Journal of Nematology 38(4):483–490. 2006.

Damage and Management of *Meloidogyne hapla* Using Oxamyl on Carrot in New York

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Abstract: The northern root-knot nematode (*Meloidogyne hapla*) is a major pathogen of processing carrot in New York, significantly reducing marketable yield and profitability. Severely infected carrots are stubby, galled and forked and therefore unmarketable. In field microplot trials in 1996 and 1998, the incidence and severity of root-galling increased and the marketable yield of carrot decreased as the initial inoculum density of *M. hapla* was increased from 0 to 8 eggs/cm^3 soil, in mineral or organic soils. The application of oxamyl at planting was effective against *M. hapla* and its damage to carrots grown in mineral and organic soils. Oxamyl application reduced root-galling severity and increased marketable yield. In commercial fields, the cost-effectiveness of oxamyl application was related to the level of soil infestation with *M. hapla*.
Key words: carrot, cost-benefit analysis, *Daucas carota*, economic threshold, *Meloidogyne hapla*, management, northern root-knot nematode, oxamyl, plant disease loss, yield loss.

Root-knot nematodes (*Meloidogyne* spp.) are major pathogens of carrot (*Daucus carota* L. var. *sativus* Hoffm.) in all production regions of the US and the world, impacting both the quantity and quality of marketable carrot yield (Sasser and Carter, 1985). To date, the northern root-knot nematode (*Meloidogyne hapla* Chitwood) is the only species that infects carrot as well as other vegetables grown on organic and mineral soils in New York (Mitkowski et al., 2002), the northeastern US, and Canada (Belair, 1992). Severe infections and damage to carrot and also onion and lettuce by *M. hapla* have occurred more frequently in recent years, especially in organic soils (Abawi and Laird, 1994; Viaene and Abawi, 1996; Abawi et al., 1997).

Symptom severity depends on the ontogeny of the plant. On mature carrot, infection by *M. hapla* initially causes small galls to develop on secondary roots. If galling occurs during the seedling stages, the carrot roots can become severely stunted and forked and therefore unmarketable. In greenhouse tests, the adverse effects of *M. hapla* on growth parameters of carrot were detectable as early as four days after seeding and resulted in only 58% of the roots being considered marketable (Slinger and Bird, 1978). However, a limited degree of stunting and forking can be tolerated on processing cultivars, since large, forked carrot roots can be trimmed into sections that can be processed further. Nevertheless, truckloads that contain 21% or more total culls are commonly rejected (Abawi, personal comm.); thus, nematode damage can lead to great economic losses. Shoot growth in a heavily infested field is often patchy and uneven due to the clustered distribution of *M. hapla* in the soil (Noe and Campbell, 1985; Widmer et al., 1999).

Chemical nematicides and crop rotation are the primary means of management of *M. hapla* on carrot, since only a few *M. hapla*-resistant germplasm lines have been identified (Vrain and Baker, 1980; Yarger and Baker, 1981a, 1981b; Belair, 1984b), and none of the processing cultivars currently grown in New York have been found to be resistant to *M. hapla* (Gugino et al., 2006). However, resistance to *M. incognita* and *M. javanica* has been identified and, in the case of resistance to *M. javanica*, was reported to be simply inherited and controlled by one or two dominant loci (Boiteux et al., 2000; Simon et al., 2000). Fumigant-type nematicides are highly effective but these chemicals are extremely toxic to non-target organisms and are used at high rates, so there is considerable concern regarding their effect on human safety and potential negative environmental impact. They are also costly and increase production costs, especially when applied unnecessarily. Oxamyl, a carbamate, is the only nonfumigant registered in New York and is the chemical most commonly applied for nematode management. Although fumigant nematicides such as 1,3-dichloropropene are registered for use on carrot in the US, they are rarely used in New York. Rotation to a nonhost or antagonistic crop is also an effective management strategy against *M. hapla* (Viaene and Abawi, 1998; Widmer and Abawi, 2000). However, current crop rotations commonly practiced by New York vegetable growers, especially on organic soils, are generally not effective, since many of the crops grown in vegetable rotations (such as onion, lettuce, potato and snap bean) are susceptible.

Several studies have investigated the damage threshold levels and various aspects of the biology of *M. hapla* on lettuce, onion and other vegetables (Olthof and Potter, 1972; Wong and Mai, 1973; Potter and Olthof, 1974; Starr and Mai, 1976; Abawi and Robinson, 1991; Viaene and Abawi, 1996). A significant positive correlation was reported between marketable yield losses of carrot and root-galling severity caused by *M. hapla* in microplots and commercial fields in Quebec, Canada. In addition, a close correlation was found between the previous and current season root-galling severity using a sequential sampling plan (Belair and Boivin, 1988). Another study in Vancouver, Canada, concluded that

Received for publication July 13, 2006.
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This project was funded in part by a NE PIAP grant (USDA-TPSU-CU-8103-1).
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This paper was edited by James LaMondia.

there was a significant negative correlation between weight of carrot roots and the initial soil population of *M. hapla* (Vrain, 1982). Although *M. hapla* is a known pathogen on carrot in New York, the incidence and severity of this nematode on carrot in New York has not been previously documented, nor have density thresholds been estimated to potentially aid in making management decisions on organic and mineral soils. Oxamyl is often applied by growers to manage *M. hapla*, but the cost-effectiveness of its application in relation to the soil nematode population also has not been documented.

To address these issues, a series of studies was conducted to: (1) estimate damage threshold densities for *M. hapla* on carrot in organic and mineral soils in New York; and (2) assess the cost benefit of oxamyl applications in commercial carrot fields for the management of *M. hapla*. A preliminary report has been previously published (Abawi et al., 1997).

Materials and Methods

Relationship between M. hapla infestation level and marketable yield—microplot trials: In 1996, 80 1.2-m-diam. microplots were established at the Vegetable Research Farm, NYSAES, Geneva, NY, using fiberglass cylinders. The cylinders were buried approximately 25-cm deep, leaving 5 cm above ground (Crosier and Abawi, 1985). The microplots were arranged 1 m apart within rows and 1.5 m apart between rows. Forty microplots contained native mineral soil (Honeoye silt loam), and 40 were filled with approximately 170 liters of organic soil (> 80% organic matter). The organic soil was obtained from the wooded border of an organic field that never previously had been in crop production. In 1996 and 1998, the microplots were infested with four initial *M. hapla* population densities of 0, 1, 2 or 8 eggs/cm^3 soil on 12 June and 20 May, respectively. Prior to infesting with *M. hapla* in 1998, all the microplots were fumigated with methyl bromide (Brom-O-Gas, Great Lakes Chemical Corp., West Lafayette, IN; 483.5 kg/ha containing 98% methyl bromide and 2% chloropicrin) to eliminate any nematodes that might have survived from previous nematode infestations. The microplot area was covered with a 6-mil clear plastic tarp and then fumigated with methyl bromide. The tarp was removed after 5 to 7 d, and the soil surface scratched with a rake and left to aerate for 7 to 10 d. Egg inoculum of *M. hapla* was propagated on and extracted from the roots of tomato cultivar 'Rutgers' grown in the greenhouse in soil infested with an isolate of *M. hapla* obtained from naturally infected lettuce from Oswego, NY. The roots were placed in 250-ml flasks, covered with 19% commercial bleach (1.14% NaOCl) and vigorously shaken for 3.5 min to release eggs from the gelatinous egg masses. The eggs were collected on a 500-µm-pore sieve and washed free of chlorine. The eggs were mixed with 4 liters of water and uniformly distributed on the soil surface then immediately incorporated into the top 10 cm of soil. Half of the microplots for each nematode density (5 microplots/nematode density/soil type) were then broadcast-treated with a recommended label rate of oxamyl (Vydate L, DuPont Crop Protection, Wilmington, DE; 18.7 liter/ha containing 0.24 kg a.i./liter), which was then incorporated into the top 10 cm of the soil. All the microplots were planted with three rows of carrot seed cultivar Oranza (66 seeds/m), with 30 cm between rows for a total of 3.3 m of row/microplot. Within each soil type, eight treatments were arranged in a randomized complete block design with five replicates. The plots were maintained according to New York State commercial production guidelines. Soil temperatures in the top 10 cm of soil ranged between an average minimum of 17.8°C and maximum of 27.5°C in 1996 and between 14.4°C and 26.7°C in 1998 during the 2 wk following infestation. Yield data were collected on 11 October 1996 and 6 October 1998. Total plant weight and root weight were recorded for 1.22 m of row /microplot, and roots were then washed and rated for marketability using a scale of 1 to 6: 1 = no lateral protrusions, galls or stunting (healthy root); 2 = 1 or 2 small lateral protrusions and a few galls; 3 = 2 or 3 lateral protrusions; 4 = taproot with three or more lateral protrusions, moderate stunting and galls; 5 = taproot with several lateral protrusions several cm long; and 6 = taproot severely forked, stunted and over 100 galls mostly coalesced (modified Belair and Boivin, 1988). Roots with root-galling severity ratings of 1 to 3 are considered marketable, while those rated 4 to 6 are unmarketable.

Determining the damage threshold densities for M. hapla on carrot: In order to estimate the damage threshold densities, the carrot yield responses to the initial inoculum densities in the microplot trials in 1996 and 1998 were fit to the Seinhorst model using the computer program SeinFit, based on the algorithm developed by Ferris et al. (1981) for calculating the best-fitting Seinhorst equation (Viaene et al., 1997). The best-fitting Seinhorst equation was determined using the grid method which calculates the optimum value for each factor in the equation in order to return the smallest residual sum of squares. The model is of the form: $y = y_m$, for $x \leq t$, $y = y_m \cdot m\ (1 - m) \cdot z^{(x-t)}$, for $x > t$, where: y = crop yield; x = the nematode population density; t = the nematode population density below which yield reduction cannot be measured; y_m = mean crop yield where the nematode density is below the tolerance limit (t); m = a constant; and z = the slope-determining parameter (Viaene et al., 1997).

Relationship between M. hapla population and marketable yield—field trials: In 1996, field trials were established in four commercial production fields with varying histories of *M. hapla* damage on vegetable crops. At each site, three to six nontreated plots (at least four rows wide depending on planter width and 6.1 m long) were established in each field. The number of replications varied depending on the collaborating grower. The remainder of the field was treated with a commercially labeled rate of oxamyl (Vydate L, DuPont Crop Protection, Wilmington, DE; 14.0 or 18.7 liter/ha containing 0.24 kg a.i./liter) as an in-furrow drench at planting. All other cultural practices for field preparation, planting and pesticide applications were made by the collaborating grower according to the New York State commercial production recommendations. The incidence and severity of *M. hapla* infections on the roots were recorded, and total and marketable yield determined between 23 and 26 September 1996.

In 1997, four fields were again selected to compare the effect of oxamyl applications on the *M. hapla* population and marketable yield of carrot. In two of the four fields, several methods of oxamyl application (in-furrow drench, broadcast, and broadcast plus in-furrow drench) were also compared to a nontreated control. In-furrow drench applications were made at planting, while broadcast applications were made concurrently with the first herbicide application. Due to nematicide application constraints, treatment strips consisting of four to eight rows (or multiples of these depending on the width of the planter) were established in each field, and then four replicate plots were established per treatment band across each field. Yield data and carrot marketability were determined on 9 September 1997 as described previously.

Cost-benefit analysis of field trials in 1996 and 1997: The cost benefit of oxamyl application to manage *M. hapla* infestations in the eight commercial production field trials conducted in 1996 and 1997 was determined using the marketable yield in the nontreated and treated plots at an estimated value of \$60/ton (1996 and 1997 estimate) and cost of oxamyl at \$14.53/liter in 1996 and 1997.

Statistical analysis: Carrot microplot yield data collected in 1996 and 1998 were analyzed using an analysis of variance test with means separated using Fisher's protected least significant difference (LSD) test (SAS 9.0, SAS Institute, Cary, NC). The yield data collected from the commercial grower field plots and the cost-benefit analysis conducted based on that yield data were analyzed using an analysis of variance test with means separated using either a two-sided *t*-test or Fisher's protected least significant difference (LSD) test (SAS 9.0, SAS Institute, Cary, NC).

Results

Relationship between M. hapla infestation level and marketable yield—microplot trials: Very low naturally occurring *M. hapla* populations were observed in the non-infested plots (0 eggs/cm^3 soil). In 1996, only 9.2% and 4.0% of the roots were infected in the non-infested organic and mineral soils, respectively, and even fewer in 1998 after the methyl bromide treatment in spring, only 1.4% of the roots in both soil types (Table 1). The data in 1996 and 1998 showed that as the initial inoculum density of *M. hapla* increased from 0 to 8 eggs/cm^3 soil, the incidence (percent of roots infected) and the severity of root-galling increased while the marketable yield of carrot decreased in both the nontreated mineral and organic soils (Table 1). In addition, the data in 1996 also suggested that the damage of *M. hapla* to carrot was greater in the mineral soil than in the organic soil. In organic soil, marketable yield of carrot was reduced by approximately 13%, 27% and 53% by *M. hapla* at initial densities of 1, 2 and 8 eggs/cm^3 soil, respectively, while these same initial inoculum densities in mineral soil caused approximately 26%, 68% and 77% reduction in marketable yield, respectively. Similar results were obtained in 1998, but differences in marketable yield among the initial inoculum densities were smaller (Table 1). Although the percent infected roots was higher at all initial inoculum levels in 1998 as compared to those observed in 1996 in the non-oxamyl treated microplots, the average root-galling severity rating of the symptomatic roots was lower and resulted generally in higher percent of marketable yield of carrot.

Increasing the initial inoculum density of *M. hapla* did not significantly reduce seedling emergence or stand establishment in the organic or mineral soils (data not shown). In these trials, the application of oxamyl, regardless of the infestation level and year, was effective in managing *M. hapla* damage on carrot in both soil types, as indicated by increased marketable yield and the observed reduction in the percent infected roots and severity of root-galling of infected roots (Table 1). Not surprisingly, the lowest marketable carrot yields among the oxamyl treated plots were obtained in those infested with the highest initial population density of *M. hapla* (8 eggs/cm^3 soil).

Determining the damage threshold densities for M. hapla on carrot: The relationship between carrot yield and the initial population density of *M. hapla* in the field microplots in 1996 and 1998 was calculated using the Seinhorst equation. The model indicated a modest fit of the yield data from the nontreated plots to the equation for the organic (r^2 = 0.54 and 0.83 in 1996 and 1998, respectively) and mineral (r^2 = 0.90 and 0.59, in 1996 and 1998, respectively) soils. The estimated nematode threshold densities of *M. hapla* to carrot grown in the nontreated organic and mineral soils in 1996 were 70 and 60 eggs/100 cm^3 soil, while in 1998 the thresholds were 15 and 190 eggs/100 cm^3 soil (Table 2). The estimated minimum yield (m) values were higher in the organic soil (0.4 in both 1996 and 1998) compared to those in the mineral soil (0.20 and 0.05 in 1996 and 1998, respectively). The latter indicated that the carrot cultivar 'Oranza' had a higher tolerance for *M. hapla*

TABLE 1. The effect of different initial *Meloidogyne hapla* infestation densities and the application of oxamyl on infection severity and marketable yield of carrot grown in microplots containing either mineral or organic soil in 1996 and 1998.

Year	Treatment[a]	Marketable yield		Roots infected (%)	Root-galling severity[c]	
		kg/1.2 m	Percent		Overall average	Average of infected
1996	Organic soil					
	0 eggs/cm^3	3.5 a[b]	98.8 a	9.2 a	1.2 a	2.7 ab
	1 egg/cm^3	3.0 ab	85.7 b	44.5 b	2.0 b	3.1 bc
	2 eggs/cm^3	2.0 bc	71.4 c	70.3 c	2.7 c	3.4 cd
	8 eggs/cm^3	1.4 c	46.2 d	87.2 d	3.5 d	3.9 d
	0 eggs/cm^3 + oxamyl	3.6 a	99.8 a	8.4 a	1.1 a	2.7 ab
	1 egg/cm^3 + oxamyl	3.3 a	97.4 a	13.4 a	1.3 a	2.9 abc
	2 eggs/cm^3 + oxamyl	3.8 a	98.2 a	10.9 a	1.2 a	2.5 a
	8 eggs/cm^3 + oxamyl	3.1 ab	95.6 ab	18.5 a	1.3 a	2.7 ab
	P	0.0060	<0.0001	<0.0001	<0.0001	0.0001
1996	Mineral soil					
	0 eggs/cm^3	4.2 b	100.0 a	4.0 a	1.1 a	1.9 a
	1 egg/cm^3	3.2 c	74.0 b	62.9 b	2.4 b	3.2 c
	2 eggs/cm^3	1.8 d	42.3 c	87.8 c	3.7 c	4.0 d
	8 eggs/cm^3	0.8 e	22.5 d	99.0 d	4.1 d	4.1 d
	0 eggs/cm^3 + oxamyl	4.8 ab	99.6 a	10.3 a	1.1 a	2.4 ab
	1 egg/cm^3 + oxamyl	4.1 b	98.4 a	9.7 a	1.2 a	3.2 c
	2 eggs/cm^3 + oxamyl	5.1 a	98.7 a	9.7 a	1.2 a	3.0 bc
	8 eggs/cm^3 + oxamyl	3.9 bc	98.9 a	11.2 a	1.2 a	2.4 ab
	P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
1998	Organic soil					
	0 eggs/cm^3	5.1 a	100.0 a	1.4 a	1.0 a	1.8 ab
	1 egg/cm^3	4.4 ab	94.8 b	69.0 c	2.0 c	2.4 b
	2 eggs/cm^3	3.8 b	88.4 c	90.9 d	2.5 d	2.7 bc
	8 eggs/cm^3	2.4 c	53.6 d	99.4 d	3.5 e	3.5 c
	0 eggs/cm^3 + oxamyl	5.0 a	100.0 a	1.0 a	1.0 a	1.4 a
	1 egg/cm^3 + oxamyl	5.0 a	99.8 a	5.4 a	1.1 b	2.2 ab
	2 eggs/cm^3 + oxamyl	5.3 a	100.0 a	2.4 a	1.0 a	1.8 ab
	8 eggs/cm^3 + oxamyl	5.1 a	99.8 a	20.4 b	1.2 b	2.1 ab
	P	<0.0001	<0.0001	<0.0001	<0.0001	0.0055
1998	Mineral soil					
	0 eggs/cm^3	5.1 a	99.8 a	1.4 a	1.0 a	1.9 a
	1 egg/cm^3	4.9 a	99.2 ab	67.4 c	1.9 b	2.3 a
	2 eggs/cm^3	4.9 a	90.6 b	83.8 d	2.3 c	2.5 ab
	8 eggs/cm^3	2.7 b	62.2 c	98.2 d	3.3 d	3.3 b
	0 eggs/cm^3 + oxamyl	5.2 a	100.0 a	2.4 a	1.0 a	1.7 a
	1 egg/cm^3 + oxamyl	5.8 a	100.0 a	5.4 a	1.1 a	1.9 a
	2 eggs/cm^3 + oxamyl	5.6 a	100.0 a	2.6 a	1.0 a	1.8 a
	8 eggs/cm^3 + oxamyl	5.3 a	100.0 a	27.2 b	1.3 a	2.1 a
	P	0.0001	<0.0001	<0.0001	<0.0001	0.0241

[a] Oxamyl was broadcast and then incorporated at a label recommended rate (18.7 liter/ha containing 0.24 kg a.i./liter) following infestation of the microplot soils with *M. hapla* eggs.

[b] Data are the means of five replicates. Means with the same letter within each column, year and soil type are not different according to Fisher's least significant difference test (LSD). *P*-values are reported.

[c] Root-galling severity was rated on a scale of 1 (no galls) to 6 (severely forked, stunted and galled roots). Carrot roots with a rating of 1 to 3 were considered marketable, while those with a rating of 4 to 6 were considered unmarketable. Overall average root-galling severity includes all the carrot roots harvested, while the average of the infected includes only the roots rated a 2 or higher on the root-galling severity scale.

infection in organic soil than when grown in the mineral soil. The application of oxamyl reduced marketable yield differentials between the treatments with different initial infestation densities, resulting in higher estimated minimum yield (m) values and insignificant r^2 values (Table 2).

Relationship between M. hapla population and marketable yield—commercial field trials: The soil in the eight commercial carrot fields evaluated in 1996 and 1997 was infested with varying levels of *M. hapla* (Table 3). Thus, the percentage of infected roots in these fields ranged from 9.8 to 100%. However, the percentage of marketable yield in the nontreated plots varied between 56.9 and 99.5%. Not surprisingly, the two fields with the lowest root-galling severity ratings (Table 3; Fields 5 and 8) had the highest percentage of marketable yield.

In the heavily infested fields, the application of the chemical nematicide oxamyl resulted in a reduction in the incidence and overall severity of *M. hapla* infections on the roots and increased both the weight and percent marketable yield of carrot. In general, the higher the incidence of *M. hapla* infection (percent roots infected) in the nontreated plots, the greater the increase in the percent marketable yield in the oxamyl-treated compared to the nontreated plots. For example, in 1996, 17.9%, 52.6%, 69.9% and 82.1% of the roots were in-

TABLE 2. Parameter estimates of the Seinhorst equation relating yield and initial *Meloidogyne hapla* infestation levels on carrot grown in field microplots containing either mineral or organic soil in 1996 and 1998.

Year	Soil type	Treatnent[a]	Parameters[b] y_m	m	z	t	r^2
1996	Organic	Nontreated	3.48	0.40	0.40	0.70	0.54
		Treated	3.57	0.85	0.55	4.30	0.04
	Mineral	Nontreated	4.22	0.20	0.40	0.60	0.90
		Treated	4.65	0.55	0.90	4.00	0.13
1998	Organic	Nontreated	5.09	0.40	0.75	0.15	0.83
		Treated	5.09	0.95	0.30	8.00	−0.00
	Mineral	Nontreated	4.99	0.05	0.90	1.90	0.59
		Treated	5.56	0.70	0.90	6.50	0.02

[a] Oxamyl (18.7 liter/ha) was broadcast and then incorporated in the treated microplots following soil infestation with *M. hapla*.

[b] The Seinhorst equation is in the form: $y = y_m$, for $x \leq$ t, $y = y_m \cdot$ m (1 − m) $\cdot$ z$^{(x-t)}$, for $x >$ t, where: y = crop yield; x = the nematode population density; t = the nematode population density below which yield reduction cannot be measured; y_m = mean crop yield where the nematode density is below the tolerance limit (t); m = a constant so that $y_m \cdot$ m equals the miminum yield; and z = the parameter determining the slope of the curve. Nematode densities are in nematodes/cm^3 of soil.

fected in fields 4, 1, 2 and 3, respectively, and the percent increase in percent marketable yield was 0.9%, 7.3%, 10.6% and 21.6%, respectively. However, these differences varied from field to field and in most cases were not statistically significant due to the small area harvested per replicate and the variability in *M. hapla* distribution within each field. All application methods of oxamyl (in-furrow drench, broadcast incorporated or their combination) significantly increased the percent marketable yield and decreased the root-galling severity ratings of infected roots. However, the broadcast application of oxamyl was more effective in reducing the incidence of infected roots and increasing marketable yield as compared to the in-furrow drench applications.

Cost-benefit analysis of field trials in 1996 and 1997: The cost benefit of oxamyl application was determined for each commercial field assessed in 1996 and 1997 using a crop value of \$60/ton of carrot and nematicide cost of \$14.53/liter (1996/1997 price) (Table 4). Labor

TABLE 3. The incidence and severity of *Meloidogyne hapla* infections and the effect of the application of oxamyl at planting on selected yield parameters of carrot in eight commercial fields in 1996 and 1997.

Year	Site[a]	Treatment[b]	Marketable yield[d] kg/3 m	Percent	Roots infected (%)	Root-galling severity[e] Overall average	Ave. of infected
1996	Field 1	Nontreated	14.7[c]	86.2	52.6	1.9	2.7
		Oxamyl	14.7	93.5	30.0	1.5	2.6
		P	0.1562	0.2964	0.0861	0.0962	0.9098
	Field 2	Nontreated	7.9	72.4	69.9	2.1	3.1
		Oxamyl	9.4	83.0	49.4	1.7	3.1
		P	0.8640	0.6144	0.5014	0.5154	0.8504
	Field 3	Nontreated	6.0	64.4	82.1	2.9	3.3
		Oxamyl	9.2	86.0	50.6	2.0	2.9
		P	0.4947	0.1153	0.0766	0.1054	0.2604
	Field 4	Nontreated	14.7	95.7	17.9	2.9	2.9
		Oxamyl	16.4	96.6	12.7	2.8	3.1
		P	0.1273	0.6751	0.4502	0.5395	0.8367
1997	Field 5	Nontreated	17.2	93.9	30.6	1.6	0.9
		Oxamyl	15.9	92.9	24.9	1.5	0.7
		P	0.1909	0.6930	0.4984	0.6204	0.6204
	Field 6	Nontreated	6.0 a	56.9 c	100.0 a	3.8 a	3.8 a
		Oxamyl (drch)	10.5 a	81.2 b	100.0 a	2.9 b	2.9 b
		Oxamyl (broadcast)	13.1 a	99.7 a	15.0 b	1.2 c	2.4 c
		Oxamyl (brd + drch)	12.4 a	99.6 a	41.8 c	1.4 c	2.1 d
		P	0.1138	<0.0001	<0.0001	<0.0001	<0.0001
	Field 7	Nontreated	5.6 c	58.3 c	99.8 a	3.6 a	3.6 a
		Oxamyl (drch)	9.3 b	88.8 b	100.0 a	3.0 b	3.0 b
		Oxamyl (brd + drch)	11.4 a	98.9 a	74.3 b	2.0 c	2.4 c
		P	<0.0001	<0.0001	0.0012	<0.0001	<0.0001
	Field 8	Nontreated	10.8	99.5	9.8	1.1	0.2
		Oxamyl	12.3	98.9	13.8	1.2	0.3
		P	0.1872	0.4460	0.3869	0.4599	0.4230

[a] All fields contained organic soil (>80% organic matter) except field 4 which contained mineral soil (Lyndonville sandy loam).

[b] Unless otherwise indicated, oxamyl was applied at the label recommended rate (14.0 or 18.7 liter/ha) as an in-furrow drench (drch) at planting. Broadcast (brd) applications were made by the grower in conjunction with the first herbicide application. Oxamyl was applied at a rate of 14.0 liter/ha on fields 1, 2, 4 and 5 and at a rate of 18.7 liter/ha on fields 3, 6 and 7. The higher rate was applied for each of the in-furrow drench and broadcast applications when the combination was applied in fields 6 and 7.

[c] Means within each column and year in fields 1, 2, 3, 4, 5 and 8 were compared using a two-sided *t*-test, and in fields 6 and 7 means were compared using Fisher's least significant difference test (LSD). *P*-values are reported.

[d] A total of 3 m of row was hand-harvested from the two center rows in the middle of each four-row plot. Percent marketable yield was calculated by dividing the marketable weight by the total root weight and multiplying by 100.

[e] Root-galling severity is rated on a scale of 1 (no galls observed) to 6 (severely forked, stunted and galled roots). Carrot roots with ratings of 1 to 3 were considered marketable while those with 4 to 6 were considered unmarketable. Overall average root-galling severity includes all the carrot roots harvested, while the average of the infected roots includes only the roots rated a 2 or higher on the root-galling severity scale.

TABLE 4. The cost benefit of applying oxamyl to commercial fields with varying *Meloidogyne hapla* infection levels in 1996 and 1997.

Year	Site[a]	Treatment[b]	Yield (t/ha)[c]	Value of crop ($/ha)[e]	Cost of oxamyl ($/ha)[f]	Net return ($/ha)[g]	Cost-benefit ($/ha)[h]
1996	Field 1	Nontreated	67[d]	4,473	0	4,473	
		Oxamyl	67	4,490	205	4,285	−188
		P	0.9686	0.9686		0.6610	
	Field 2	Nontreated	63	4,208	0	4,228	
		Oxamyl	76	5,008	205	4,789	+561
		P	0.6396	0.6396		0.7296	
	Field 3	Nontreated	47	3,173	0	3,173	
		Oxamyl	74	4,900	272	4,625	+1,450
		P	0.0593	0.0593		0.1015	
	Field 4	Nontreated	78	5,226	0	5,226	
		Oxamyl	87	5,814	205	5,609	+383
		P	0.1273	0.1273		0.3046	
1997	Field 5	Nontreated	78	5,243	0	5,219	
		Oxamyl	74	4,838	205	4,631	−613
		P	0.1909	0.1909		0.0640	
	Field 6	Nontreated	47 a	3,175 c	0	3,175 c	
		Oxamyl (drench)	85 b	5,589 b	272	5,318 b	+2,142
		Oxamyl (broadcast)	105 a	6,956 b	272	6,684 a	+3,509
		Oxamyl (brd + drch)	101 ab	6,620 ab	544	6,076 ab	+2,901
		P	<0.0001	<0.0001		0.0002	
	Field 7	Nontreated	45 c	2,958 c	0	2,958 b	
		Oxamyl (drench)	74 b	4,957 b	272	4,865 a	+1,730
		Oxamyl (brd + drch)	92 a	6,096 a	544	5,799 a	+2,597
		P	<0.0001	<0.0001		0.0004	
	Field 8	Nontreated	87	5,750	0	5,750	
		Oxamyl	99	6,545	272	6,274	+524
		P	0.1872	0.1872		0.3647	

[a] All fields contained organic soil (>80% organic matter) except field 4 which contained mineral soil (Lyndonville sandy loam).
[b] Unless otherwise indicated, oxamyl was applied at the label recommended rate (14.0 or 18.7 liter/ha) as an in-furrow drench (drch) at planting. Broadcast (brd) applications were made by the grower in conjunction with the first herbicide application.
[c] Yield (t/ha) was calculated based on the kg/3 m yield harvested per plot and the growers' row spacing.
[d] Means within each column and year in fields 1, 2, 3, 4, 5 and 8 were compared using a two-sided *t*-test, and in fields 6 and 7 means were compared using Fisher's least significant difference test (LSD). *P*-values are reported.
[e] Calculated based on the 1996/1997 estimatee crop value of $60/ton.
[f] Calculated based on the 1996/1997 price of $14.53/liter.
[g] Net return = the value of the crop minus the cost of oxamyl application(s).
[h] Labor costs associated with oxamyl application were not included in the cost-benefit analysis and considered minimal since in-furrow drench applications were made in conjunction with other production practices.

costs were not factored into the cost-benefit analysis as they were minimal, given that oxamyl is applied in conjunction with other production practices. The in-furrow drench application was made during planting, and the broadcast application was made in conjunction with the pre-plant herbicide application. In six of the eight fields, the application of oxamyl was cost-effective, increasing profits between $383 and $3,509/ha, depending on the method of application and the level of nematode soil infestation. However, these differences were only significant ($P < 0.1$) in three of the test fields. In the two fields with low *M. hapla* infestation levels and where marketable carrot yield was only reduced by 1.0 and 7.3% as compared to the nontreated plots (Table 4; Fields 1 and 5), the application of oxamyl was not cost-effective. Although the level of nematode infestation was low in field 8 in 1997 (Table 3), the application of oxamyl was cost-effective probably due to the uneven and higher soil population of *M. hapla* in the plot area as compared to the average infestation level of the entire field. The broadcast application of oxamyl was found to be a more cost-effective application in controlling damage of *M. hapla* to carrots as compared to the in-furrow drench method in the commercial trial conducted in field 6. It was also highly effective in the microplot trials conducted in 1996 and 1998. The double application of oxamyl as an in-furrow drench and as a broadcast did not significantly increase the percent marketable yield and therefore was not any more cost-effective than the broadcast application. The significant benefit of oxamyl application in terms of net return was only observed in fields with the highest incidence of root infections ($P \leq 0.1$) (Tables 3,4; Fields 3, 6, and 7).

DISCUSSION

The results of this study clearly demonstrated that the damage to carrot roots caused by *M. hapla* can result in significant yield losses and reduced profitability under New York growing conditions. The reduction in carrot quality (marketability) rather than total quantity of yield due to infections by *M. hapla* observed in this study has been reported previously for this species (Vrain et al., 1979) and also *M. incognita* (Huang and Charchar, 1982). However, reductions in quantity of carrot yield have also been observed when infection by *M. hapla* occurred early in the season (Slinger and Bird, 1978; Vrain, 1982). Oxamyl, the only nonfumigant type nematicide registered for use on carrots in New York, was effective at reducing the damage and yield losses associated with *M. hapla* infection. It has also been used to effectively manage *M. hapla* in Canada (Vrain et al., 1979; Belair, 1984a) and in other carrot-producing regions. Oxamyl applied as an in-furrow drench at planting, the most common application method used by growers, was effective at increasing marketable yield and reducing root-galling severity in commercial fields. However, the results of the studies in microplots and in commercial field trials indicated that oxamyl applied as a broadcast spray and then incorporated was more effective at reducing damage by *M. hapla* and increasing marketable yield, especially in organic soils. The latter is probably due to the limited movement of oxamyl in soils with high organic matter content when applied as an in-furrow drench. In fields with the high incidence of infection by *M. hapla*, there was an economic benefit to the application of oxamyl, although differences in marketable yields were not always statistically significant. In contrast, in fields with low *M. hapla* infestation levels the application of oxamyl was not cost-effective, which suggests the need and usefulness of assessing the pre-plant level of field infestation with *M. hapla* to aid in deciding whether or not to apply a nematicide.

In our field microplots, the estimated damage threshold density was 0.15 and 0.7 eggs/cm^3 in organic soil and 0.6 and 1.9 eggs/cm^3 in mineral soil in 1996 and 1998, respectively. In other similar studies, yield losses caused by *M. hapla* on carrots were reported for preplant nematode infestation densities of 0.2 and 2.0 J2/cm^3 of soil in Michigan (Slinger and Bird, 1978) and Canada (Vrain et al., 1979), respectively. The higher damage threshold densities calculated for both soils in 1998 may be attributed to lower root-galling severity as a result of environmental conditions that were more favorable for plant growth. Similar effects have been previously reported for *M. hapla* on lettuce (Viaene and Abawi, 1996) and *M. incognita* on tomato (Barker et al., 1976). Also, the higher degree of damage observed on carrot grown in mineral soil in 1996 was probably stress-induced by the high temperature and low rainfall conditions that prevailed during the season. Although useful, nematode threshold densities are estimates at best and should be considered in context with the climate, prevailing weather conditions, cultural practices and geographic location (Ferris, 1978) as demonstrated by the variability between years in these microplot trials.

Oxamyl use for managing *M. hapla* will continue to be an important tool for growers in New York. However, there is a great need to develop other viable management practices and to implement an IPM program against *M. hapla*. Crop rotation with nonhost crops and use of antagonistic cover crops are effective control measures for *M. hapla* (Mojtahedi et al., 1991; Belair, 1992; Leroux et al., 1996), although they are not commonly practiced in vegetable rotations in New York. Also, sources of resistance to *M. hapla* have not been identified, and all commercial cultivars are susceptible (Vrain and Baker, 1980; Yarger and Baker, 1981a, 1981b; Gugino et al., 2006). In addition, an understanding of the nematode soil infestation level is necessary for any management strategy to be effective. As demonstrated in these commercial field trials, it is not cost-effective to apply oxamyl when soil nematode infestation levels are low, nor would it be cost-effective to rotate a field out of a cash crop to a nonhost crop if it is not necessary. Although the establishment of damage threshold values as estimated using the Seinhorst and other such equations is desirable to aid in making management decisions, they can be highly variable depending on field and environmental conditions. The use of a simple, visual soil bioassay with lettuce or other appropriate susceptible host can provide a rough estimate of the level of *M. hapla* infestation and aid the grower in making the necessary management decisions (Abawi et al., 2005). Continued research on assessing soil nematode infestation levels will enable growers to cost-effectively select and implement the management tactics available against *M. hapla* not only in carrot fields but in fields containing other susceptible vegetable crops and to also implement a whole farm management strategy for this nematode.

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