Performance of Methyl Bromide Alternatives in Strawberry

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SUMMARY. Field studies were conducted to compare the performance of several methyl bromide (MBR) alternative programs on sting nematode (*Belonolaimus* spp.) control and marketable yield of 'Camarosa' strawberry (*Fragaria × ananassa*). The tested fumigation programs were 1) MBr + chloropicrin (Pic; 67:33 v/v) at 350 lb/acre, 2) Pic + metam sodium (MNa) at 300 lb/acre and 37.5 gal/acre, 3) 1,3-dichloropropene (1,3-D) + Pic at 35 gal/acre, 4) 1,3-D + Pic and dazomet at 35 gal/acre and 200 lb/acre, 5) propylene oxide at 45 gal/acre, 6) furfural + allyl isothiocyanate (AITC) at 600 lb/acre, 7) furfural and MNa at 56 and 50 gal/acre, 8) furfural + AITC at 400 lb/acre followed by four furfural applications of 6 gal/acre/injection, 9) furfural and MNa at 37 and 33 gal/acre followed by four furfural applications of 6 gal/acre/injection, 10) fosthiazate and Pic at 4.5 and 150 lb/acre, and 11) a nontreated control. The fumigation programs consisting of 1,3-D + Pic and dazomet, 1,3-D + Pic, Pic and MNa, and fosthiazate and Pic proved to be as valuable as the grower-standard MBr + Pic on strawberry plant vigor, sting nematode control, and early and total marketable yields.

Strawberry production in Florida occurs between October and March on ≈7100 acres, with a reported value of ≈\$180 million (U.S. Department of Agriculture, 2005). Sting nematode is one of the most economically important soil-borne pests in strawberry production (Noling, 2005). In Florida, it is a limiting factor for successful growth and yields, causing significant injuries to root tips, hence decreasing the plant's ability to absorb water and nutrients (Noling, 2005). Affected fields initially show localized and uneven growth with chlorotic plants, eventually extending the damage to the whole planted area (Jardine and Todd, 1990).

Florida strawberries are grown using the annual hill system, where beds are pressed and fumigated before placing drip irrigation lines and polyethylene mulch (Peres et al., 2006). Soil fumigation with methyl bromide (MBR) was an effective

means of controlling sting nematode populations. However, this fumigant has been phased out in compliance with the Montreal Protocol, because it is an ozone-depleting molecule (Watson et al., 1992). One of the leading MBr alternatives is 1,3-dichloropropene (1,3-D) + chloropicrin (Pic), which merges the nematocidal activity of 1,3-D with the fungicide Pic and has shown to be an effective means to control soil-borne diseases and nematodes in tomato (*Lycopersicon esculentum*) (Gilreath et al., 2004; Jones et al., 1995). In strawberry nurseries, De Cal et al., (2004) found that Pic and 1,3-D were comparable with MBr for soil-borne disease control. Bell pepper (*Capsicum annuum*) research revealed effective nematode control under mulched beds with

preplant applications of 1,3-D + Pic (Eger, 2000; Mirusso et al., 2002).

Dazomet, metam sodium (MNa) and allyl isothiocyanate (AITC) break down in the soil, producing isothiocyanate, which is a potent biocide (Ajwa et al., 2003b; Rodriguez-Kabana (2005)). Commercially, dazomet is mostly sold as solid granules and powder, which must be incorporated into the soil to initiate activation, whereas MNa and AITC are available in liquid formulations, providing application flexibility because they can be either directly sprayed on the soil and incorporated or drip injected. Previous studies suggested that MNa could be inconsistent in soil-borne pest control (Fennimore et al., 2003; Locascio et al., 1997), whereas other research has found that it can be a viable MBr alternative (Ajwa et al., 2003a). Despite these discrepancies, MNa is a relatively low-cost product that could be soil sprayed or drip applied, and further research is necessary to determine its efficacy in combination with other fumigants.

Propylene oxide is an all-purpose fumigant of broad-spectrum control against soil-borne diseases, nematodes, and weeds (López-Aranda et al., 2004; Norton, 2004). After soil application, it is microbially decomposed and transformed to propylene glycol, a food additive (Warren, 2004). In tomato, sting nematode populations rapidly decreased at 570 L·ha⁻¹ or higher (Santos and Gilreath, 2005). Furfural, a natural byproduct of sugarcane (*Saccharum officinarum*) processing, is another molecule proposed by Rodriguez-Kabana (2005) as an effective MBr alternative to control nematodes in greenhouse studies. Despite all these studies, little information exists on the effect of combinations of soil fumigants on sting nematode control and on

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
0.1242	gal/100 ft	L·m ⁻¹	8.0520
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
2.2417	ton/acre	t·ha ⁻¹	0.4461

strawberry yield. Therefore, the objective of this study was to compare promising MBr alternatives for soil fumigation in Florida strawberry.

Materials and methods

Studies were conducted in two locations in west-central Florida during the 2002–2003 strawberry season. The experimental plots were established at Chancey Farms and at the Gulf Coast Research and Education Center of the University of Florida, located in Dover and Bradenton respectively. Predominant soils in both locations are deep-sand spodosols with organic matter content of less than 2% and a pH between 7.1 and 7.4. Both experimental sites have a history of moderate to heavy sting nematode infestations, which can severely limit crop yield when they are not controlled.

Eleven treatments were distributed in a randomized complete-block design with six replications. The fumigation programs were 1) MBr + Pic (67:33 v/v) at 350 lb/acre; 2) Pic + MNa at 300 lb/acre and 37.5 gal/acre respectively; 3) 1,3-D + Pic at 35 gal/acre; 4) 1,3-D + Pic and dazomet at 35 gal/acre and 200 lb/acre respectively; 5) propylene oxide at 45 gal/acre; 6) furfural + AITC at 600 lb/acre; 7) furfural and MNa at rates of 56 and 50 gal/acre respectively; 8) furfural + AITC at 400 lb/acre followed by four furfural applications of 6 gal/acre per injection; 9) furfural and MNa at rates of 37 and 33 gal/acre respectively, followed by four furfural applications of 6 gal/acre per injection; 10) fosthiazate and Pic at rates of 4.5 and 150 lb/acre respectively; and 11) a nontreated control.

Before fumigant application, the soil was prebedded and starter fertilizer (200 lb/acre of 15N–0P–24.9K) was applied on bed tops and immediately rototilled within the top 6 inches of the soil. Twenty-one days before transplanting, MBr + Pic, Pic, 1,3-D + Pic, and propylene oxide were injected about 6 inches deep into the finished beds using a nitrogen-gas-propelled fumigation rig with three chisels per bed. Fumigant delivery was controlled by flowmeters, which were calibrated to deliver the desired amounts of the fumigants. In plots treated with 1,3-D + Pic and dazomet, the latter was applied on the

surface of the finished beds with a conventional fertilizer spreader, and watered twice on the same day with 6789 gal/acre/application to enhance fumigant release, whereas 1,3-D + Pic was injected the following day. Furfural, furfural + AITC, MNa, and fosthiazate were drip injected through three irrigation lines (0.45 gal/min/100 ft of bed; T-Tape Systems International, San Diego, CA) buried 1 inch deep, and dissolved in a volume of 27,154 gal/acre/application. The Pic and MNa were injected at 21 and 14 d before transplanting respectively. Fosthiazate was applied 3 d before transplanting. The first application of furfural + AITC and furfural and MNa occurred 14 d before transplanting, and the four subsequent applications took place at 4, 7, 11, 15, and 18 weeks after transplanting (WAT).

Planting beds were 24 inches wide on the top, 28 inches wide on the base, and 10 inches tall, and they were covered with black high-density polyethylene mulch (1.25 mil thick; Pliant Corp., Schaumburg, IL). In Dover, experimental units consisted of a single 45-ft plot, whereas in Bradenton the plots were 50 ft long. Bare-root ‘Camarosa’ strawberry transplants (≈ 10 inches tall), obtained from a commercial strawberry nursery in North Carolina, were planted in double rows separated 12 inches apart, and with an in-row spacing of 15 inches. Within 1 h after transplanting, the experimental sites were sprinkler irrigated between 6 and 8 h per day for ≈ 2 weeks. This procedure helps to provide enough moisture to the soil through the planting holes and row middles to ensure proper transplant establishment. Irrigation, drip fertilization, frost protection, and insecticide and fungicide applications followed recommended commercial practices for Florida strawberry production (Peres et al., 2006).

Sting nematode populations were determined at 10, 13, and 17 WAT by extracting soil samples with a soil probe (1 inches wide by 8 inches deep) from the rhizosphere of 20 strawberry plants per plot, and the nematodes were separated and counted from 100 mL soil using a standard sieving and centrifugation procedure (Jenkins, 1964). At both locations, strawberry plant vigor was

estimated at 8 and 13 WAT. Plant vigor was determined using a scale from 0% to 100%, where 0% equals plant death and 100% indicates optimum growth. The latter was defined as strawberry plants with fully developed foliage, flowers and fruits according to their vegetative stage, and plants free of leaf deformations, chlorosis, or damage. To assess plant vigor, treatments were compared within each replication. Marketable fruit weight was collected twice per week, resulting in 19 and 22 harvests in Dover and Bradenton respectively. Fruit harvests began about at 7 WAT. Early fruit yield was determined by adding the marketable fruit weights from all the December and January harvests.

Plant vigor values were expressed as percentages and transformed with arc sine square root before analysis of variance to normalize the treatment means, whereas the sting nematode populations were transformed with $\log_{10}(\text{observation} + 1)$ before analysis of variance. The significance of the main effects and of the treatment-by-location interaction on each variable were examined with analysis of variance ($P = 0.05$). When significant differences were obtained, treatment means were separated using the Waller–Duncan multiple comparison procedure (SAS version 8; SAS Institute, Cary, NC).

Results and discussion

There was no significant treatment-by-location interaction for each variable. Therefore, only the data from the Dover location are discussed. Fumigant programs significantly affected sting nematode populations at 10, 13, and 17 WAT. At 10 WAT, the treatments with the combinations of MBr + Pic, Pic and MNa, 1,3-D + Pic, and 1,3-D + Pic and dazomet were equally effective against sting nematode, with populations ranging between one and four juveniles per 100 mL soil (Table 1). At the same time, the first three combinations provided the same nematode control as the combined program of fosthiazate and Pic. Soil samples collected 3 weeks later revealed a similar sting nematode response to the fumigants, with the highest populations in all four treatments containing furfural, the nontreated control, and propylene oxide. At 17 WAT, there were

two well-defined groups of treatments with regard to sting nematode control. The combinations of 1,3-D + Pic and dazomet, 1,3-D + Pic, Pic and MNa, fosthiazate and Pic, and MBr + Pic drastically reduced sting nematode populations to less than 20 juveniles per 100 mL soil, whereas the remaining treatments had a similar performance against sting nematode as the nontreated control.

Strawberry plant vigor at 8 and 13 WAT was influenced by the application of the soil fumigants (Table 2).

Plants in plots treated with either 1,3-D + Pic and dazomet, 1,3-D + Pic, Pic and MNa, fosthiazate and Pic, or MBr + Pic were the most vigorous ($\geq 78\%$) at 8 WAT, whereas the rest of the treatments were mostly less than 50% vigor. A similar trend continued throughout the growing season, as revealed by plant vigor readings taken at 13 WAT. Interestingly, the treatments with the highest plant vigor at 13 WAT were the same with the highest sting nematode control, which likely suggests that there is a

close relationship between root nematode infestations and growth reduction in strawberry.

Both early and total marketable strawberry fruit weights were affected by the application of fumigants. The lowest early fruit yields were obtained in plots treated with propylene oxide, the nontreated control, and the four programs that included furfural (Table 2). The combinations of 1,3-D + Pic and dazomet, 1,3-D + Pic, Pic and MNa, and fosthiazate and Pic proved to be as valuable as the grower-standard MBr + Pic, with early fruit weights ranging between 2.50 and 2.94 tons/acre. With regard to total fruit weight, the same promising treatments previously described had the highest total yields, averaging ≈ 11 tons/acre (Table 2).

Previous research has demonstrated that 1,3-D + Pic is comparable with MBr + Pic for nematode control in vegetable crops, which agrees with the results found in the current study (Gilreath et al., 2004). Similarly, Gilreath et al. (2005), in discussing a long-term study of fumigants on bell pepper, found that MNa + Pic was equally effective as MBr + Pic in bell pepper for sting nematode control, and provided similar fruit weight. Although high rates of propylene oxide have shown promising results against sting nematode populations in tomato (Santos and Gilreath, 2005), this fumigant underperformed for strawberry in this experiment. A similar situation occurred with

Table 1. Influence of soil fumigants on sting nematode populations at 10, 13, and 17 weeks after transplanting (WAT) in strawberry fields at Dover, FL, in 2002–03.

Fumigants ^z	Rate (units/acre) ^y	Sting nematodes (juveniles/100 mL soil) ^x		
		10 WAT	13 WAT	17 WAT
Nontreated control	—	12 abc	25 a	57 a
MBr + Pic	350 lb	4 cde	6 de	4 bc
Pic and MNa	300 lb + 37.5 gal	4 de	6 cde	6 bc
1,3-D + Pic	35 gal	2 de	4 de	4 bc
1,3-D + Pic and dazomet	35 gal + 200 lb	1 e	2 e	1 c
Propylene oxide	45 gal	18 abc	22 a	45 a
Furfural + AITC	600 lb	23 ab	42 a	60 a
Furfural and MNa	56 gal + 50 gal	22 ab	26 a	36 a
Furfural + AITC	400 lb	12 ab	16 abc	49 a
Furfural (four times)	6 gal			
Furfural and MNa	37 gal + 33 gal	26 a	20 ab	50 a
Furfural (four times)	6 gal			
Fosthiazate and Pic	4.5 lb + 150 lb	6 bcd	13 bcd	18 b

^zAITC, allyl isothiocyanate; MBr, methyl bromide; MNa, metam sodium; 1,3-D, 1,3-dichloropropene; Pic, chloropicrin.

^y1 lb/acre = 1.1209 kg·ha⁻¹, 1 gal/acre = 9.3540 L·ha⁻¹.

^xNematode populations transformed with log₁₀ (observation + 1) before analysis of variance and treatment means were separated with Waller–Duncan multiple comparison procedure ($P \leq 0.05$). Nontransformed values are presented. 1 juvenile/100 mL = 37.8541 juveniles/gal. WAT, weeks after transplanting.

Table 2. Influence of soil fumigants on strawberry plant vigor at 8 and 13 weeks after transplanting (WAT), and early and total marketable yield in Dover, FL, in 2002–03.

Fumigants ^z	Rate (units/acre) ^y	Plant vigor (%) ^x		Early yield (tons/acre) ^y	Total yield (tons/acre) ^y
		8 WAT	13 WAT		
Nontreated control	—	30 def	17 d	0.83 ef	2.52 e
MBr + Pic	350 lb	80 a	78 a	2.73 a	11.01 a
Pic and MNa	300 lb + 37.5 gal	82 a	80 a	2.81 a	11.11 a
1,3-D + Pic	35 gal	82 a	81 a	2.89 a	11.21 a
1,3-D + Pic and dazomet	35 gal + 200 lb	78 a	84 a	2.94 a	11.80 a
Propylene oxide	45 gal	49 bc	46 bc	1.68 cd	6.40 cd
Furfural + AITC	600 lb	41 cd	29 cd	1.35 de	3.96 de
Furfural and MNa	56 gal + 50 gal	62 b	56 b	2.00 bc	7.92 bc
Furfural + AITC	400 lb	22 ef	18 d	0.67 f	2.16 e
Furfural (four times)	6 gal				
Furfural and MNa	37 gal + 33 gal	34 cde	23 d	1.03 ef	3.50 e
Furfural (four times)	6 gal				
Fosthiazate and Pic	4.5 lb + 150 lb	79 a	78 a	2.50 ab	9.97 ab

^zAITC, allyl isothiocyanate; MBr, methyl bromide; MNa, metam sodium; 1,3-D, 1,3-dichloropropene; Pic, chloropicrin.

^y1 lb/acre = 1.1209 kg·ha⁻¹; 1 gal/acre = 9.3540 L·ha⁻¹; 1 ton/acre = 2.2417 t·ha⁻¹.

^xPlant vigor values expressed as a percentage scale where 100% is optimum plant vigor and 0% is plant death. Data transformed with arc sine square root before analysis of variance and treatment means were separated with Waller–Duncan multiple comparison procedure ($P \leq 0.05$). WAT, weeks after transplanting.

furfural, which had been indicated as an effective nematicide in greenhouse conditions (Rodríguez-Kabana, 2005), failing to control sting nematode effectively in the current study. In summary, this study determined that fumigation programs containing 1,3-D + Pic, Pic and MNa, and fosthiazate and Pic are valuable alternatives to MBr + Pic for sting nematode control in strawberry.

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