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Root-Knot Nematode Management in Double-Cropped Plasticulture Vegetables

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Abstract: Combination treatments of chisel-injected fumigants (methyl bromide, 1,3-D, metam sodium, and chloropicrin) on a first crop, followed by drip-applied fumigants (metam sodium and 1,3-D ± chloropicrin) on a second crop, with and without oxamyl drip applications were evaluated for control of *Meloidogyne incognita* in three different tests (2002 to 2004) in Tifton, GA. First crops were eggplant or tomato, and second crops were cantaloupe, squash, or jalapeno pepper. Double-cropped vegetables suffered much greater root-knot nematode (RKN) pressure than first crops, and almost-total yield loss occurred when second crops received no nematicide treatment. On a first crop of eggplant, all fumigants provided good nematode control and average yield increases of 10% to 15 %. On second crops, higher application rates and fumigant combinations (metam sodium and 1,3-D ± chloropicrin) improved RKN control and increased yields on average by 20% to 35 % compared to the nonfumigated control. Oxamyl increased yields of the first crop in 2003 on average by 10% to 15% but had no effect in 2004 when RKN failed to establish itself. On double-cropped squash in 2003, oxamyl following fumigation provided significant additional reduction in nematode infection and increased squash yields on average by 30% to 75%.

Key words: Cucurbitaceae, fumigants, *Meloidogyne* spp., oxamyl, pesticide drip applications, Solanaceae.

Micro-irrigation tubing is widely used for delivery of water and fertilizer in polyethylene film mulched beds (Camp, 1998). Drip irrigation systems also can be used to apply emulsified formulations of soil fumigants, a technique that has received increased interest with the pending loss of methyl bromide (Anonymous, 1992; Csinos et al., 2000). Application of soil pesticides through drip irrigation systems offers many benefits in that it: (i) increases a grower's flexibility, (ii) reduces the potential for worker exposure, and (iii) allows growers to continue using the same drip lines, plastic mulch, and residual nutrients for successive crops (Ajwa et al., 2002). Disadvantages are the dependence on soil water movement and soil characteristics to achieve uniform treatment of the bed, especially when dealing with fumigants. The sandy soils of the southeastern US drain rapidly due to high sand content, and horizontal water movement is often inadequate to achieve fumigation over the entire bed (Csinos et al., 2002). Regardless of these potential problems, in double-cropped vegetable systems, pesticide drip applications are often the only option a grower has to control nematodes and other soilborne pests and diseases in the second crop. In the subtropical climate of the southeastern US, polyethylene film mulched beds are commonly used for two to four vegetable crops before they are destroyed (double or multiple cropping). Particularly on these second and later crops, soilborne pests and diseases become problematic due to population increase on the previous vegetable crop(s) and higher soil temperatures (and shorter pathogen life cycles) in summer and fall, when second crops are usually planted.

Among the most damaging pests in plastic mulch vegetable culture in the Southeast are the root-knot nematodes (*Meloidogyne incognita* and *M. arenaria*). Root-knot nematodes (RKN) have a very wide host range, which includes all vegetables commonly grown in plasticulture. The nematodes typically become a problem in sandy soils, especially during summer and fall when temperatures are high.

Metam sodium, emulsified formulations of 1,3-dichloropropene (1,3-D), and 1-3-D plus chloropicrin are currently the only registered soil fumigants that can be applied through the drip tape. These fumigants, though used mainly as chisel-applied fumigants on first crops, have received considerable interest for the past 10 yr as alternatives to the soil fumigant methyl bromide, which is being phased out due to its ozone-depleting effect (Anonymous, 1992). Oxamyl (Vydate) is an oxime carbamate used to control nematodes, mites, and insects. As a systemic pesticide, it is suggested for use as a pre-planting, at-planting, and post-planting treatment. Oxamyl is used in a variety of formulations and is currently one of the only available post-plant nematicides registered for vegetables in the southeastern US. In vegetable plasticulture, oxamyl has received renewed interest in methyl bromide alternative programs as a post-plant drip application following pre-plant fumigation with 1,3-D and/or metam sodium. Improved vigor and fruit quality of tomato and pepper using such combinations have been observed (Desaeger et al., 2004a).

The objectives of this research were to: (i) evaluate the efficacy of drip-applied fumigants for nematode control and (ii) assess the effect of additional at- and post-plant applications of oxamyl in double-cropped vegetable systems.

Materials and Methods

Site description and land preparation: Experiments were conducted at the University of Georgia Coastal Plain

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Experiment Station, Tifton, GA, on a Fuquay loamy sand (88% sand, 8% silt, 4% clay; pH 5.5-6.0; <2% organic matter; loamy, siliceous thermic Arenic Plinthic Paleudults). The experimental area had a history of vegetable crops prior to initiation of these studies and was naturally infested with *M. incognita*.

All plant beds were formed between 1 and 28 March using a commercial tractor-drawn bed-shaper either after rain or overhead irrigation to ensure proper soil moisture and bed formation. Soil moisture was determined with the gravimetric method (Brady, 1974) and was measured at 60% to 80% of field capacity. Before bed formation, the soil was disc-harrowed and turned 25 to 30-cm deep with a moldboard plow. Beds were 10-m long, 81-cm wide x 15 to 18-cm high, with 1.82-m spacing center to center of the beds and a 3.8-m-wide alley between blocks. Beds were covered with black polyethylene mulch (low-density polyethylene (LDPE), thickness 50 µm) (PlastiTech, Saint-remi,Québec). Prior to planting the second crop in July or August, the plastic mulch was painted white to reduce soil heating, which can be excessive in summer and fall. All experiments were done in randomized complete blocks with five replicates/treatment.

General management: A single drip tape was installed 2 to 4 cm below the surface in the center of the beds as the plastic mulch was applied. All experiments used Aqua-Traxx premium high-flow drip tape with 30.5-cm spacing between emitters and a flow rate of 1.14 liters/hr at 0.68 kg/cm^2 pressure. Water was applied through drip tape every day or every second day, depending on crop need.

Fertilization: Experimental areas were broadcast fertilized with NPK fertilizer (10-10-10) prior to bed formation and treatment application. Pre-plant fertilizer rates ranged from 400 to 700 kg/ha, depending on soil analysis and crop fertilization recommendations. Fertilizer was incorporated with a rototiller approximately 10-cm deep. A total of 1,300 kg/ha post-plant fertilizer (4-0-8) per crop was applied in equal applications twice a week through the drip system, using a CO_2 pressurized stainless steel tank which was connected to the drip irrigation system. A 6% Ca-micronutrient solution was applied weekly on spring crops, each time at 0.2 liters/ha, via drip beginning at flowering to reduce the incidence of blossom end rot.

Fumigation and oxamyl-applications: Table 1 summarizes the treatments with different combinations of methyl bromide + chloropicrin applied with a chisel (MBR), 1,3-dichloropropene + chloropicrin applied with a chisel (C35), metam sodium applied as a spray + chloropicrin applied with a chisel (MS + PIC), 1,3-D (94 %) applied through the drip irrigation system (1,3-D-EC), 1,3-D (61%) + chloropicrin (33%) applied through the drip irrigation system (1,3-D + C), and metam sodium (42 %) applied through the drip irrigation system (MS). The chisel injector had two chisel shanks spaced 30 cm apart for injecting chemicals 20- to 25-cm deep (MBR, PIC and C35) and was also equipped with a combination rototiller for spraying chemicals (MS). Polyethylene mulch was laid over the treated soil surface within 15 min after fumigation.

Treatments on second crops were injected through the irrigation system using a CO_2 pressurized stainless steel tank, which was connected to the drip irrigation system. All drip-applied fumigants (1,3-D, 1,3-D + chloropicrin, and metam sodium) were applied over a 6-hr period in 200 liters water/10-m bed length: (i) 1,3-D as Telone EC (94% 1,3-D) (1,3-D-EC), (ii) 1,3-D + chloropicrin as InLine (60.8% 1,3-D + 33.3% chloropicrin) (1,3-D + C), and (iii) metam sodium as Vapam HL (42% sodium methyl dithiocarbamate) (MS) (Table 1).

Oxamyl (as Vydate L; 24% oxamyl a.i.) was applied three times, starting at planting and at 10 (summer) or 14 (spring) and 20 (summer) or 28 (spring) d after planting at 18 kg a.i./ha/application. Injection times for oxamyl varied depending on the bed coverage that was required (Csinos et al., 2002). As oxamyl is not volatile, placement in target areas of root development is critical. Oxamyl was applied over 1 hr for about 15-cm bed coverage at planting (as roots were still limited to the center of the bed), over 2 hr for about 25-cm bed coverage for the second application, and over 3 hr for 30- to 35-cm bed coverage for the third application.

Crop management: Greenhouse-grown seedlings (four-leaf-stage) were planted 30 to 60 cm apart, depending on crop, in single rows using a hole-puncher combined with a mechanical-hand transplanter and water tank. Planting holes were cut into the center of the plastic bed adjacent to the drip tape. Dead or dying seedlings were replaced during the first week. Soil temperature at 10-cm depth was measured for each experiment, and

TABLE 1. Overview of the different trials and keys for fumigation treatment codes.

	1st Crop (Spring)		2nd Crop (Summer)	
Trial – Year	Crop	Treatment(s)[a]	Crop(s)	Treatment(s)
Trial 1 – 2002	Eggplant	None	Cantaloupe	1,3-D-EC, 1,3-D + C, MS
Trial 2 – 2003	Eggplant	MBR, C35 ± oxamyl	Squash	1,3-D + C, MS ± oxamyl
Trial 3 – 2004	Tomato	MBR, MS + PIC ± oxamyl	Squash + Jalapeno pepper	MS ± oxamyl

[a] MBR = Methyl bromide (67% + 33% chloropicrin) (chisel-applied); C35 = 1,3-D (61%) + chloropicrin (33%) (chisel-applied); MS + PIC = Metam sodium (42%) (sprayed) + chloropicrin (chisel-applied); 1,3-D-EC = 1,3-D (94%) (drip-applied); 1,3-D + C = 1,3-D (61%) + chloropicrin (33%) (drip-applied); MS = Metam sodium (42 %) (drip-applied).

rainfall was recorded within 200 m of the experimental site. Foliar applied fungicides and insecticides were sprayed once a week (according to recommended practices and using different combinations of copper hydroxide, mancozeb, chlorothalonil, permethrin, esfenvalerate, methomyl, indoxacarb, and spinosad) (Anonymous, 2005). In the summer tests, starting at planting and with 2-wk intervals, additional drip applications of imidacloprid were applied to control sucking and virus-transmitting insects. Glyphosate was sprayed between beds to control weeds as required.

Experiment 1, 2002, eggplant followed by cantaloupe: On 11 March 2002, all test plots were covered with black polyethylene mulch, and eggplant seedlings (cv. Black Beauty) were planted adjacent to the drip tape 2 d later. The eggplant was allowed to reach full maturity. The first crop was then destroyed and plant debris, except for the dried stalks and roots, removed. On 1 July, MS (351 liters/ha or 701 liters/ha) was injected through the drip tape in designated plots. 1,3-D-EC (122 liters/ha or 168 liters/ha) and 1,3-D + C (126 liters/ha or 192 liters/ha) treatments were applied during the next 3 d (Table 1). Cantaloupe (cv. Athena) seedlings were transplanted 60 cm apart within rows on 29 July. A stand count was made on 12 August and a vigor rating done on 20 August.

Soil cores for nematode density determination were collected at final harvest of the first crop (eggplant) and at flowering stage (28 August) and final harvest (20 October) of the second crop (cantaloupe). On 28 August, an early root gall index (0-10) was determined for 3 plants/plot. Following final harvest on 28 October, a root gall evaluation was done on 10 plants/plot. Shoot and root weights were recorded on 8 October (3 individual plants/plot). All cantaloupes were hand-harvested from the center 6-m bed area (10 plants). Fruits from each harvest were separated into marketable and cull, counted, and weighed on 10 and 16 October.

Experiment 2, 2003, eggplant followed by squash: On 28 March 2003, the soil fumigants MBR (at 336 kg/ ha) and C35 (at 168 liters/ha) were chisel-applied and all test plots covered with black polyethylene mulch. Eggplant seedlings (cv. Black Beauty) were transplanted 30 cm apart adjacent to the drip tape on 17 April. Oxamyl was drip-applied at planting (April 17) and at 2 and 4 wk post-planting.

Stand counts and plant vigor ratings were done at 14, 28, and 42 d after planting (DAP). Soil cores for nematode density determination were collected before fumigation (24 March), at planting (17 April), and at harvest (9 July). An early root gall evaluation was performed on 3 plants/plot on 4 June (at flowering stage) and again on 10 plants/plot following final harvest on 22 July. Shoot and root weights were recorded at eggplant flowering stage (4 June) on 3 plants/plot. All eggplants were hand-harvested from the 5 m center area of each bed (15 plants/plot). Fruits from each of four harvests, on 13, 19, and 26 June and 3 July, were separated into marketable and cull fruits, counted, and weighed.

Following eggplant, beds were fumigated through the drip irrigation system with MS (468 liters/ha) or 1,3-D + C (168 liters/ha) on 24–25 July. Nontreated beds were sprayed with glyphosate to kill eggplant. Squash seedlings (cv. Crookneck) were transplanted 30 cm apart adjacent to the drip tape on 15 August. Oxamyl was drip-applied 3 (18 August), 10, and 20 DAP.

Stand counts were made the first week after planting, and plant vigor ratings (1–10 scale) were done at 14 and 21 DAP. Soil cores for nematode density determination were collected at planting (15 August) and at final harvest (7 October). Root gall assessments were performed on 12 September at flowering stage (on 3 plants/plot) and after harvest on 7 October (10 plants/plot). All squash were hand-harvested from the center 5 m of each bed (15 plants per/plot). Fruits from each of five harvests, on 19, 22, 26, 30 September and 6 October, were separated into marketable and cull fruits, counted, and weighed.

Experiment 3, 2004, tomato followed by squash/jalapeno pepper: On 1 March 2004, the soil fumigants MBR (336 kg/ha) and MS (sprayed at 351 liters/ha) plus PIC (chisel-injected at 112 kg/ha) were applied and all test plots covered with black polyethylene mulch. Tomato seedlings (cv. Amelia) were transplanted 45 cm apart on 26 March. Oxamyl was drip-applied at planting (26 March) and at 2 and 4 wk post planting.

Stand counts and plant vigor ratings were done at 15 and 42 DAP. Soil cores for nematode density determination were collected before fumigation (24 February), at planting (26 March), and at harvest (8 July). On 18 May (at flowering stage), root gall severity was assessed on 3 plants/plot and again on 10 plants/plot following final harvest on 1 July. Plant weights (root + shoot) were recorded at flowering stage of tomato (18 May) on 3 plants/plot. All tomato fruits were hand-harvested from the 5 m center area of each bed (10 plants/plot). Fruits from each of three harvests, on 8, 17, and 23 June, were separated into marketable and cull fruits, counted, and weighed. White mold (*Sclerotium rolfsii*) was fairly common in the test, and incidence and number of wilted plants were recorded.

Following tomato, all beds, except for the nontreated control, were drip-fumigated with MS (at 351 liters/ha) on 21 July. Nontreated beds were sprayed with glyphosate to kill tomato. Beds were split in two, and each half was randomly assigned to receive either squash or jalapeno pepper seedlings (15 plants each). Squash seedlings (cv. Prelude) and Jalapeno pepper were transplanted on 17 August. Plant spacing was 30 cm in both subplots. Oxamyl was drip-applied 1 DAP (18 August), and 10 and 20 d afterwards.

Stand counts were made the first week after planting, and plant vigor ratings were done at 14 and 28 DAP. Soil cores were collected at planting (17 August) and at final harvest (20 October for squash and 5 November for jalapeno pepper). On 16 September (at flowering stage of squash) an early root gall evaluation was done on 3 plants/plot. Again, following final harvest on 18 October, 10 squash plants/plot were evaluated for root galls. Jalapeno pepper roots (10 plants/plot) were evaluated at final harvest on 5 November. All squash and jalapeno pepper fruits were hand-harvested from the 3 m center area of each sub-plot (10 plants/sub-plot). Each harvest was separated into marketable and cull fruits, counted, and weighed. There was a total of four squash harvests, on 21, 29 September and on 5 and 12 October, and two jalapeno pepper harvests, on 18 and 28 October.

Data collection and analysis: Nematode population densities in the soil were determined on the first crop (before fumigation, at plant and at harvest) and at plant and at harvest of the second crop from 12 soil cores (2.5-cm-diam. × 25-cm-deep) from each plot. Soil cores were mixed, and nematodes were extracted from a 150-cm^3 sub-sample by centrifugal flotation (Jenkins, 1964). Root galls were rated on a 0-to-10 scale, with 0 = no galls, 1 = very few small galls, 2 = numerous small galls, 3 = numerous small galls of which some are grown together, 4 = numerous small and some big galls, 5 = 25% of roots severely galled, 6 = 50% of roots severely galled, 7 = 75% of roots severely galled, 8 = no healthy roots but plant is still green, 9 = roots rotting and plant dying, 10 = plant and roots dead (Zeck, 1971).

Plant vigor ratings were conducted during the first half of the growing season on a 1-to-10 scale, with 10 representing vigorous, healthy plants and 1 representing dead plants. Fresh root and shoot weights were taken at the flowering stage of the crop. Fruits were hand-harvested, separated into marketable and cull fruits, counted and weighed. Cull fruits included small-sized, blemished, and diseased fruits.

All data were analyzed using analysis of variance or the general linear model procedures with SAS (SAS Institute, Inc., Cary, NC). The numbers of nematodes in the soil were transformed by log (x + 1) wherever necessary according to a normality test. Least significant differences were used to separate treatments in tables, and the standard error of means (SE) was used in figures. Differences between two means were analyzed using single-degree-of-freedom contrasts.

Results

Plant-parasitic nematodes in the experimental area were predominantly the root-knot nematode *M. incognita* (RKN) mixed with low populations of *Paratrichodorus* spp. (stubby root nematode). *Belonolaimus longicaudatus* (sting nematodes), *Mesocriconema* spp. (ring nematodes), and *Helicotylenchus* spp. (spiral nematodes) were present in low abundance and not presented.

Experiment 1, 2002, eggplant followed by cantaloupe: Large numbers of RKN were present in soil following a first crop of eggplant (Table 2). All drip-applied fumigants reduced nematode numbers and gall indices at the flowering stage of cantaloupe (30 DAP) compared to the nontreated control (NTC) (Table 2, Fig. 1A). By final harvest, nematode numbers in soil were not different, but root gall indices in the fumigated beds, especially with the MS + 1,3-D + C combination, were still lower than the nontreated beds (Table 2, Fig. 1A). Root gall indices were intermediate with MS alone and with the lowest 1,3-D + C rate. Stubby root nematodes were reduced by all drip-applied fumigants at flowering stage of cantaloupe ($P = 0.04$), but by harvest, populations were actually greater ($P = 0.06$) in some fumigant treatments than in the nontreated control (Table 2).

Cantaloupe growth was severely limited by RKN, and shoot weight (but not root weight) at flowering stage was significantly ($P = 0.01$) increased by fumigation (129 g/plant for nonfumigated beds as compared to 500 g/plant for fumigated beds). Negative correlations

Table 2. Nematode soil populations before fumigation (at harvest of a first crop of eggplant) and after fumigation (at flowering and at harvest of a second crop of cantaloupe), 2002, Black Shank Farm, Tifton, GA.

		At harvest 1st crop 18 June		At flowering 2nd crop 28 August		At harvest 2nd crop 28 October	
Fumigant	Rate l ha^{-1}	RKN[a]	SRN	RKN	SRN	RKN	SRN
1,3-D-EC	126	1,666	24	11 b	6 b	203	32 b
1,3-D-EC	168	1,768	44	0	8 b	1,108	86 a
1,3-D + C	122	4,690	26	9 b	7 b	206	38 ab
1,3-D + C	192	2,750	22	6 b	3 b	1,632	43 ab
MS	701	4,678	27	2 b	4 b	598	43 ab
1,3-D + C + MS	122 + 351	2,638	52	9 b	2 b	441	20 b
1,3-D-EC + MS	126 + 351	2,808	34	0	1 b	398	18 b
NTC	—	1,008	20	372 a	20 a	648	11 b
F probability		NS	NS	<0.01	0.04	NS	0.06

[a] RKN = Root-knot nematode (*Meloidogyne* spp.); SRN = Stubby root nematode (Trichodoridae); numbers are per 150 cm^3 soil.

Data are means of five replications. Means in the same column followed by the same letter are not different ($P = 0.05$) according to LSD test. No letters indicate non-significant difference.

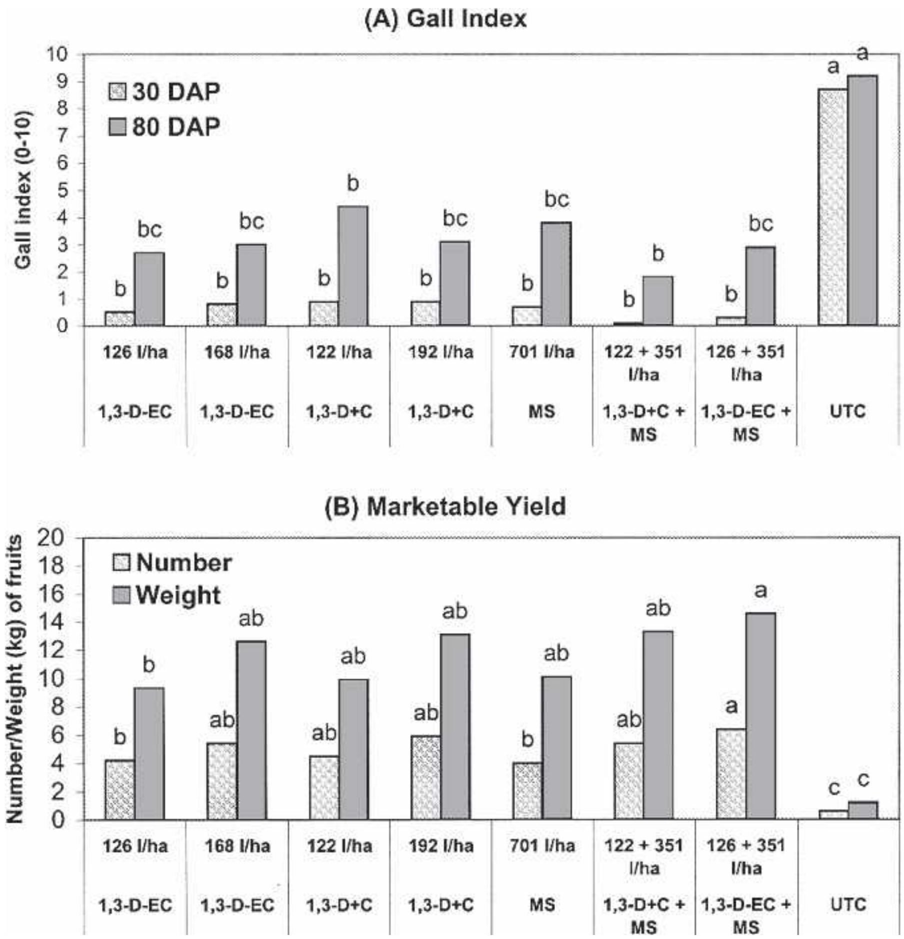

Fig. 1. Effects of drip-applied soil fumigants on root-knot nematode gall indices (A) and total marketable yield (B) of double-cropped cantaloupe, fall 2002, Black Shank Farm, Tifton, GA. Data are means of five replications. Bars within the same series having the same letter are not different ($P = 0.05$) according to LSD test.

were found between root gall severity and cantaloupe plant vigor ($y = -0.15x^2 + 1.02x + 6.3$; $r^2 = 0.53$, $P \leq 0.01$, whereby x = root gall index and y = plant vigor) and yield ($y = -0.25x^2 + 1.54x + 9.7$; $r^2 = 0.50$, $P \leq 0.01$, whereby x = root gall index and y = total number of marketable fruits). Several pests and diseases that were not controlled by fumigation (melon worm, downy mildew, and papaya ringspot virus) limited potential cantaloupe yields uniformly among treatments. Among the drip-fumigated treatments, the MS + 1,3-D combinations and the higher application rates of 1,3-D (+C) resulted in 20% to 35% higher yields than the lower application rates of 1,3-D (+C) and MS by itself (Fig. 1B). The lowest cantaloupe yields were in the NTC.

Experiment 2, 2003, eggplant followed by squash: Root-knot nematode soil populations were significantly reduced at planting and at eggplant harvest following fumigation (Table 3). Numerically, oxamyl reduced at-harvest soil populations of RKN following fumigation with C35 but not following MBR and NTC. Although gall indices at flowering and harvest of eggplant were low for all treatments, fumigation reduced nematode galling compared to the NTC without oxamyl at both stages (Table 4). Oxamyl reduced gall indices in the NTC at flowering but not at harvest. Other plant-parasitic nematodes, stubby, sting, and ring nematodes, were all reduced following fumigation at planting of eggplant but no longer at harvest (Table 3). Stubby root densities at harvest of eggplant were increased following oxamyl (Table 3). Plant vigor of eggplant was significantly improved following oxamyl up to 42 DAP (Table 4). No difference in shoot and root weight at 42 DAP was noted (data not shown). Greatest total marketable yield was recorded following fumigation with C35 and drip applications of oxamyl (Table 4). Oxamyl applications did not increase eggplant yield following methyl bromide but increased yield following C35 by 10% and following the NTC by 15%. Oxamyl applications increased yield over no oxamyl for the first three harvests ($P = 0.07$, data not given) but not for the fourth and final harvest.

High RKN population densities were noted at planting of the second crop (squash) in the NTC (Table 3). At-planting RKN soil populations were significantly reduced by MS and 1,3-D+C, as were populations of stubby root and ring nematodes (Table 3). Gall indices

TABLE 3. Effects of soil fumigation with and without oxamyl drip applications on populations of plant-parasitic nematodes on a first crop of eggplant (spring) and a second crop of squash (summer), Black Shank Farm, Tifton, GA, 2003.

Fumigant 1st crop[a]	Fumigant 2nd crop[a]	Oxamyl[b] (1st and 2nd crop)	Eggplant first crop: At planting RKN[c]	At planting SRN	At harvest RKN	At harvest SRN	Squash second crop: At planting RKN	At planting SRN	At harvest RKN	At harvest SRN
MBR	1,3-D+C	Yes	2 b	0 c	108 b	62 ab	0 b	8 ab	4 c	6 bc
MBR	1,3-D+C	No	0 b	0 c	52 b	54 b	6 b	10 ab	82 b	32 a
C35	1,3-D+C	Yes	3 b	0 c	13 b	144 a	0 b	2 b	16 bc	0 c
C35	1,3-D+C	No	0 b	0 c	108 b	34 b	1 b	6 ab	58 bc	14 abc
C35	MS	Yes	6 b	0 c	2 b	90 ab	6 b	8 ab	6 c	2 bc
C35	MS	No	0 c	0 c	54 b	58 ab	4 b	3 b	100 b	21 ab
NTC	1,3-D+C	Yes	66 a	9 b	3,118 a	46 b	6 b	2 b	78 b	4 bc
NTC	NTC	No	42 a	18 a	2,876 a	20 b	1,176 a	20 a	551 a	32 a
F probability fumigation			<0.01	0.04	<0.01	NS	<0.01	0.04	<0.01	NS
F probability oxamyl			—	—	NS	0.02	—	—	<0.01	<0.01

F probability fumigation x oxamyl was not significant.
[a] Fumigant treatments on the 1st crop were applied 28 March (MBR at 336 kg/ha; C35 at 168 l/ha); fumigant treatments on the 2nd crop were applied 24–25 July (1,3-D+C at 168 l/ha; MS at 468 l/ha).
[b] Oxamyl (as Vydate L) was applied at a rate of 0.77 liter/ha/application through the drip tape at planting (17 April) and 14 and 28 d afterwards on the 1st crop, and at planting (15 August) and 10 and 20 d afterwards on the 2nd crop.
[c] RKN = Root-knot nematode (*Meloidogyne* spp.); SRN = Stubby root nematode (Trichodoridae); numbers are per 150 cm^3 soil. Pre-fumigation nematode populations were on average 85 RKN and 23 SRN/150 cm^3 soil. Data are means of five replications. Means in the same column followed by the same letter are not different ($P = 0.05$) according to LSD test. NS = non-significant difference.

at flowering and harvest of squash were reduced by fumigation and by oxamyl ($P \leq 0.01$) (Fig. 2A). Although root galling on squash following fumigation with MS and 1,3-D+C was reduced compared to the NTC ($P \leq 0.01$), the reduction was not always consistent among plant replicates within a plot. Additional applications of oxamyl resulted in a more uniform reduction of galling over the entire plot. Root-knot nematode population densities at harvest of squash were still less ($P < 0.01$) in plots that were fumigated as well as in plots that received additional oxamyl (Table 3). Stubby root nematodes were not affected by fumigation but were reduced following additional oxamyl applications (Table 3). Squash plant vigor was improved by fumigation ($P < 0.01$) but not by oxamyl drip applications (data not shown). Low yields were recorded in the NTC (Fig. 2B). Squash yields in fumigated plots showed small differences between MS and 1,3-D+C. Oxamyl increased yields in fumigated plots by 30% following MS and by 35% to 75% following 1,3-D+C.

Experiment 3, 2004, tomato followed by squash/jalapeno pepper: At-planting nematode population densities were low (<10 RKN/150 cm^3 soil) for all treatments. Root-knot nematode levels showed a small increase in the NTC, but gall indices (GI) at flowering and harvest of tomato were low (GI < 1) for all treatments, including the NTC (data not shown). Stubby root nematode populations at harvest were lower following oxamyl ap-

TABLE 4. Effects of soil fumigation with and without oxamyl drip applications on root-knot nematode gall indices, plant vigor, and total marketable yield in a first crop of eggplant, spring 2003, Black Shank Farm, Tifton, GA.

Fumigant[a]	Rate (per ha)	Oxamyl[b]	Root gall index[c] (0–10) 45 DAP	80 DAP	Plant vigor[d] (1–10) 14 DAP	28 DAP	42 DAP	Marketable yield Number	Weight (kg)
MBR	336 kg	Yes	0 b	0.3 b	6.4 b	8.8 a	9.0 a	81 ab	66.8 b
MBR	336 kg	No	0 b	0.3 b	6.0 b	6.8 a	7.4 a	80 ab	68.6 ab
C35	168 l	Yes	0 b	0.0 b	6.6 b	7.6 a	8.6 a	97 a	84.1 a
C35	168 l	No	0 b	0.2 b	5.9 b	7.1 a	8.5 a	90 a	75.4 ab
NTC	—	Yes	0.3 b	2.5 a	8.1 a	8.5 a	9.1 a	85 ab	72.8 ab
NTC	—	No	0.9 a	2.6 a	6.3 b	6.6 a	7.8 a	69 b	61.6 b
F probability fumigation			<0.01	<0.01	0.07	NS	NS	0.02	0.02
Average oxamyl			0.3 b	0.9 a	7.0 a	8.3 a	8.9 a	88 a	74.6 a
Average no oxamyl			0.9 a	1.0 a	6.1 b	6.8 b	7.9 b	80 a	68.5 a
F probability oxamyl			0.06	NS	0.01	0.02	0.03	NS	NS

F probability fumigation x oxamyl was not significant.
[a] Fumigant treatments were applied 28 March.
[b] Oxamyl (as Vydate L) was applied at a rate of 0.77 liter/ha/application through the drip tape at planting (17 April) and 14 and 28 d afterwards.
[c] Root Gall Index 0-to-10 scale defined in Materials and Methods.
[d] Plant vigor ratings 1-to-10 scale with 10 = live and healthy plants and 1 = dead plants; Marketable yield is per 5-m bed length. Data are means of five replications. Means in the same column followed by the same letter are not different ($P = 0.05$) according to LSD test; no letters indicate non-significant difference; NS = not significant ($P > 0.10$).

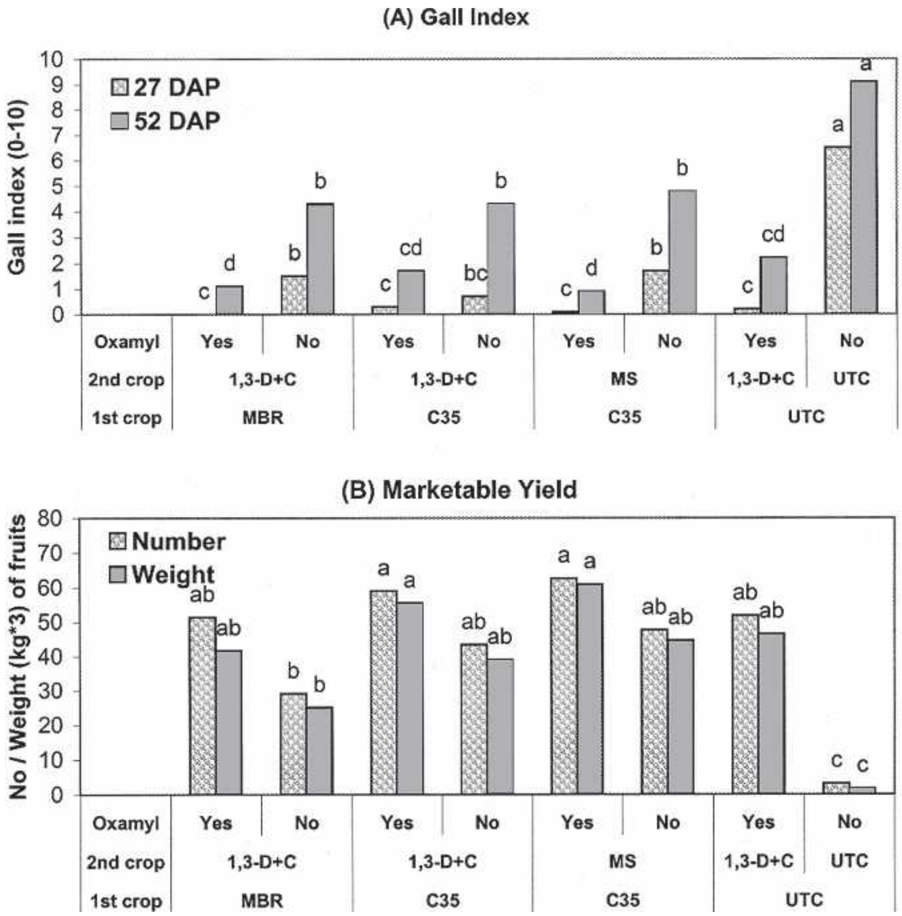

FIG. 2. Effects of soil fumigation with and without oxamyl drip applications on root-knot nematode gall indices (A) and total marketable yield (B) of double-cropped crookneck squash, fall 2003, Black Shank Farm, Tifton, GA. Bars within the same series having the same letter are not different ($P = 0.05$) according to LSD test.

plications (36 without vs. six nematodes with oxamyl, $P = 0.01$), irrespective of application rate and fumigant type. Tomato plant vigor was similar for all treatments (data not shown). Lowest total marketable tomato weight was observed in the NTC (Table 5), which was probably due to higher incidence of white mold (*Scle-*

TABLE 5. Effects of soil fumigation with and without oxamyl drip applications on total marketable yield of tomato (first crop, spring) and yield and gall index of crookneck squash and jalapeno (second crops, fall), 2004, Black Shank Farm, Tifton, GA.

			First crop		Second crops					
			Number	Weight (kg)	Number		Weight (kg)		Gall Index[c]	
Fumigants on 1st crop[a]	Fumigants on 2nd crop[a]	Oxamyl[b] l ha^{-1}	Tomato		Squash	Jalapeno	Squash	Jalapeno	Squash	Jalapeno
MBR	MS	0	435	94.0	31	121	5.99	1.894	0.1	0
MBR	MS	0.77	404	94.0	31	93	5.90	1.403	0.0	0
MBR	MS	1.54	417	99.4	31	95	4.90	1.518	0.1	0
MS + PIC	MS	0	476	104.0	26	88	4.63	1.205	0.1	0.2
MS + PIC	MS	0.77	393	93.1	28	93	5.45	1.217	0.1	0
MS + PIC	MS	1.54	420	99.9	29	77	5.27	1.115	0.0	0
NTC	MS	0	389	86.8	26	82	4.36	1.177	1.2	0.7
NTC	NTC	0	380	86.3	28	111	4.99	1.626	1.7	1.4
F probability fumigation 1st crop			NS	NS	NS	NS	NS	0.05	—	
F probability fumigation 2nd crop			—	—	NS	NS	NS	NS	<0.01	<0.01
F probability oxamyl			0.08	NS	NS	NS	NS	NS	NS	NS

[a] Fumigant treatments on the 1st crop were applied on 1 March; fumigant treatments on the 2nd crop were applied on 24 and 25 July.
[b] Oxamyl (as Vydate L) was applied through the drip tape at planting (26 March) and 2 and 4 wk afterwards (1st crop) and at planting (18 August) and 10 and 20 d afterwards (2nd crop).
[c] Root Gall Index 0-to-10 scale defined in Materials and Methods.
Marketable yield is per 5-m bed length (1st crop) and per 3-m bed length (2nd crops).
Data are means of five replications. Means in the same column followed by the same letter are not different ($P = 0.05$) according to LSD test. NS = non-significant difference.

rotium rolfsii) in the nonfumigated plots. Marketable number of tomato fruits were reduced (P = 0.08) by increasing oxamyl application rate.

At planting of the second crops, root-knot, stubby root, ring, and spiral nematode population densities were low and reduced following fumigation with metam sodium (data not shown). Limited buildup of RKN was noted throughout the second season, and RKN soil populations remained low at harvest of squash and were somewhat greater at harvest of jalapeno pepper in the NTC (142 RKN/150 cm^3 soil). Gall indices, though low throughout the test, were significantly reduced by fumigation (Table 5). Stubby root nematode densities at harvest were reduced by oxamyl on squash but not on jalapeno pepper (data not given). As a second crop, squash or jalapeno pepper yields were not affected by any treatment, but greater jalapeno pepper yield weight was noted when the first crop was fumigated with MBR as compared to MS + PIC (Table 5).

Discussion

Root-knot nematode damage on first crops in spring was low and yield losses were small. Root-knot nematodes often cause only limited damage on first crops in spring, due to low initial nematode populations and relatively cool soils early in the season. However, high nematode densities were found toward the end of the spring season on crops that were not fumigated. Both chisel-applied fumigants MBR and C35 provided similar nematode control on a first crop of eggplant in spring 2003. The efficacy of MBR and MS+PIC in spring 2004 is not known as RKN failed to increase that year. This was surprising as pre-fumigation nematode levels were similar to those of 2003. Possibly, the high levels (on average 80 nematodes/150 cm^3 soil) of mononchid (predatory) nematodes that were noted in this test and/or other bio-control mechanisms that were not quantified may have been responsible. In pot experiments, increasing populations of the predatory nematode *Mononchoides striatus* were found to reduce RKN damage on tomato (Khan and Park, 2004).

Double-cropped vegetables in summer suffered much greater damage from RKN due to increased populations resulting from the first crop, especially when the first crop was not fumigated. Also, higher soil temperatures in summer when the second crop was grown (on average 27°C, as opposed to 16-24°C in early-to-late spring) would have resulted in shorter RKN life cycles and increased nematode damage. The life cycle of *M. incognita* on tomato takes 63 d at 16°C and only 20 d at 30°C (Ploeg and Maris, 1999). Root-knot nematodes were the major yield-limiting factor on double-cropped vegetables, and when plots were not fumigated, plants were severely stunted and almost total yield loss occurred. Relative to the NTC, drip-applied soil fumigants, even at low application rates, resulted in good control of RKN on double-cropped vegetables. However, increasing fumigant application rates, combining different fumigants (MS + 1,3-D), or having additional applications at- and post-plant of oxamyl improved nematode control and increased crop yields. Treatment efficacy on the second crop, in terms of nematode control and crop yield, was not affected by the fumigant that was used on the first crop.

Additional applications at- and post-plant of oxamyl were more effective on the second crop than on the first crop in 2003, with spring (eggplant) yield increase ranging from 10% to 15%, and fall (squash) yield increase ranging from 30% to 75%. The yield increases on first crops are similar to what we observed in previous spring trials (Desaeger et al., 2004a). The larger yield increases due to oxamyl on second crops can be explained by the greater nematode pressure on these crops, hence more scope for additional nematode control and yield increase. Also, soil fumigation is probably less effective on second crops as compared to first crops, because (i) shank injection (using two injection points) on first crops is expected to give a more uniform fumigant distribution as compared to drip injection (using one injection point) on second crops; (ii) old beds are more compacted, resulting in less uniform water (and chemical) movement as compared to new beds; and (iii) due to buildup on the previous crop, old beds not only have greater actual nematode soil populations but decomposing nematode-infected roots from the first crop also provide a long-term nematode inoculum source for the second crops. Fumigants, such as metam sodium and 1,3-D, are not very volatile and therefore not as effective in penetrating roots as methyl bromide (McKenry, 1987). Also, fumigant volatilization losses are greater on second crops, due to planting holes from the first crop and higher temperatures at the time of fumigation. Under these conditions, additional nematicide applications at- and post-plant are likely to significantly improve nematode control. Although in sandy soils in the southeastern US lateral movement of water is difficult to achieve with drip irrigation systems having 90% or more sand (Csinos et al., 2002), fumigation applications through the drip irrigation system for loamy sand do not necessarily pose as much of a challenge, as the technique has shown equally good control of nematodes as chisel-injected applications when done on a first crop (Desaeger et al., 2004a, 2004b). However, drip-applied 1,3-D did seem to increase the risk of phytotoxicity and required longer plant-back times in spring (Desaeger and Csinos, 2005).

Oxamyl did not improve vegetable yields when RKN was not a significant pest factor, as was the case in 2004. Without nematode pressure, oxamyl applications tended to decrease tomato yields. The major benefit of oxamyl appears to derive from additional RKN control after fumigation. It also seems to contradict the so-called "carbamate kick" theory, in which a growth-stimulating response irrespective of pest control is sometimes ascribed to carbamate chemicals such as aldicarb and oxamyl (Rethwisch and Kruse, 1998).

Low populations of *Paratrichodorus* spp., *Belonolaimus longicaudatus*, *Mesocriconema* spp., and *Helicotylenchus* spp. contributed little to overall crop damage or yield differences. Even stubby root nematodes, which were recovered at higher levels, did not appear to compromise yield. Fumigation effects were similar for all nematode species, with reduced populations at plant and increased at final crop harvest. At-harvest populations of stubby root nematodes, however, were decreased following oxamyl applications in three out of four tests, as opposed to only one out of four tests in the case of RKN. Thus, oxamyl may provide more consistent control of stubby root but not RKN. It is not clear why in spring 2003 plots with oxamyl applications had increased numbers of stubby root nematodes. As C35 and oxamyl also resulted in the greatest yields, this may have been largely due to the greater abundance of nematode feeding sites in these plots.

These studies clearly showed that RKN can cause extensive damage to double-cropped vegetables. High residual nematode populations from the first crop, combined with limited nematode control options and beds that are more difficult to fumigate, all provide conditions conducive for severe crop losses. Although residual populations from the first crop could be reduced by planting a RKN-resistant tomato or pepper cultivar in spring (Thies et al., 2004), these cultivars do not possess resistance to tomato spotted wilt virus. This would most likely limit adoption of nematode-resistant cultivars in large parts of the southeastern US. Therefore, nematode control on second crops, at least in the short term, will largely depend on the use of chemicals. The available array of nematicides in double-cropped vegetables is limited, consisting of only three registered pre-plant soil fumigants (metam sodium, 1,3-D, and chloropicrin) and even fewer post-plant nematicides (e.g., oxamyl) in the United States. None of these products alone will provide adequate nematode control on double-cropped vegetables under the conditions of this test and combinations of fumigants and/or of a fumigant + nematicide seem to be necessary to avoid yield losses.

Literature Cited

Ajwa, H. A., Trout, T., Mueller, J., Wilhelm, S., Nelson, S. D., Soppe, D., and Shatley, D. 2002. Application of alternative fumigants through drip irrigation systems. Phytopathology 92:1349–1355.

Anonymous. 1992. Methyl bromide: Its atmospheric science, technology, and economics. Synthesis report. United Nations Environment Programme, Methyl bromide interim scientific and technology and economic assessment. June 1992, Nairobi, Kenya.

Anonymous. 2005. 2005 Georgia pest management handbook. Special bulletin 28. Cooperative Extension Service, The University of Georgia, College of Agricultural and Environmental Sciences. http://www.pubs.caes.uga.edu/caespubs/PM-Handbook.htm

Brady, N. C. 1974. The nature and properties of soils. New York: MacMillan.

Camp, C. R. 1998. Subsurface drip irrigation: A review. Transactions of the American Society of Agricultural Engineers 41:1353–1367.

Csinos, A. S, Laska, J. E., and Childers, S. 2002. Dye injection for predicting pesticide movement in micro-irrigated polyethylene film mulch beds. Pest Management Science 58:381–384.

Csinos, A. S., Sumner, D. R., Johnson, W. C., Johnson, A. W., McPherson, R. M., and Dowler, C. C. 2000. Methyl bromide alternatives in tobacco, tomato, and pepper transplant production. Crop Protection 19:39–49.

Desaeger, J. A., and Csinos, A. S. 2005. Phytotoxicity associated with drip-applied 1,3-dichloropropene and chloropicrin in vegetables produced with plastic mulch. HortScience 40:700–707.

Desaeger, J., Csinos, A., Timper, P., Hammes, G., Seebold, K. 2004a. Soil fumigation and oxamyl drip applications for nematode and insect control in vegetable plasticulture. Annals of Applied Biology 145:59–70.

Desaeger, J., Eger, J., Csinos, A., Gilreath, J. P., Olson, S. M., and Webster, T. M. 2004b. Movement and biological activity of drip-applied 1,3-dichloropropene in raised beds in the southeastern U.S. Pest Management Science 60:1220–1230.

Jenkins, W. R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.

Khan, Z., and Park, S. D. 2004. Efficacy of a predatory nematode, *Mononchoides striatus* (Diplogasterida: Neodiplogasteridae), against *Meloidogyne incognita* on tomato. European Society of Nematologists, XXVII ESN International Symposium, Rome, Italy, 14–18 June 2004 (Abstr.).

McKenry, M. V. 1987. Control strategies in high-value crops. Pp. 329–349 *in* R. H. Brown and B. R. Kerry, eds. Principles and practice of nematode control in crops. New York: Academic Press.

Ploeg, A. T., and Maris, P. C. 1999. Effects of temperature on the duration of the life cycle of a *Meloidogyne incognita* population. Nematology 1:389–393.

Rethwisch, M. D., and Kruse, M. 1998. Effect of late winter 1998 Furadan 4F alfalfa stubble treatment on alfalfa growth and alfalfa weevil, aphid, and three cornered alfalfa hopper populations. University of Arizona College of Agriculture 1999 Forage and Grain Report. http://ag.arizona.edu/pubs/crops/azl147/

Thies, J. A., Davis, R. F., Mueller, J. D., Fery, R. L., Langston, D. B., and Miller, G. 2004. Double-cropping cucumbers and squash after resistant bell pepper for root-knot nematode management. Plant Disease 88:589–593.

Zeck, W. M. 1971. A rating scheme for field evaluation of root-knot infestations. Pflanzenschutz Nachrichten Bayer AG 24:141–144.