	188.1a	148.7a	264.1a	285.6a	199.4a	136.4a	141.4a	260.7a	280.1a
Mean	226.2	179.5	142.9	273.1	266.1	209.2	150.2	131.4	263.5	268.2

[a] Fumigant column indicates the fumigant used for runner plant production at the high elevation nursery. [b] 1999 column indicates the early yield (g plant^{-1}) in the fruit production field (Moguer) in 1999. Means sharing the same letters within a column are not different according to the Duncan's multiple range test (P = 0.05).

«Viveros California» nursery. The MB alternatives Daz, MB-Pic and Pic had the lowest interaction scores for both nurseries; they were therefore the most stable MB alternatives in strawberry nurseries across agro-environments.

Generally there were no significant differences among fumigants for each year of the experiment. Therefore, the effect of both high elevation nurseries source fumigants on fruit yield at Moguer and Cartaya was not significant over the five years (Tables 4 to 7). Total and early yield were higher at the «Rio Eresma» nursery, at Moguer, than at the «California» nursery (Tables 4 and 5). However, these traits had lower values at the «Rio Eresma» nursery at Cartaya compared to at the «California» nursery (Tables 6 and 7). These results reinforce the AMMI analysis.

For the percent second-class yield (figures not given) The MB alternatives and agro-environments had a similar overall distribution pattern in both biplots for PSEYIELD and PSTYIELD. Agro-environments showed little interaction across MB alternatives and gave a low discrimination among MB alternatives. A clear difference was apparent between nurseries. Analysis of agro-environment and MB alternative effects showed that MB-Pic at Mo00 and MB-VIF at Ca00 had the highest percent second-class yield while Pic alone and Daz were the most stable MB alternatives across agro-environments.

Table 6. Total strawberry fruit yield at Cartaya from 1999 to 2003 from strawberry plants produced at «Rio Eresma» and «California» nurseries from 1998 to 2002

Fumigant[a]	Total yield (g plant^{-1})									
	«Rio Eresma»					«California»				
	1999[b]	2000	2001	2002	2003	1999	2000	2001	2002	2003
MB-VIF	776.6a	M[c]	966.5a	1,089.0a	1,139.2a	865.7a	M	811.8a	1,241.8a	1,186.1a
MB-Pic	852.8a	M	863.7a	1,051.9a	1,235.0a	866.0a	M	882.7a	1,181.0a	1,165.4a
Pic	911.2a	M	835.9a	1,050.0a	1,208.0a	939.6a	M	789.6a	1,226.7a	1,238.3a
Daz	737.3a	M	829.3a	1,094.3a	1,227.3a	887.0a	M	867.5a	1,200.9a	1,200.3a
TC35	780.2a	M	792.0a	1,042.6a	1,154.4a	787.5a	M	807.9a	1,289.9a	1,238.4a
Check	695.6a	M	813.7a	1,096.2a	1,197.9a	887.5a	M	910.5a	1,255.9a	1,201.7a
Mean	792.3	M	850.2	1,070.6	1,093.6	872.2	M	845	1,232.7	1,205

[a] Fumigant column indicates the fumigant used for strawberry plant production at the high elevation nursery. [b] 1999 column indicates the total yield (g plant^{-1}) in the fruit production field (Cartaya) in 1999. [c] M: missing values. Means sharing the same letters within a column are not different according to the Duncan's multiple range test (P = 0.05).

Table 7. Early strawberry fruit yield at Cartaya from 1999 to 2003 from strawberry plants produced at «Rio Eresma» and «California» nurseries from 1998 to 2002

Fumigant[a]	Early yield (g plant^{-1}) «Rio Eresma»					«California»				
	1999[b]	2000	2001	2002	2003	1999	2000	2001	2002	2003
MB-VIF	274.3abc	202.8a	142.1a	251.1a	261.4a	267.2ab	289.3a	191.3a	275.9abc	302.8a
MB-Pic	255.1bc	210.8a	161.9a	224.5a	280.3a	274.8ab	331.1a	171.8a	229.2c	287.7a
Pic	296.9a	230.0a	145.9a	269.0a	302.7a	355.1a	293.3a	123.4a	305.2ab	320.8a
Daz	256.4bc	234.8a	154.1a	276.6a	307.9a	270.8ab	309.4a	178.2a	268.1abc	312.3a
TC35	242.2c	245.5a	161.5a	264.0a	306.9a	289.7ab	306.1a	172.2a	309.0a	337.2a
Check	291.9ab	238.4a	162.9a	284.5a	313.6a	253.5b	306.9a	194.3a	246.4bc	326.5a
Mean	269.5	227	154.7	261.6	295.5	285.2	306	171.8	272.3	314.5

[a] Fumigant column indicates the fumigant used for strawberry plant production at the high elevation nursery. [b] 1999 column indicates the early yield (g plant^{-1}) in the fruit production field (Cartaya) in 1999. Means sharing the same letters within a column are not different according to the Duncan's multiple range test (P = 0.05).

The MB alternative x agro-environment interaction was not significant for average early fruit weight, showing that MB alternatives rankings were consistent across agro-environments. Only differences among the agro-environments were highly significant. In addition, a multiple means comparison (Tukey's test, $\alpha = 0.05$) was performed. Cartaya-year combination agro-environments had a greater ($P \leq 0.05$) average fruit weight than Moguer-year combination agro-environments.

The MB alternatives Daz, Pic from the «California» nursery and MB-VIF from the «Rio Eresma» nursery had the highest percent plant survival (99%). The MB alternatives TC35 from the «Viveros Rio Eresma» nursery and control from «Viveros California» had the lowest survival (97.4 to 98%). The MB alternatives Daz and MB-Pic (at both nurseries) appeared together in the biplot (not shown) and displayed a similar mean above the overall mean and the smallest interaction. Thus, they are the most stable MB alternatives, for strawberry plant survival, across agro-environments.

Discussion

Reduced plant numbers were found where plants were grown without fumigation at both high-elevation nurseries compared to plants produced on fumigated soils (Fig. 1 and Table 2). The results showed no difference in Huelva strawberry production fields at Moguer and Cartaya by plants that were propagated at both high-elevation nurseries («Rio Eresma» and «California») on non-fumigated or fumigated soil (Fig. 2 and Tables 4 to 7). Larson (1997) indicated that the fumigation history of nursery propagation has less effect on fruit yield than the fumigant ultimately applied for fruit production. This could be a possible explanation as also reported by Zahangir *et al.* (2005).

Another factor that may minimize differences between non-fumigated and fumigated soils in strawberry production fields could be plant choice. Weak and poorly formed plants were not chosen, thus most plants selected for transplanting were healthy looking.

Thus, strawberry production in Moguer and Cartaya was not affected by prior fumigation treatment in the high-elevation nurseries, provided plants of sufficient quality and vigour to support fruit yield in commercial fruit production fields were selected. These results are similar to those of Fennimore *et al.* (2001) and Zahangir *et al.* (2005).

Biplots showed that the main influences on the agronomic response of the plant material, in the fruit production area, were derived from two factors, although obviously, another factor that may maximize differences is the year. The first factor was location: total strawberry fruit yield was significantly higher at Cartaya (above the mean yield in all years) than at Moguer (below the mean yield in all years). These differences may be related to the different soil fumigation systems used at each location: solarization plus biofumigation in Moguer *versus* MB:Pic 50:50 w/w shank application at Cartaya. The second factor was the nursery: the «Viveros California» nursery plants had positive carryover effects at Cartaya, while «Viveros Río Eresma» nursery plants had positive carryover effects ay Moguer (Fig. 1).

The results also suggested that Pic and TC35 could replace MB at high-elevation nurseries in Spain (Fig. 2). López-Medina *et al.* (2003) suggested that these fumigants could also be valid short-term alternatives for fruiting-field soil fumigation. Other investigators have found similar alternative fumigants for strawberry nurseries. For example, De Cal *et al*. (2004) demonstrated that pre-plant soil fumigation of strawberry nurseries with TC35, Pic alone or Dazomet gave significant reductions of diseases, similar to that obtained with MB:Pic. Although in this trial iodomethane plus Pic (IMPic) or Pic followed by Dazomet or TC35 followed by Dazomet were not evaluated as potential fumigants, Zahangir *et al.* (2005) found that these alternatives could be potential alternative fumigants in Californian strawberry nurseries.

De Cal *et al.* (2004) reported that although TC35 and Pic are registered and available for use as soil fumigants in Spain, there is some resistance, by regulators, in some countries to their use at relatively high rates. However, only 1,3-D:Pic (TC35) is registered but not Pic alone, and it is possible to use TC35 at one-half the recommended dose, under VIF film, to achieve effective disease control in strawberry nurseries. Although chloropicrin has considerable utility as a stand-alone soil fumigant it is more likely to be used in sequential applications with metam sodium to give effective weed control (Fennimore *et al.,* 2001; Duniway, 2002). On the other hand, numerous experiments and grower trials have been conducted with drip and/or shank applied TC35 for strawberry production and it is likely to become one of the preferred alternatives to MB:Pic for strawberry production in California (Duniway, 2002). Nevertheless, further research is needed on these and other long-term alternatives to MB. For strawberry nurseries, weed control and yield inconsistency remain to be addressed (López-Aranda *et al.*, 2004). These difficulties have been highlighted by the fact that most Montreal Protocol Article 2 countries have applied for MB CUN (2005 MB critical use nominations) for strawberry fruit and stolon production.

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