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Effects of Cropping Sequences on Population Densities of *Meloidogyne hapla* and Carrot Yield in Organic Soil[1]

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Abstract: The influence of various cropping sequences on population densities of *Meloidogyne hapla* and carrot yield was studied in organic soil under microplot and field conditions. Spinach, radish, barley, oat, and wheat were poor or nonhosts for *M. hapla*. Population densities of *M. hapla* were maintained or increased on cabbage, celery, lettuce, leek, marigold, and potato. Marketable percentage and root weight of carrots were greater following spinach, oat, radish, and fallow-onion than those following two crops of onion or carrot in microplots. Under field conditions, the carrot–onion–oat–carrot cropping sequence decreased *M. hapla* population densities and provided a 282% increase in marketable yield of carrot compared to a carrot monoculture. Two consecutive years of onion increased *M. hapla* population densities causing severe root galling and a 50% yield loss in the following crop of carrot. Based on root-gall indices, carrots could be grown economically for 2 years following radish, spinach, and oat, but not following onion and carrot without the use of nematicides.

Key words: carrot, cereal, cropping sequence, *Daucus carota, Meloidogyne hapla,* management, nematode, organic soil, northern root-knot nematode, rotation, vegetable crop.

The northern root-knot nematode, *Meloidogyne hapla* Chitwood, is a major pest of carrot (*Daucus carota* L.) grown in muck soil in southwestern Quebec (7,14). Symptoms of *M. hapla* infection include galling, large proliferation of secondary roots, and taproot malformation such as severe forking and stunting (15). In infested organic soils, fumigation with high rates of 1,3-dichloropropene is the standard treatment used for nematode control. The unreliability of expensive soil fumigation (16) and the environmental and health hazards associated with pesticide use have increased the interest in alternative nematode management practices.

Crop rotation is an effective method for reducing nematode populations and limiting crop damage (11). In many carrot-producing areas, practical rotation crops are limited by environmental or economic factors. The percentages of *M. hapla*-infected carrot roots were reduced 5–7% in field plots following 2 consecutive years of onion or radish production, compared to a 90% loss in the carrot monoculture (18). In Poland, rotation with a cereal crop provided an increase in marketable carrot, as compared to potato or onion (5).

The objectives of this study were to i) select crops adapted to Quebec climatic conditions to suppress *M. hapla* populations and ii) assess the influence of various cropping sequences on the population density of *M. hapla* and carrot yield under microplot and field conditions. Multiple experiments were conducted to determine if observed effects were repeatable.

MATERIALS AND METHODS

The experiments were conducted from 1981 to 1987 in organic soil at the Agriculture Canada Experimental Farm at Sainte-Clotilde, Quebec. The northern root-knot nematode, *M. hapla,* used in these experiments was a local population obtained from an infested carrot field and increased on tomato, *Lycopersicon esculentum* Mill. cv. Rutgers in the greenhouse. Inoculum consisted of a mixture of heavily galled tomato roots chopped into 1- to 2-cm segments and the potting medium from which tomatoes had been grown approximately 90 days in a greenhouse. The inoculum was spread on the entire soil surface and raked into the upper 15-cm layer. In all experiments, plots were fertilized annually with 500 kg/ha N-P-K (5-15-30) at the beginning of the growing season. Cultural practices were conducted according to Que-

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bec's agricultural recommendations for each crop (1).

At harvest of carrot, a root-gall index (0–5) was used to estimate nematode damage: 0 = no galling, no forking, no stunting, marketable; 1 = 1–10 galls on secondary roots, taproot not affected, marketable; 2 = 10–50 galls, none coalesced, taproots with light forking, no stunting, marketable; 3 = 50–100 galls with some coalesced, forking, no stunting, unmarketable; 4 = more than 100 galls with many coalesced, severe forking and moderate stunting, unmarketable; 5 = more than 100 galls, mostly coalesced, severe stunting, unmarketable. Based on the root-gall index, an economic threshold of 0.65 was developed for *M. hapla* in muck-grown carrots (3). The final *M. hapla* second-stage juvenile (J2) population densities in each plot were assayed by processing a 100-cm^3 soil subsample by a modified Baermann pan method (13). Nematode counts were transformed using $\log_{10}$ (x + 1) for statistical analysis. Data were subjected to analysis of variance, and treatment means were separated by Waller-Duncan k-ratio *t*-test.

Selection of M. hapla *suppressive crops*

Plastic containers (25 cm d × 60 cm deep) were buried in muck soil, pH 4.8–5.5, containing over 80% organic matter to form microplots. Plots were arranged in a randomized complete-block design with six replicates. *Meloidogyne hapla* was not isolated from the soil samples on the experimental site before initiation of the experiment. *Meloidogyne hapla* inoculum was applied to the soil surface and incorporated 15 May 1980, as described in the previous section. Carrot cv. Gold Pak 61 was grown as a cover crop for 1 year before the trial in order to increase nematode population densities. The average preplant *M. hapla* population density was 29 ± 3 J2/100-cm^3 soil in 1981. Plant species chosen in this series of experiments were barley (*Hordeum vulgare* cv. Laurier), cabbage (*Brassica oleracea* var. *capitata* cv. Penn State), carrot (*Daucus carota* cv. Gold Pak 61), celery (*Apium graveolens* var. *dulce* cv. Utah), leek (*Allium porrum* cv. Alaska), lettuce (*Lactuca sativa* var. *capitata* cv. Ithaca), marigold (*Tagetes patula* cv. Tangerine), oat (*Avena sativa* cv. Dorval), onion (*Allium cepa* cv. Pronto), potato (*Solanum tuberosum* cv. Russet Burbank), radish (*Raphanus activus* cv. Scarlet globe), spinach (*Spinacia oleracea* cv. America), and wheat (*Triticum aestivum* cv. Laurier). Seeds of each crop were planted 14 May 1981 in each plot, and seedlings were thinned 1 week after emergence to 1 cabbage, 12 carrots, 1 celery, 6 leeks, 1 lettuce, 3 marigolds, 6 onions, 1 potato, 25 radishes, 25 spinach, and 40 small grains/plot.

Soil samples for nematode assays were collected from each microplot 8 September 1981. Each sample consisted of three soil cores 2.5 cm d × 15 cm deep. All plots were planted to carrot 1 June 1982. Carrots were harvested, graded for marketability 112 days after planting, and rated for root galls according to the predescribed scale. Soil samples for nematode assays were collected from the microplots at harvest as described previously.

Cropping sequences in microplots

Two experiments were conducted simultaneously following the same protocol except when specified. Microplots (1 × 2 m) bordered with galvanized steel frames were fumigated with 98% methyl bromide + 2% chloropicrin (100 g/m^2). All plots were covered with plastic at treatment time. After a 1-week exposure, plastic covers were removed and plots were tilled twice during the 1-week aeration period. Infestation with *M. hapla* was carried out as previously described 15 days after fumigation. Carrot was grown as a cover crop for 1 year to increase nematode population densities. The microplots were sampled and nematode population densities were assayed as previously described. The average population density was 12 ± 3 J2/100-cm^3 soil in the upper 15-cm soil layer 18 May 1983. Based on the results of the previous microplot experiments, the crops used in the sequences included carrot (C), spinach (S), onion (On), oat (Oa), and radish (R). Planting dates were 1 June 1983, 4 June 1984, 3 June 1985, and 2 June 1986. Each year seeds of all crops were planted in two 2-m rows, 45 cm apart in each microplot.

When the cropping sequences were completed, all microplots were planted to carrot. Carrots were harvested 106–130 days after planting, graded, weighed, and rated for root galls according to the predescribed scale. Soil samples for nematode assays were collected at harvest. Each sample consisted of six cores 5 cm d × 15 cm deep collected from the rows.

Experiment 1: Two-year cropping sequences of C-On, C-R, C-Oa, C-S, C-Fallow (F), and C-C were investigated. Each cropping sequence was replicated six times in a complete randomized-block design. When the cropping sequences were completed, all plots were planted to carrot the following year.

Experiment 2: Three-year cropping sequences of C-On-On, C-R-R, C-Oa-Oa, C-S-S, C-F-On, and C-C-C were investigated. Each sequence was replicated six times in a complete randomized-block design. When the cropping sequences were completed, all plots were planted to carrot for 2 consecutive years.

Cropping sequences under field conditions

In 1984, a 0.3-ha plot was infested with *M. hapla* inoculum and planted to carrot for 1 year to increase the nematode population densities. The average *M. hapla* population density was 85 ± 22 J2/100-cm^3 soil in the upper 15-cm soil layer 1 June 1985. Plots 1.8 × 4 m were arranged in a randomized complete-block design with four replicates. Crops included in the sequences were carrot, onion (OP = onion cv. Pronto, OT = onion cv. Trapp 8), radish, spinach, and oat. Three-year cropping sequences of C-OP-R, C-S-S, C-R-Oa, C-R-R, C-OP-S, C-OP-Oa, C-S-R, C-C-Oa, C-OP-OP, C-OT-OT, and C-C-C were investigated. Planting dates were 1 June 1984, 15 May 1985, and 14 May 1986. All plots were planted to carrot 3 June 1987. At harvest, carrots from three rows 1 m long were removed from each plot, graded for marketability, weighed, and rated for root galls according to the predescribed scale. Soil samples for nematode assays were collected at harvest. Each sample consisted of 8–10 soil cores (5 cm d × 15 cm deep) collected from each row.

RESULTS

Selection of M. hapla *suppressive crops*

The final *M. hapla* J2 population densities were low in spinach, onion, radish, barley, oat, fallow, wheat, and marigold plots (Table 1). Large numbers of *M. hapla* J2 occurred in plots of potato, cabbage, lettuce, leek, carrot, and celery. The percentage of marketable carrots and root-gall indices of carrot following marigold, potato, cabbage, lettuce, leek, carrot, and celery was below the economic threshold. A significant ($P \leq 0.01$) negative ($r = -0.74$) linear relationship ($Y = 86.89 - 0.13X$) occurred between the percentage of marketable carrot roots and final J2 population densities.

Cropping sequences in microplots

Experiment 1: Population densities of *M. hapla* J2 were near or below detectable levels in all cropping sequences, except the carrot monoculture (Table 2). Marketable yields of carrots following weed-free fallow, spinach, and onion were greater than those following oat, radish, and carrot. Similarly, the percentage of marketable carrots was increased ($P \leq 0.05$) in all cropping sequences when compared to the carrot monoculture. There was a significant ($P \leq 0.01$) negative ($r = -0.97$) linear relationship ($Y = 70.37 - 0.40 X$) between the percentage of marketable carrots and final nematode population densities.

Experiment 2. Final *M. hapla* J2 population densities were low following 2 consecutive years of spinach, oat, and radish; intermediate after fallow–onion and onion–onion; and highest in the carrot monoculture (Table 3). Marketable percentage and root weight of carrots in 1985 were greater following spinach, oat, radish, and

TABLE 1. Effect of selected crops on *Meloidogyne hapla* population densities and carrot grown in microplots.

		Carrot—1982		
Crop 1981	Pf 8 September 1981	Marketable roots (%)	Root-gall index (0–5)	Pf 20 September 1982
Spinach	10 b	100 a	0.3 c	15 fg
Onion	3 b	99 a	0.1 c	28 gh
Radish	10 b	99 a	0.4 c	8 h
Barley	3 b	99 a	0.2 c	86 de
Oat	0 b	97 a	0.2 c	69 de
Fallow†	13 b	97 a	0.3 c	30 g
Wheat	2 b	90 a	0.4 c	76 de
Marigold	37 b	65 b	1.9 b	482 bc
Potato	436 a	59 bc	2.4 ab	350 bc
Cabbage	140 a	58 bc	1.8 b	158 cde
Lettuce	280 a	58 bc	2.0 b	218 bcd
Leek	200 a	44 bc	2.3 ab	1,363 a
Carrot	990 a	38 cd	2.2 ab	1,942 a
Celery	460 a	25 d	3.3 a	648 ab

Means followed by different letters in columns are different ($P \leq 0.05$) according to Waller-Duncan k-ratio t test. Pf = number *M. hapla* second-stage juveniles per 100 cm^3 soil at sampling date.

† Plots maintained weed-free by handweeding.

fallow-onion than those following two crops of onion or carrot. Carrot yield and quality following onion–onion and carrot–carrot were unsuitable for commercial trade. After the crop of carrot in 1985, J2 population densities were low in plots previously planted to spinach and oat; intermediate in plots previously planted to radish and fallow–onion; and high in plots previously planted to onion–onion and carrot–carrot. In the second year following the cropping sequence, the highest yield and percentage of marketable roots of carrot came from plots previously planted to spinach, oat, and radish. Yields of carrot in 1986 following F-On-C, On-On-C, and C-C-C were unsuitable for commercial trade.

Cropping sequences under field conditions

There were no differences ($P \leq 0.05$) in initial *M. hapla* population densities among cropping sequences (data not included). In 1986, final *M. hapla* population densities (Pf) were lower in all cropping sequences than those in the carrot monoculture (Table 4). The percentage of marketable carrots in 1987 was below the economic threshold (60%) in the C-C-Oa-C, C-OP-OP-C, C-OT-OT-C, and C-C-C-C crop-

TABLE 2. Effect of cropping sequences on *Meloidogyne hapla* population densities and carrot grown in microplots.

		Carrot—1984			
Cropping sequence 1982–1983–1984	Pf 18 May 1983	Marketable roots (%)	Marketable roots (t/ha)	Root-gall index (0–5)	Pf 8 October 1984
C-F-C†	0 b	80 a	46.6 a	0.6 d	3 d
C-S-C	2 b	73 ab	48.3 a	1.1 c	100 c
C-On-C	0 b	70 b	46.6 a	1.3 bc	60 c
C-Oa-C	0 b	67 bc	38.3 b	1.0 cd	123 bc
C-R-C	0 b	61 c	35.3 b	1.8 b	199 bc
C-C-C	152 a	9 d	5.0 c	4.3 a	616 a

Means followed by different letters in columns are different ($P \leq 0.05$) according to Waller-Duncan k-ratio t test. Pf = number *M. hapla* second-stage juveniles per 100 cm^3 soil at sampling date.

† C = carrot, F = weed-free fallow, S = spinach, On = onion, Oa = oat, and R = radish.

TABLE 3. Effect of cropping sequences on *Meloidogyne hapla* population densities and carrot grown in microplots.

Cropping sequence 1982–83–84–85–86	Pf 8 October 1984	Carrot 1985 Marketable roots (%)	Carrot 1985 Marketable roots (t/ha)	Carrot 1985 Root-gall index (0–5)	Carrot 1985 Pf 28 October 1985	Carrot 1986 Marketable roots (%)	Carrot 1986 Marketable roots (t/ha)	Carrot 1986 Root-gall (0–5)	Carrot 1986 Pf 1986
C-S-S-C-C†	3 c	91 a	63.3 a	0.1 c	2 d	71 a	50.0 a	0.7 c	56 b
C-Oa-Oa-C-C	6 c	90 a	65.0 a	0.1 c	4 cd	75 a	45.0 a	0.8 c	83 b
C-R-R-C-C	2 c	86 a	50.0 b	0.2 c	32 bc	64 ab	46.7 ab	0.7 c	107 b
C-F-On-C-C	85 b	84 a	65.0 a	0.3 c	181 bc	55 ab	31.7 b	2.0 b	589 a
C-On-On-C-C	107 b	47 b	33.3 c	1.9 b	1,391 a	32 c	18.3 c	3.6 a	862 a
C-C-C-C-C	626 a	9 c	8.3 d	4.1 a	1,663 a	42 bc	25.0 b	2.6 b	605 a

Means followed by different letters in columns are different ($P \leq 0.05$) according to Waller-Duncan k-ratio *t* test. Pf = number *M. hapla* second-stage juveniles per 100 cm^3 soil at sampling date.

† C = carrot, S = spinach, Oa = oat, R = radish, F = weed-free fallow, and On = onion.

ping sequences. The weight of marketable roots of carrot was highest in the C-OP-Oa-C cropping system. The root-gall index of carrots following onion cv. Trapp 8 in the C-OT-OT-C cropping system was higher ($P \leq 0.05$) than those following onion cv. Pronto in the C-OP-OP-C cropping system. In 1987, numbers of J2 Pf were greater in the C-C-Oa-C, C-OP-OP-C, C-OT-OT-C, and C-C-C-C cropping systems than the others.

DISCUSSION

The results of this study confirmed the reproductive capability of *M. hapla* from southwestern Quebec on selected agricultural crops in rotation. Spinach, radish, wheat, oat, and barley reduced *M. hapla* population densities in crop rotations, thus providing increases in the percentage of marketable roots in the following susceptible crop of carrot. Wheat, oat, and barley were nonhosts or resistant to *M. hapla* isolates from other agricultural areas (5,12). In Quebec, radish and spinach are grown as early season vegetables and are effective trap crops, harvested well before *M. hapla* matures to the egg-laying stage (2). Weed-free fallow was no more effective than a poor host crop in reducing *M. hapla* population densities in organic soil. This cul-

TABLE 4. Effect of cropping sequences on *Meloidogyne hapla* population densities and carrot grown in field conditions.

Cropping sequence 1984–85–86–87	Pf 1 October 1986	Carrot—1987 Marketable roots (%)	Carrot—1987 Marketable roots (t/ha)	Carrot—1987 Root-gall index (0–5)	Carrot—1987 Pf 29 September 1987
C-OP-R-C†	3 c	85 a	40.4 ab	0.02 e	0 b
C-S-S-C	2 c	85 a	37.1 ac	0.01 e	1 b
C-R-Oa-C	3 c	84 a	40.4 ab	0.60 de	1 b
C-R-R-C	3 c	84 a	30.0 cd	0.13 de	1 b
C-OP-S-C	4 bc	83 a	42.1 ab	0.15 de	1 b
C-OP-Oa-C	4 bc	83 a	44.6 a	0.03 de	2 b
C-S-R-C	2 c	79 a	33.3 bd	0.11 de	4 b
C-C-Oa-C	3 c	59 b	26.3 d	1.04 bc	80 a
C-OP-OP-C	6 bc	54 b	27.9 cd	0.69 cd	83 a
C-OT-OT-C	12 b	49 b	26.3 d	1.38 b	214 a
C-C-C-C	232 a	29 c	11.7 e	2.07 a	607 a

Means followed by different letters in columns are different ($P \leq 0.05$) according to Waller-Duncan k-ratio *t* test. Pf = number *M. hapla* second-stage juveniles per 100 cm^3 soil at sampling date.

† C = carrot, OP = onion cv. Pronto, R = radish, S = spinach, Oa = oat, and OT = onion cv. Trapp 8.

tural practice is not recommended because of its influence on soil erosion and subsidence (6). Population densities of *M. hapla* were maintained or increased on cabbage, celery, lettuce, leek, marigold, and potato; therefore these crops should not be used in rotations developed for carrot production in organic soil infested with *M. hapla.* These results are consistent with previous work on the management of *M. hapla* isolates from Michigan (4) and Ohio (17,18).

Onion was an intermediate host for *M. hapla.* Although the final J2 population densities on onion at harvest were low compared to those on carrot, these results and those from other studies showed that the *M. hapla* population densities on onion was sufficient to cause severe yield losses to carrot grown in muck soil (5,9). In some cases, 2 consecutive years of onion resulted in less marketable roots in the following crop of carrot than a carrot monoculture (data not included). The reason a single crop of onion is more effective than two crops in reducing *M. hapla* population densities is unknown. The results indicated that Pronto, an early-maturing onion cultivar, supported lower numbers of *M. hapla* than Trapp 8, a late-maturing cultivar. These results were also supported by the root-gall indices of carrot following onion. An earlier report suggested that the reproduction rate of *M. hapla* was affected by onion cultivars (8).

A successful cropping sequence for managing *M. hapla* population densities would be most likely achieved by using a 2-year rotation with two poor hosts such as radish or spinach. These crops are not subject to yield losses by *M. hapla* in organic soil (unpubl.). Based on root-gall indices, carrot could be grown economically for a second year following radish, spinach, and oat, but not onion and carrot. Although very effective in managing *M. hapla* population densities, 2 consecutive years of cereal crops would not be economically feasible on these high-valued organic soils. Although rotation can be recommended for suppressing crop damage from *M. hapla,* practical rotation of crops in a carrot-producing area is limited by environmental and economic factors. Care must be exercised in selecting appropriate rotation crops; they must be poor hosts or nonhosts for the nematode and economically feasible to produce. The C-OP-Oa-C cropping sequence reduced *M. hapla* population densities and provided the largest carrot yield. This would be an effective nematode management strategy for many carrot growers in Quebec's organic soil without the use of nematicides. Onion is the second major crop grown in the area and could be incorporated into a cropping sequence. The use of a cereal crop in a rotation would also be effective in controlling other major pests such as weeds and insects in these soils (19). The use of residue from cereal crops would also improve cohesion, structure, and water-holding capacity and reduce subsidence and erosion in these organic soils (6). There is evidence that green manure amendment with small grain shoots has a detrimental effect on the survival of root-knot nematodes (10). A cereal crop preceding a crop of carrot could reduce soil compaction and increase the quality and quantity of carrots produced the following year.

These results indicated that *M. hapla* population densities increased rapidly on carrot after 1 year of rotation with a poor host or a nonhost crop. These experiments were conducted on small cultivated areas heavily infested with *M. hapla.* The impact of the cropping sequences may have been underestimated from the large production fields. Further evaluations will be necessary under large areas, but a 1- or 2-year rotation with a nonhost or a poor host crop could be successful in managing *M. hapla* in carrot production fields.

An awareness of the host status of common agricultural crops to *M. hapla* should provide the basis for rational nematode management decisions in Quebec. Use of poor host or nonhost crops may be beneficial in managing *M. hapla* population densities in intensive cropping systems and reducing the dependence on nematicides.

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