Journal of Berry Research 6 (2016) 37–46
DOI:10.3233/JBR-150112
IOS Press

Chemical soil fumigation for raspberry nursery in Jalisco (Mexico)

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Received 27 July 2015; accepted 13 October 2015

Abstract. We evaluated the effectiveness of alternative fumigants on weed control, soil pests, plant growth and marketable roots production in a commercial nursery located at high-elevation and low latitude (Ciudad Guzman, Jalisco) during 2013 and 2014. Treatments were: Methyl bromide with chloropicrin (MB:CP); 1,3-dichloropropene:CP (1,3D:CP); CP alone; metam sodium (MS) alone; dimethyl disulphide with CP (DMDS:CP); and sequentially applied CP and MS (CP+MS). A Rotary Spading Machine was used for MS and CP followed by MS. All treatments except MS and CP+MS in 2014 controlled *Rhizoctonia* and all controlled *Phytophthora* in 2013, but none controlled *Fusarium* in soil. No significant nematode, *Verticillium* and *Pythium* populations were detected in nursery soil before treatments. No diseased plants were observed throughout the cultivation cycle. Densities and fresh weights of graminoid weeds were significantly reduced by MB:CP and CP+MS, but none of the fumigants controlled all forbs. Only *Echinochloa crus-galli*, *Digitaria* spp., *Sonchus oleraceus*, and *Amaranthus hybridus* densities and biomass were reduced 50–78% by all fumigants. The highest commercial yield of raspberry roots and plant emergence were recorded with MB:CP and 1,3D:CP, while CP and MS only increased plant emergence. Finally, two years of work on MB alternatives were not sufficient to provide reliable recommendations on this critical need, therefore MBTOC recommended CUN for MB in 2015.

Keywords: *Rubus idaeus*, soil disinfestation, plant multiplication, methyl bromide, metam sodium, 1,3-dichloropropene, chloropicrin, dimethyl disulphide, weed control, yields

1. Introduction

Raspberry production in México is a dynamic and growing industry, where an increasingly important sector is the production of raspberry nursery stock. In 2013, there were more than 2,078 ha of raspberry fruit production in Mexico (1,511 ha in Jalisco, 290 ha in Michoacan and 229 ha in Baja California) (SAGARPA-Servicio de Información Agroalimentaria y Pesquera-SIAP) and production continues to expand. However, there are no official statistics for raspberry nursery acreage. It is estimated that there were approximately 310 ha in 2014 and 350 ha in 2015 of raspberry nureries. This represents the 230% increase in acreage since 2009. The nurseries are located in several locations in Jalisco (Ciudad Guzman, Tapalpa and others) and Michoacan, with recent additional locations in Puebla State. Central Mexico (Michoacán and Jalisco) grows "off-season" plants at low

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latitude (19/20ºN parallel) and has nurseries at high-elevation areas (1,600 to 2,000 m above sea level) to produce the plant material for strawberry and caneberries [1, 2].

Very few studies have been published on soil fumigation for raspberry nurseries in international journals. Raspberry nurseries must produce disease-free plants to meet marketplace, certification and export requirements. Nursery phytosanitary requirements are high, because even minor disease infestations in nurseries can cause severe epidemics in production fields. Historically, transplants for Mexican raspberry production have been purchased from California, but due to the rapidly growing Mexican nursery sector, more and more fruit producers are able to obtain their planting stock in México. Nursery fields are fumigated during November and December in Mexico. The mother plants (roots) are transplanted during February. Raspberry roots are harvested during the following December to late-February, to be transplanted into production fields a few months later, starting in May. Rotations with cereals (sorghum and corn) and pasture land are common with three to five year interval between raspberry nursery plantings.

Soil-borne fungal pathogens (such as *Phytophthora* spp., *Verticillium* spp., *Rhizoctonia* spp., *Pythium* spp., and *Fusarium* spp.), crown gall (*Agrobacterium tumefasciens*), root lesion nematode (*Pratylenchus penetrans*) and weeds are common pests of Mexican strawberry and raspberry nurseries. Phytophthora root rot caused by *P. fragariae* var. *rubi* is the most serious root disease of red raspberries in many growing regions (Walters, pers.com.). Raspberry roots are also very sensitive to excessive moisture and lack of oxygen in the soil for extended periods of time. These conditions cause decay and root death [3–5].

Best roots are produced in non-infested soils with good drainage. The use of raised beds and proper irrigation management can improve drainage and aeration of roots, thus, reducing disease incidence and severity. Pre-plant fumigation can reduce initial disease inoculum and allow plant establishment in heavily infected sites, though the pathogen will often recolonize the site with time [5].

The application of methyl bromide (MB) in raspberry nurseries is recent in Mexico, but MB has been classified as an ozone depleting substance and has been banned in all countries of Montreal Protocol (MP) with the exception of possible critical use exemptions (CUE) [6–8]. In Mexico commercially-available alternatives to MB are CP alone, MS, MK, dazomet, 1,3-dichloropropene (1,3-D), and 1,3-D:CP mixture and, recently, dimethyl disulphide (DMDS), alone and/or in combination with CP (cofepris.gob.mx). Soil fumigation with 1,3-D:CP, CP and MS are the most widespread chemical solutions for strawberry fruit and nursery production in conventional areas of production in the world [9]. DMDS alone or in combination with CP, MS and/or dazomet have been evaluated for strawberry nursery in Spain since 2002 [10–13], but never for raspberry nursery. The challenge for MB alternatives is to maintain commercial root yields and quality at the level of MB. So far, no specific research has been conducted on soil fumigation and MB alternatives for raspberry nurseries in Mexico; and very few articles have been presented in peer-reviewed publications on this topic.

Appropriate viable alternatives to MB are necessary for raspberry nurseries in Mexico currently and in the long term. Our objectives were: a) to identify alternative soil disinfestations treatments that control soil-borne pests and weeds and produce commercial root yields similar to MB treatment; and b) to carry forward the most promising treatments to commercial-scale evaluations. Preliminary results in 2010–2013 were previously published [2].

2. Materials and methods

Fumigation trials were conducted in 2013 and 2014 at the high-elevation Driscoll's nursery (Rancho La Autopista) located in Ciudad Guzmán (Jalisco, Mexico) (1,560 m above sea level and latitude 19º 41' N). Trials were conducted in replicated experiments. The nursery was never fumigated before; the cropping history was a rotation of corn with sorghum.

Mother plant roots of cv. 'Maravilla' were planted in each replicated experimental trial. Standard cultural practices for commercial root plants production were followed (Infante, pers.com.). Replicated plot experiments

Table 1
Fumigation treatments in 2013 and 2014

Treatment	Application methods and rates	2013	2014
T0 No trat.	Non-fumigated	No	Yes
T1 (MB:CP)	Broadcast (flat) shank-applied, 400 kg/ha (50/50 w/w), transparent HDPE tarp	Yes	Yes
T2 (1,3D:CP)	Broadcast (flat) shank-applied, 400 kg/ha (65/35 w/w) (commercial product Piclor®), transparent HDPE tarp	Yes	Yes
T3 (CP)	Broadcast (flat) shank-applied, 400 kg/ha (100% CP), transparent HDPE tarp	Yes	Yes
T4 (CP+MS)	Sequential applied broadcast (flat) shank-applied CP (250 kg/ha) transparent HDPE tarp followed by Rotary Spader (working width of 2.25 m) MS (500 l/ha)	Yes	Yes
T5 (MS)	Broadcast (flat) injected with Rotary Spader (1000 l/ha)	Yes	Yes
T6 (DMDS:CP)	Broadcast (flat) shank-applied, 281 l/ha Paladin® (79/21 w/w), transparent TIF tarp	No	Yes

Cv. 'Driscoll Maravilla' in 2013 and 2014.

were in sandy loams soils with pH of 5.4–6.3 and 1.9–2.4% organic matter. Fumigation treatments, rates and methods of application at each site are listed in Table 1. Treatments (five in 2013 and seven in 2014) were arranged in a randomized complete block design with four replicates per treatment in 2013 and seven replicates per treatment in 2014. Fumigant treatments were applied during the second half of December 2012 and mid-January 2014. Commercial raspberry roots were harvested during the first week of January in 2014 and 18 to 20 December in 2014. Individual plots were 162.5 m^2 in 2013 and 600 m^2 in 2014.

Each season, plants (raspberry roots) were planted in a double rows in 1.20 m wide beds separated by 0.5 m wide furrows. Plants were placed 0.30 m from the edges of the beds at the rate of 500 kg/ha. Plants were irrigated as needed by sprinkler with 10 m spacing between heads in all directions. The dates of planting were March 13, 2013 and March 18-19, 2014.

To quantify the soil fungal populations, the levels of soil-borne fungi in each plot of replicated plots were estimated as colony forming units (CFU) g^{-1} dry soil, before (December, 6, 2012 and January 10, 2014) and after fumigant treatments (February, 10, 2013 and February, 10, 2014) (Table 2). Prior to treatment application five soil samples from the whole nursery were randomly taken in a zigzagged pattern from the 0–15 cm depth and mixed to make composite samples. All soil samples were dried at room temperature in open bags and then passed through a 10.0-mm-mesh sieve. Then samples were shipped to specialized laboratory to estimate colony forming units (CFU) g^{-1} dry soil, on Potato-dextrose agar medium (PDAs), and selective media for *Fusarium* spp., *Pythium* spp., *Verticillium* spp., *Phytophthora* spp. and *Rhizoctonia* spp., following methodology described by De Cal et al. [10, 11]. The same soil samples were also used to determine nematode populations before and after fumigation treatments following sieving/centrifugation methodology described by Jenkins [14].

Before planting in 2014, 50 raspberry mother plants of cv. 'Driscoll Maravilla' were randomly selected from the total amount of plants to be used in the experimental fields to evaluate their sanitary status. These mother plants were grown in MB:CP fumigated Driscoll's Mexican nursery. The plants were transferred to humid chambers and the presence/absence of fungal pathogens on the plants was determined and species identified following methodology described by De Cal et al. [10].

Raspberry disease incidence in each plot and year was recorded three times after transplanting throughout the season in 2013 and five times in 2014. Twenty raspberry plants in the central part of the beds of each plot were sampled on May 20, June 20 and July 15, 2013 and April, 8, May 8, July 10, August 6 and November 27, 2014. The plants were examined visually and the number of plants with external disease symptoms (e.g. collapse, wilt, rot, necrosis, etc.) was recorded. These plants were taken to the laboratory to determine casual agents as described previously for raspberry mother plants in 2014. The incidence of diseased plants was calculated as the percentage of symptomatic plants in the twenty samples in each plot and date. Also, the incidence of the scarab beetles in the subfamily *Melolonthinae*, *Phyllophaga* sp. genus (June Bug, Gallina ciega), in each plot and year

Table 2
Fungal populations (CFU g^{-1} dry weight of soil) before and alter fumigation treatments in 2013 and 2014

Treatment	*Fusarium*		*Verticillium*		*Pythium*		*Rhizoctonia*		*Phytophthora*	
	Before	After	Before	After	Before	After	Before	After	Before	After
2013 Replicated plot experiments										
T1 (BM:CP)	50	96.25a	0	0a	0	21.50a	25	0a	50	0a
T2 (1,3D:CP)	50	121.75a	0	0a	0	121.75a	25	0a	50	0a
T3 (CP)	50	21.50a	0	0a	0	7.50a	25	0a	50	0a
T4 (CP+MS)	50	146.50a	0	0a	0	21.50a	25	0a	50	0a
T5 (MS)	50	177.75a	0	0a	0	180.75a	25	0a	50	0a
2014 Replicated plot experiments										
T0 Untreated	250	105.00c	0	0b	0	0b	66	0b	50	61.00a
T1 (BM:CP)	250	38.57c	0	0b	0	0b	66	0b	50	8.57a
T2 (1,3D:CP)	250	91.71c	0	20.29b	0	0b	66	0b	50	32.14a
T3 (CP)	250	54.71c	0	4.29b	0	0b	66	0b	50	46.00a
T4 (CP+MS)	250	237.29b	0	82.43a	0	37.43a	66	21.29ab	50	0a
T5 (MS)	250	380.00a	0	32.14ab	0	21.43ab	66	26.57a	50	37.43a
T6 (DMDS:CP)	250	74.57c	0	0b	0	0b	66	0b	50	55.71a

Treatments followed by the same letter within a column are not significantly different according to the LSD test ($P < 0.05$).

was recorded twice during each season: in July and at the end of September. One soil sample (2 kg) was taken in the central part on each replication at 30 cm depth. Each sample was carefully examined on worktable for presence or absence of *Phyllophaga* sp. beetles.

To monitor weed populations, sample quadrats were placed in each plot for the duration of each season of cultivation. There were two 6.5 m^2 quadrats per replicate in 2013 and one 15 m^2 per replicate in 2014. Weeds in the sample quadrats were collected on five (2013) and seven (2014) dates from mid-April until mid-October, 2013 and from mid-February (before planting) until end of September, 2014. At each sampling date weed species were identified, counted to determine weed densities by species, and removed with roots to determine total fresh weights.

To monitor the growth of raspberry plants the height of ten plants in the central part of the bed in each plot was measured three times (May, 21, June, 24 and July, 22) in 2013 and four times (April, 29, June, 5, July, 29 and November, 28) in 2014. Additionally, plant emergence was monitored in 2014. The number of raspberry plants emerged on three different dates (April, 24, May, 21 and June, 20) in 2014 was recorded in two different sections of the beds (2 m long each). The plants were machine-harvested from the replicated experiments: first, pruned above-ground and then the roots were excavated. The removal of above-ground parts was carried out with rotovators during the day. The roots were harvested during the night (using plant diggers), loaded and delivered to sorting sheds in plastic "pallets" by refrigerated trucks. Trained crews sorted and weighed marketable roots for each plot and replication.

The processing of the commercial roots included: pressurized washing with water, hand-cleaning, spray application with standard fungicides (e.g., iprodione) and packing in 12 kg-capacity carton boxes. There are no official criteria for raspberry roots quality after harvest in nursery. For this reason, we followed standards given by the nursery owners (Infante, pers. com.). During sorting all thick lignified roots without adventitious buds and remainders of crown were eliminated. Also, in 2014 prior to machine-harvesting, plants from three randomly selected 1 m^2 areas in the central part of each plot were harvested by hand and processed as described previously. Commercial root weights harvested inside these three areas were recorded.

Data for fungal and nematode populations, symptomatic plants, emergence and growth of plants, weed densities, fresh weed weights and root yields were subjected to a two-way analysis of variance (ANOVA) using the STATISTIX 8.0 program (Analytical Software, Ltd., La Jolla, CA, USA). Significant differences were considered at the 5% probability level unless otherwise stated. When significant differences were found, Fisher's least significant difference (LSD) test was used to compare mean values.

3. Results and discussion

Soil fungal populations before and after fumigation treatments are shown in Table 2. All treatments except MS and CP+MS in 2014 controlled *Rhizoctonia* and all controlled *Phytophthora* in 2013. Phytophthora root rot is an important disease caused by several species of *Phytophthora*, the most dangerous and common in caneberries is *P. fragariae* var. *rubi*. Phytophthora root rot is commonly found in soils that remain saturated for periods of time, such as in low areas with clay soils or near leaking irrigation lines [15], but it was not the case for soils in the trials at "La Autopista" nursery. Soil fumigation with 1,3D:CP (Telone C-35 commercial product), similar to our T2 (1,3D:CP) treatment is commonly used to control *Phytophthora* populations [5]. *Fusarium* populations (*F. solani, F. subglutinans, F. equiseti, F. oxysporum*), were not reduced in replicated plot experiments in 2014 (Table 2). *Pythium* spp. and *Verticillium albo-atrum* were detected at extremely low levels before and after treatments. In California, Verticillium wilt caused by *V. dahliae* is rarely found in raspberries but it can be a difficult disease to manage [5]. Verticillium wilt management includes avoidance of fields with recent crop history of highly susceptible vegetable crops [5], but that was not the case for these experiments in Mexico. However, fields that have been infested with weeds that are hosts of *Verticillium* spp. such as pigweed (*Amaranthus* spp.), nightshades (*Solanum* spp.), and lambsquarters (*Chenopodium album)* can also contain high levels of the fungal microsclerotia [5]. Soil fumigation with 1,3D:CP (Telone C-35 commercial product), similar to our T2 (1,3D:CP) and with CP (NutraPic commercial product) similar to our T3 (CP) treatment are commonly used to control Verticillium wilt [5].

In 2013, small populations of non-pathogenic nematodes (*Criconemoides, Tylenchorhynchus, Paratylenchus* and *Aphelenchus* genera) were detected before and after treatments. Only small nematode populations (*Aphelenchus*) were detected in 2013 after treatments: 0 (in T1 (BM:CP) and T4 (CP+MS)), 9.00 in T3 (CP) and 19.25 in T2 (1,3D:CP) for individuals per 100 g dry weight of soil, with no significant differences ($P < 0.05$) among treatments.

Analysis of a sample of mother plants in 2014 (cv. 'Driscoll Maravilla') before planting showed presence of fungal pathogens such as *F. solani*, *R. solani* and *Pythium* spp. in roots and *F. solani* and *Alternaria* spp. in leaves; however, no presence of pathogenic bacteria was detected in the plant samples (data not shown).

Generally, no diseased plants were observed throughout the cultivation cycles. The exception was a single plant in 2013 in T4 (CP+MS) with presence of *F. solani*, *Cercospora sp*., *Colletotrichum sp*., and *Alternaria sp*.

Twenty one weed species were observed in the study of which seven were present in all locations and years: barnyardgrass (zacate de agua) (*Echinochloa crus-galli*), bermudagrass (grama) (*Cynodon dactylon*), Canadian horseweed (cola de caballo) (*Conyza canadensis*), burcucumber (chayotillo) (*Sicyos angulata*), roundleaf geranium (cilantrillo) (*Geranium rotundifolium*), crabgrasses (zacate fresadillo) (*Digitaria* spp.), and common sowthistle (borraja) (*Sonchus oleraceus*). Only weed densities and biomass of *Echinochloa crus-galli*, *Digitaria* spp., *Sonchus oleraceus*, and *Amaranthus hybridus* were significantly reduced by treatments (Table 3).

Weed life cycles (annual and/or perennial) were classified in two main categories following USDA Plant Database criteria (graminoids and forbs) [16]. Graminoids included six species: *Cynodon dactylon*, *Digitaria* spp., *Echinochloa crus-galli*, tufted lovegrass (zacate estrella) *Eragrostis pectinacea*, sorghum (zacate milpilla) (*Sorghum bicolor*), and corn (maíz) Zea mays. The 15 forb species were: Spanish needles (aceitilla) *Bidens pilosa*, *Conyza bonariensis*, *Conyza canadensis*, little mallow (malva) *Malva parviflora*, *Sonchus oleraceus*, cutleaf groundcherry (tomatillo) *Physalis angulata*, *Lepidium* sp., lambsquarters (quelite cenizo) *Chenopodium album*,

Table 3
Weed densities and fresh weights for main weeds species

	2013		2014	
	Wt (g/m^2)	Num/m^2	Wt (g/m^2)	Num/m^2
	Barnyardgrass (Zacate de agua) (*Echinochloa crus-galli*)			
T0 untreat.	–	–	99.3ab	1.8a
T1 (MB:CP)	15.5b	0.2a	1.6b	0.1b
T2 (1,3D:CP)	76.3ab	0.6a	19.8b	0.2b
T3 (CP)	108.9a	1.9a	38.8ab	0.6b
T4 (CP+MS)	13.8b	0.3a	10.4b	0.1b
T5 (MS)	40.4ab	0.2a	20.1b	0.3b
T6 (DMDS:CP)	–	–	127.5a	0.9ab
	Crabgrasses (Zacate fresadillo) (*Digitaria* spp.)			
T0 untreat.	–	–	513.2a	16.1a
T1 (MB:CP)	27.5c	1.6c	3.4c	0.2b
T2 (1,3D:CP)	158.5a	8.8a	16.1c	0.3b
T3 (CP)	161.9a	10.3a	75.8c	1.4b
T4 (CP+MS)	39.8 bc	1.7c	79.5 bc	2.2b
T5 (MS)	129.0ab	6.4b	24.1c	1.3b
T6 (DMDS:CP)	–	–	379.6ab	7.2ab
	Common sowthistle (Borraja) (*Sonchus oleraceus*)			
T0 untreat.	–	–	107.8a	5.7a
T1 (MB:CP)	2.5a	0.20a	47.1b	2.0bc
T2 (1,3D:CP)	4.0a	0.10a	21.7b	1.5c
T3 (CP)	9.6a	0.20a	35.1b	1.6c
T4 (CP+MS)	10.4a	0.90a	51.4b	2.0bc
T5 (MS)	7.3a	0.30a	106.9a	3.9ab
T6 (DMDS:CP)	–	–	50.9b	2.2bc
	Canadian horseweed (Cola de caballo) (*Conyza canadensis*)			
T0 untreat.	–	–	31.1a	1.3a
T1 (MB:CP)	5.0a	0.40a	14.1ab	1.3a
T2 (1,3D:CP)	1.2a	0.20a	13.0b	0.7a
T3 (CP)	3.1a	0.40a	13.8ab	1.0a
T4 (CP+MS)	1.7a	0.30a	10.2b	0.9a
T5 (MS)	4.6a	0.40a	20.0ab	1.2a
T6 (DMDS:CP)	–	–	10.2b	1.0a
	Burcucumber (Chayotillo) (*Sicyos angulata*)			
T0 untreat.	–	–	284.1a	2.4a
T1 (MB:CP)	102.3a	3.1a	61.1b	0.7b
T2 (1,3D:CP)	157.3a	4.2a	109.1b	1.9ab
T3 (CP)	105.3a	3.7a	62.1b	0.9b
T4 (CP+MS)	69.8a	3.9a	94.9b	1.0ab
T5 (MS)	188.0a	3.3a	43.2b	0.5b
T6 (DMDS:CP)	–	–	159.0ab	1.6ab

(*Continued*)

Table 3
(*Continued*)

	2013		2014	
	Wt (g/m^2)	Num/m^2	Wt (g/m^2)	Num/m^2
Roundleaf geranium (Cilantrillo) (*Geranium rotundifolium*)				
T0 untreat.	–	–	10.9b	1.8b
T1 (MB:CP)	0.4b	0.04a	103.3ab	6.1b
T2 (1,3D:CP)	0.0b	0.00a	85.6ab	26.4ab
T3 (CP)	1.5b	0.02a	9.0b	1.5b
T4 (CP+MS)	6.3a	0.08a	307.0a	46.9a
T5 (MS)	3.7ab	0.10a	58.1ab	5.6b
T6 (DMDS:CP)	–	–	124.1ab	17.3ab
Tree tobacco (Gigantecimarrón) (*Nicotiana glauca*)				
T0 untreat.	–	–	6.0c	2.2c
T1 (MB:CP)	1.2b	0.1b	42.3c	7.9c
T2 (1,3D:CP)	1.3b	0.4b	191.3a	32.1a
T3 (CP)	15.4a	1.3a	6.1c	2.1c
T4 (CP+MS)	1.0b	0.1b	148.3ab	24.4ab
T5 (MS)	0.0b	0.0b	7.9c	0.9c
T6 (DMDS:CP)	–	–	118.6bc	19.7b
Hairy fleabane (Rama negra) (*Conyzabonariensis*)				
T0 untreat.	–	–	90.4b	2.9a
T1 (MB:CP)	3.1a	0.40a	124.8b	2.3a
T2 (1,3D:CP)	8.7a	0.30a	149.0b	2.7a
T3 (CP)	3.1a	0.20a	23.0c	0.6a
T4 (CP+MS)	0.4a	0.06a	258.7a	5.5a
T5 (MS)	2.1a	0.30a	25.8c	0.7a
T6 (DMDS:CP)	–	–	263.5a	5.6a
Smooth pigweed (Quelitebledo) (*Amaranthus hybridus*)				
T0 untreat.	–	–	89.1a	1.90a
T1 (MB:CP)	0	0	0.1b	0.01b
T2 (1,3D:CP)	0	0	35.6ab	0.05b
T3 (CP)	0	0	0.7b	0.05b
T4 (CP+MS)	0	0	0.5b	0.01b
T5 (MS)	0	0	0.0b	0.00b
T6 (DMDS:CP)	–	–	1.1b	0.01b

Treatments followed by the same letter within a column (for each weed) are not significantly different according to the LSD test ($P < 0.05$).

common purslane (verdolaga) *Portulaca oleracea*, Mexican pricklypoppy (chicalote) *Argemone mexicana*, *Sicyos angulata*, roundleaf geranium (cilantrillo) *Geranium rotundifolium*, smooth pigweed (quelite bledo) *Amaranthus hybridus*, tall morningglory (campanilla) *Ipomoea purpurea*, and the shrub tree type of tree tobacco (gigante cimarrón) *Nicotiana glauca*.

Numbers and fresh weights of graminoids were significantly reduced by MB:CP and CP+MS compared to CP alone in 2013 and by all fumigant treatments compared to untreated in 2014 (Table 4). In general, all treatments failed to control forbs, with exception of CP alone in 2014 that reduced biomass of forbs 86% compared to

Table 4
Total weed densities and fresh weights in 2013 and 2014

Treatments	Fresh weight (g/ m^2)			Number of weeds (no./m²)		
	Graminoids	Forbs	Total	Graminoids	Forbs	Total
			2013			
T1 (MB:CP)	43.6b	116.9a	160.5b	1.8b	4.3a	6.1b
T2 (1,3D:CP)	238.8a	206.6a	445.4a	9.6ab	5.7a	15.3ab
T3 (CP)	276.4a	151.5a	427.9a	12.5a	6.3a	18.8a
T4 (CP+MS)	64.8b	89.8a	154.6b	2.2b	5.2a	7.4ab
T5 (MS)	193.5ab	217.0a	410.5a	7.6ab	4.6a	12.2ab
			2014			
T0 untreat.	679.1a	652.6ab	1331.7a	18.5a	17.9b	36.4ab
T1 (MB:CP)	6.1c	393.9ab	400.0 bc	0.3b	15.8b	16.1b
T2 (1,3D:CP)	35.7c	701.1ab	736.8abc	0.5b	46.5a	47.0a
T3 (CP)	115.9bc	119.9b	235.8c	2.0b	8.0b	10.0b
T4 (CP+MS)	91.7c	895.5a	987.2abc	2.6b	45.5a	48.1a
T5 (MS)	64.7c	451.1ab	515.8abc	2.2b	12.7b	14.9b
T6 (DMDS:CP)	509.7ab	703.9ab	1213.6ab	8.0b	34.8ab	42.8a

Treatments followed by the same letter withina column are not significantly different according to the LSD test ($P < 0.05$).

Table 5
Plant emergence and plant height in 2014

Treatment	Plant emergence (canes per lineal meter of bed)			Plant height (cm)			
	April, 24	May, 21	June, 20	April, 29	June, 5	July 29	November, 28
T0 untreat.	10.9a	8.3c	11.4 d	15.0a	37.5c	121.9b	122.3a
T1 (MB:CP)	11.5a	12.7ab	14.7abc	15.8a	41.0ab	136.5a	131.8a
T2 (1,3D:CP)	11.3a	13.5a	16.0ab	15.5a	43.2a	132.6a	130.3a
T3 (CP)	10.7a	11.9ab	17.0a	14.9a	40.9ab	130.4a	129.0a
T4 (CP+MS)	9.3a	10.3bc	13.4cd	16.5a	39.8bc	131.9a	127.9a
T5 (MS)	8.8a	9.9bc	15.5abc	17.5a	41.2ab	130.0a	128.5a
T6(DMDS:CP)	12.2a	11.3abc	13.9bcd	16.4a	40.7abc	132.5a	127.1a

Treatments followed by the same letter withina column are not significantly different according to the LSD test ($P < 0.05$).

CP+MS but even after CP treatment forbs densities were similar to untreated check (Table 4). After treatments, forb species accounted for 72% and 84% (of the total fresh weight and weed number) in 2014 (Table 4). This suggests the weed population shift favouring forbs after soil fumigation and the need for effective tools for their management.

Plant emergence in May 2014 was 53% greater, on average in T1 (BM:CP), T2 (1,3D:CP), T3 (CP) compared to untreated check (Table 5). In June 2014 these treatments and T5 (MS) had about 38% more canes than in untreated check and these canes were about 10% taller. At the end of July plants in all fumigation treatments were significantly (7–12%) taller than in untreated check (Table 5). This suggests beneficial effects of these fumigation treatments on plant growth and productivity. No significant effects were observed in 2013 (data not shown).

Table 6
Commercially harvested raspberry root weights (cv. 'Driscoll Maravilla')

Treatment	2013	2014
	kg.ha^{-1}	
T0 untreat.	–	1,272.4c
T1 (MB:CP)	5,453.2a	3,574.3a
T2 (1,3D:CP)	4,569.1ab	3,291.8ab
T3 (CP)	3,730.1b	3,040.6ab
T4 (CP+MS)	3,758,0b	2,756.4b
T5 (MS)	4,084.0ab	2,659.1b
T6 (DMDS:CP)	–	2,990.9ab

Treatments followed by the same letter within Exp. column are not significantly different according to the LSD test ($P < 0.05$).

Commercial yields of raspberry roots (cv. 'Driscoll Maravilla´) also showed clear benefits of soil fumigation. In 2014 root yields were 209 to 280% greater after fumigant treatments compared with no fumigation (Table 6). The highest root yields in experimental plots were observed after MB:CP and 1,3D:CP treatments in both years. These yield data are in agreement with plant emergence and height data (Table 5).

Finally, two years of work at one location on chemical MB alternatives were not sufficient to provide reliable recommendations on this critical need, therefore Methyl Bromide Technical Options Committee (MBTOC) [17] recommended MB for Critical Uses (CUN) for the Mexican Raspberry Nursery industry in 2015. It has been also suggested that on-farm trials are more important than trials on research stations for raspberry nursery production [18]. The highest priorities for the North American nursery operators were economic analysis of alternatives, followed by fumigation trials in commercial nurseries. Fumigant trials conducted on research stations and long-term (typically non-chemical) trials received lower priorities. Similarly, it has been emphasized that soil fumigation is a costly procedure that raspberry nurseries conduct to reduce the risk of even costlier events: inadvertently distributing plants contaminated with soilborne pathogens or nematodes (Walters, pers.com.). Thus, the efficacy of a soil fumigant is, overall, more important than its cost for the nursery production, but the choice of fumigant can significantly impact production costs. In a comparison of efficacy and economics of fumigants in raspberry nurseries in Washington and California 1,3D:CP in commercial formulations Telone C-35 and Pic-Clor 60 at the standard application rates were at least as effective as MB for pathogen and nematode control, and substantially less expensive (Walters, pers.com). Estimates of income based on root yield indicate that the non-fumigated controls performed well, primarily due to the savings in fumigation costs (Walters, pers.com.). However, without fumigation, the levels of pathogens *Phytophthora rubi*, *Agrobacterium tumefaciens* and *Pratylenchus penetrans* were significantly higher in untreated soil than in fumigated plots [19, 20]. Infestation with *Pratylenchus penetrans* alone could lead to an unmarketable crop [21] and pest populations are likely to increase over time without soil fumigation. Nevertheless, for different agro-environmental conditions such as central Mexico, it is necessary to continue on-farm evaluations of alternative fumigants for raspberry nurseries with focus on improved methods of application, evaluation of new alternative treatments with consideration of potential economic viability of these alternatives treatments. It is essential to carry out commercial field-scale demonstrations of most promising alternative fumigant treatments to facilitate technology transfer and adoption.

Acknowledgments

This study was supported a Pilot Project from The Mexican Government, through the Secretary of Environment and Natural Resources (SEMARNAT), in cooperation with the United Nations Industrial Development

Organization (UNIDO) (2013-2014). The authors wish to thank to Driscoll's company and all their technical staff (Antonio Infante, Alfonso Begines, Araceli Rosales, Felipe Ruiz, Arturo Terrones and others) and workers in Ciudad Guzmán nurseries.

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