MANAGEMENT OF ROOT-KNOT NEMATODES AND NUTSEDGE WITH FUMIGANT ALTERNATIVES TO METHYL BROMIDE IN NORTH FLORIDA U.S.A. TOMATO PRODUCTION[1]

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Summary. Four field trials were conducted to determine efficacy of soil fumigant alternatives to methyl bromide for control of root-knot nematodes (*Meloidogyne* spp.) and nutsedge (*Cyperus* spp.) in tomato. Chemical treatments, rates, and combinations varied but generally included 1,3-dichloropropene (1,3-D), methyl bromide, metam sodium, dazomet, and chloropicrin (Pic). The herbicide pebulate was applied to all treatments except methyl bromide and the controls to provide suppression of nutsedge. Black polyethylene mulch and drip irrigation tubing were laid concurrently with or immediately after chemical application. Data collection in the tests included fruit yield, root gall indices, second-stage root-knot nematode juvenile (J2) numbers and nutsedge populations. Methyl bromide, methyl bromide + Pic, and 1,3-D + Pic produced greatest reduction in root galling and J2 population densities in these tests while the dazomet and metam sodium treatments provided variable reductions. Nutsedge population densities were reduced by 1,3-D + Pic + pebulate, Pic + pebulate and the methyl bromide treatments. Dazomet + pebulate and metam sodium + pebulate provided intermediate reductions in nutsedge population densities. Average tomato yields across trials and among treatments mirrored root galling, second-stage juvenile numbers and nutsedge population densities. Mean yields for methyl bromide, 1,3-D + Pic, Pic, dazomet (high rate), metam sodium (high rate), and the control were 58, 54.2, 49.5, 50.8, 51.7, and 50.3 mt/ha. Data from these tests indicated that soil treatments with 1,3-D + Pic provided greatest control of root-knot nematodes and nutsedge and produced higher average tomato fruit yields compared to the other methyl bromide alternatives and rates tested.

Fresh market tomato is an important vegetable crop in Florida, U.S.A. During the 1999-2000 season, the crop was grown on over 17,000 ha and valued at U.S. $418 million dollars (Anonymous, 2000a). The production system almost universally practiced by growers in Florida is an intensively managed raised-bed system which includes methyl bromide fumigation, polyethylene mulch, drip or seepage irrigation, and trellising. This system produces yields that can exceed 60 mt/ha and has been in use for over 25 years (Overman and Martin, 1978). The application of methyl bromide, sometimes mixed with chloropicrin, has been a critical component of this system (Noling and Becker, 1994). However, methyl bromide is scheduled to be phased out in the United States by 2005 (Anonymous, 2000b). Total use rates for 2003 have been reduced by 70% from the levels used in the 1991 baseline year.

Two of the most serious pest problems in Florida vegetable production systems are plant-parasitic nematodes and nutsedge (Locascio *et al.*, 1994; Dunn and Noling, 1997). The major nematode problems include species in the genera *Meloidogyne* and *Rotylenchulus*. Nutsedge, including both yellow (*Cyperus esculentus* L.) and purple (*C. rotundus* L.), are major weed problems. However, the widespread use of methyl bromide has effectively controlled nematode and nutsedge problems in Florida. Unless viable alternatives are developed, these pest problems and possibly others are expected to intensify with the loss of methyl bromide. Possible chemical replacements for methyl bromide have been reported from other production areas of Florida and include combinations of 1,3-dichloropropene, chloropicrin, and pebulate (Locasio *et al.* 1997; Gilreath *et al.*, 1998). However, tests in these production areas, were conducted in sandy soils whereas tomato production in the north-western portion of Florida is on heavier soil types that include clay subsoils. The tests reported here, therefore, were conducted to determine the performance of potential chemical methyl bromide replacements under edaphic and environmental conditions of the northwest Florida production area.

MATERIALS AND METHODS

Four field tests were conducted between 1993 and 1996 at the University of Florida North Florida Research and Education Center, Quincy, Florida in sandy loam soil. The sites were infested with root-knot nematodes [mainly *Meloidogyne javanica* (Treub) Chitw.] and/or yellow and purple nutsedge. Tests were conducted with commercially available soil fumigants and were arranged in a randomised complete block design with four to six replications. Before fumigation, soil was prepared by moldboard ploughing and double-disking in early March. Fertilizer was broadcast at the rate of 196-61-196 of N-P_2O_5-K_2O kg/ha and disc-incorporated. Chemical treatments, rates and combinations varied among tests but generally included 1,3-dichloropropene

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(1,3-D), methyl bromide, metam sodium, dazomet and chloropicrin (Pic) (Tables I-IV). All chemicals were applied on 0.91-cm-wide raised beds (15 cm high) formed in 1.8 m wide rows resulting in a 50% broadcast application rate. Applications of methyl bromide, 1,3-D, and Pic were made using nitrogen gas as the propellant through a flow meter system and injected into the soil to 25 cm depth with 3 chisels spaced 30 cm apart. Black polyethylene mulch (1.25-mm thick) and double wall drip tubing were laid concurrently with chemical application. Dazomet was applied to the soil surface with a Gandy applicator and some metam sodium treatments were sprayed onto the soil surface. They were incorporated to 15 cm depth, beds formed and polyethylene mulch laid immediately afterward. Other metam sodium treatments were applied through the drip tube after bed formation and polyethylene mulch application. These treatments were made through drip tubing (10 mm thick) in water delivered at a total rate of 7.5 l per meter of row. The tubing was located 15 cm from the bed centre and buried 3-4 cm deep. In all tests, tomatoes (*Lycopersicon esculentum* Mill.) were transplanted 51 cm apart in the middle of the bed row.

Data collection in each test included fruit yield, root gall indices, and nutsedge populations. All harvest data were generated from plot samples run across a fruit grading line (TEW Manufacturing Co.) that had standard belts to separate fruit into medium, large and extra-large categories. A small fruit eliminator was used to remove fruit too small to market. Root gall indices were determined at the end of harvest on 12 plants in each plot and estimated using a 0-10 scale where 0 = no root galling and 10 = 100% of the root system galled. Six soil cores (2.5 cm diam) were collected in each single row plot, and 12 cores from the centre two rows of the four row plots. Soil from each plot was composited and a 100 cm^3 sub-sample processed by centrifugal flotation (Jenkins, 1964). Second-stage juveniles (J2) of root-knot nematodes were counted. Specific methods for other test parameters are listed under each test. All data were analysed with ANOVA and means separated with Duncan's multiple range test.

Test 1. The experimental design was a randomised complete block with four replications, and plots were 19.8 m long and one row wide. Yield data were collected from the centre 12 plants in each plot. One metam sodium and the two dazomet treatments were applied to the bed surface on 25 February 1993. The three metam sodium drip applications treatments were applied through the drip tube on 2 March. The methyl bromide and 1,3-D + Pic treatments were applied through chisels on 10 March. 'Colonial' tomatoes were transplanted on 23 March, and fruit was harvested on 17, 24, and 30 June. On 8 July, 12 plants from each plot were excavated and root gall assessments recorded.

Test 2. The experimental design was a randomised complete block design with six replications. Individual plots were 13.7 m long and one row wide. Yield data were collected from the centre 12 plants of each plot. All chemical treatments were applied on 8 March 1994. Application of the dazomet and one metam sodium treatment were made to the soil surface and the other metam sodium treatment was applied through drip tubing. The remaining treatments were applied by chisel injection. 'Colonial' tomatoes were transplanted on 24 March, and fruit was harvested on 20 and 27 June and 5 July. On 8 July, 12 plants from each plot were excavated and root gall assessments recorded.

Test 3. The experimental design was a randomised complete block design with four replications. Plots were 19.8 m long and four rows wide. Yield data were collected from the centre 12 plants selected from the centre two rows of each plot. The metam sodium and dazomet treatments were surface applied whereas all other treatments were injected with chisels. Due to a history of nutsedge at the site, pebulate at 4.5 kg a.i./ha was broadcast and incorporated to 15 cm depth on all treatment plots except the methyl bromide and control treatments. Chemical treatments were made on 13 March 1995. 'Agriset 761' tomatoes were transplanted on 27 March, and fruit harvested on 19 and 30 June and 10 July. On 13 July, 12 plants from each plot were excavated and root gall assessments recorded. Nutsedge densities were recorded from the centre 1.5 m row of the centre two rows in all treatment plots on 3 May.

Test 4. The experimental design was a randomised complete block with four replications. Plots were 19.8 m long and four rows wide. Yield data were collected from the centre 12 plants of the two centre rows. Metam sodium and dazomet were applied to the bed surface, whereas all other treatments were injected with chisels. Pebulate was applied to the bed surface at 4.5 kg a.i./ha in all treatments except methyl bromide and control plots and was incorporated to 15 cm deep. All treatments were applied on 28 February 1996. 'Agriset 761' tomatoes were transplanted on 25 March. Fruit was harvested on 19 June, 26 June and 8 July. Nutsedge population densities were recorded from the centre 1.5 m of the centre two rows on 1 May. Numbers of dead plants due to *Fusarium* wilt race 3 were counted on 26 June. On 16 July, 12 plants from each plot were excavated and root gall assessments recorded.

RESULTS

In Test 1, all treatments except the two drip tube applications of metam sodium significantly reduced root galling compared to the control (Table I). Methyl bromide produced the greatest reduction in root galling followed by the surface-applied metam and 1,3-D + Pic treatments. Total fruit yields were not increased significantly by any treatments, but highest yields corresponded to the two treatments with the lowest root gall indices.

In Test 2, lowest root-gall ratings were in the 1,3-D + Pic and methyl bromide + Pic treatments (Table II).

Table I. Effect of fumigant treatments on root gall ratings index and marketable fruit yield of 'Colonial' tomatoes, Test 1.

Treatment	Rate/ha broadcast	Root gall index (0-10)	Yield mt/ha[y]
Methyl bromide (98%)[w]	263 kg	0.6 d[x]	68.2 a
Metam sodium[u]	935 l	2.4 c	65.3 a
1,3-D +Pic (17%)[w]	200 l	2.6 c	62.3 a
Dazomet[u]	336 kg	4.4 b	57.9 a
Metam sodium[v]	701 l	4.4 b	59.2 a
Dazomet[u]	168 kg	4.5 b	63.4 a
Metam sodium[v]	467 l	5.2 ab	60.5 a
Metam sodium[v]	935 l	5.3 ab	62.0 a
Control	----	6.6 a	62.6 a

[y] Includes medium, large and extra large marketable grade sizes.
[x] Column means followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.
[w] Treatments were applied with chisels during polyethylene mulch application.
[v] Applied through drip tubing on the bed.
[u] Surface applied, incorporated, then bedded and polyethylene mulch applied.

Table II. Effect of fumigant treatments on root gall index, second-stage *Meloidogyne* spp. juveniles, and marketable fruit yield of 'Colonial' tomatoes, Test 2.

Treatment	Rate/ha broadcast	Root gall index (0-10)	Juveniles/ 100 cm^3 soil	Yield mt/ha[y]
1,3-D + Pic (17%)[w]	327 l	0.7 e[x]	13 c	48.2 a
Methyl bromide + Pic (67/33)[w]	392 kg	1.0 e	32 c	55.7 a
Methyl bromide (98%)[w]	448 kg	2.1 de	119 bc	54.6 a
Pic[w]	392 kg	3.3 cd	1030 ab	53.8 a
Control	----	4.2 bc	933 ab	51.0 a
Metam sodium[v]	935 l	5.0 ab	1611 a	51.7 a
Dazomet[v]	448 kg	6.2 a	8872 a	52.9 a
Metam sodium[u]	935 l	6.5 a	5559 a	51.1 a

[y] Includes medium, large and extra large marketable grade sizes.
[x] Column means followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.
[w] Treatments were applied with chisels during polyethylene mulch application.
[v] Surface applied, incorporated, then bedded and polyethylene mulch applied.
[u] Applied through drip tubing on the bed.

Table III. Effect of fumigant treatments on nutsedge population density and marketable fruit yield of 'Agriset 761' tomatoes, Test 3.

Treatment	Rate/ha broadcast	Nutsedge plants/m²	Yield mt/ha[z]
1,3-D + Pic (17%)[y]	327 l	0.0 b[x]	66.2 ab
Methyl bromide + Pic (67/33)[y]	392 kg	1.0 b	68.0 a
Pic[y]	392 kg	3.0 b	52.4 bc
Dazomet[w]	448 kg	3.9 b	50.4 c
Metam sodium[w]	935 l	16.7 ab	55.5 a-c
Control	----	35.4 a	55.2 a-c

[z] Includes medium, large and extra large marketable grade sizes.
[y] Treatments were applied with chisels during plastic mulch application.
[x] Column means followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.
[w] Surface applied, incorporated, then bedded and polyethylene mulch applied.

Table IV. Effect of fumigant treatments on nutsedge population density, root gall index, second-stage *Meloidogyne* spp. juveniles, and marketable fruit yield of 'Agriset 761' tomatoes, Test 4.

Treatment	Rate/ha broadcast	Nutsedge plants/m²	Root gall index (0-10)	Juveniles/ 100 cm³ soil	Yield mt/ha[y]
Methyl bromide (67/33)[w]	392 kg	6.6 b[x]	0.1 b	1 a	43.4 a
1,3-D + Pic (17%)[w]	327 l	13.2 b	0.5 b	52 a	40.0 a
Metam sodium[v]	935 l	59.3 ab	2.1 ab	450 a	37.4 a
Dazomet[v]	448 kg	56.8 ab	0.1 b	11 a	41.8 a
Pic[w]	392 kg	1.7 b	0.1 b	3 a	42.3 a
Control	---	129.2 a	3.5 a	515 a	32.4 a

[y] Includes medium, large and extra large marketable grade sizes.
[x] Column means followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.
[w] Treatments were applied with chisels during polyethylene mulch application.
[v] Surface applied, incorporated, then bedded and polyethylene mulch applied.

These were significantly lower than all other treatments except the methyl bromide application. Two treatments, dazomet and metam sodium (drip applied) resulted in significantly higher root gall ratings than the control. Root-knot nematode J2 population densities were significantly lower in the 1,3-D + Pic, methyl bromide + Pic and the methyl bromide treatments compared to the control. Populations of J2 did not differ among the other chemical treatments and the control. Highest total fruit yields were in the methyl bromide and methyl bromide + Pic treatments, but yields did not differ among chemical treatments or the control. Significant correlations were not found between total yield and at harvest root-knot nematode populations (log^{10}) or root galling. The correlation between nematode populations and root galling, however, was highly significant ($P \leq 0.001$).

In Test 3, nutsedge population densities were significantly reduced by all treatments except metam sodium as compared to the control (Table III). No differences in nutsedge population densities were found among chemical treatments. Root gall indices were very low and data are not shown. Total fruit yield did not differ among chemical treatments and the control. However, the 1,3-D + Pic and methyl bromide + Pic treatments produced significantly higher yields than the dazomet treatment.

In Test 4, nutsedge population densities were significantly reduced by the methyl bromide + Pic, 1,3-D + 17% Pic and Pic alone compared to the control (Table IV). All treatments except metam sodium reduced root gall indices compared to the control. Population densities of J2 did not differ among chemical treatments or the control. Due to *Fusarium* wilt race 3, plant mortality ranged from 8.7 to 40% (data not shown). All treatments except dazomet reduced incidence *Fusarium* wilt compared to the control. A significant correlation ($P \leq 0.04$) was found between total yield and at harvest J2 nematode populations but not root galling ($P \leq 0.08$). However, the correlation between log_{10} nematode populations and root galling was highly significant ($P \leq 0.001$).

DISCUSSION

Methyl bromide, methyl bromide + Pic, and 1,3-D + Pic treatments produced the greatest reduction in root galling caused by *Meloidogyne* spp. in these tests. In Test 1, the 200 l/ha rate of 1,3-D + Pic significantly reduced root galling compared to the control but galling was higher than the standard methyl bromide treatments. In the other three tests where the higher rate of 1,3-D + Pic (327 l/ha) was evaluated, reductions in root galling were similar between this treatment and the methyl bromide + Pic standard, indicating an increased level of nematode control. The dazomet and metam sodium treatments provided variable reductions in root galling and, in one trial, produced significantly higher galling than the control. These chemicals produced similar root gall index reductions in only one of three tests compared to the methyl bromide standards and 1,3-D + Pic. Similarly, metam sodium applied on the surface and incorporated or via a drip tube provided only marginal reductions in root galling compared to the control. The relative nematicidal effectiveness of the chemicals used in our tests agrees with those of others (Locasio *et al.*, 1997; Lamberti *et al.*, 1998; Ingham *et al.*, 2000).

No differences in nutsedge population reductions were observed between 1,3-D + Pic, Pic or the methyl bromide treatments. Pic is not known to directly kill nutsedge, but, observations suggest that it enhances tuber germination, which results in greater susceptibility to pebulate. Dazomet + pebulate and metam sodium + pebulate provided intermediate reductions in nutsedge populations when compared to the other chemical treatments. Results indicate less effectiveness of these materials in reducing nutsedge populations, even in conjunction with pebulate. Other studies also indicated that nutsedge control with a combination of 1,3-D + Pic + pebulate was comparable to methyl bromide alone and methyl bromide + Pic while nutsedge control with dazomet and metam sodium was less effective (Locasio *et al.,* 1997; Gilreath *et al.*, 1998).

Significant yield differences were not found among treatments and the control. The raised bed, polyethylene mulch system of tomato production provides an optimal environment for plant growth thus increasing plant tolerance to nematodes and weed competition. However, average yield differences across trials and among treatments generally mirrored root gall and nutsedge population reductions. Mean yields for methyl bromide, 1,3-D + Pic, Pic, dazomet (high rate), metam sodium (high rate), and the control were 58, 54.2, 49.5, 50.8, 51.7, and 50.3 mt/ha, respectively. Even apparently small yield differences can have significant economic impacts, however, since the crop value can exceed U.S.$ 25, 000/ha (Anonymous, 2000a).

Data from these tests indicate that soil treatments with 1,3-D + Pic provided the greatest control of root galling caused by root-knot nematodes and nutsedge populations and higher average yields compared to other methyl bromide alternatives and rates tested. This treatment averaged 86 to 97% of the yield from the methyl bromide + Pic standard and was shown to be the most viable methyl bromide alternative for tomato production in northwest Florida. However, further study should be conducted to determine optimum of rates, combinations and application methods for metam sodium, dazomet and Pic.

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