Using Crop Rotation to Control *Meloidogyne hapla* Chitwood and Improve Marketable Carrot Yield

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Abstract. The influence of various crop rotations on population densities of *Meloidogyne hapla*, the northern root-knot nematode, and subsequent carrot yields was studied in organic soil under field conditions. Seven 3-year sequences with barley (*Hordeum vulgare* L.), carrot (*Daucus carota* L.), onion (*Allium cepa* L.), or weedy fallow, all with carrot as the third-year crop, were replicated six times in a completely randomized block design. Carrot monoculture, two seasons of weedy fallow, or carrot followed by onion resulted in high *M. hapla* population densities and severe root damage on carrot the third year. Barley followed by onion or onion followed by barley harbored low *M. hapla* population densities and provided the highest yields, with 56.8 and 47.2 t marketable carrots/ha, respectively, compared to 2.2 t·ha⁻¹ in the carrot monoculture. A single crop of barley reduced nematode population densities and provided 88% and 73% marketable carrot roots in the subsequent years. High *M. hapla* population densities and the high proportion of culls recorded in plots in weed fallow emphasize the importance of an effective weed management program for successfully using crop rotation against root-knot nematode in muck-grown carrot.

The northern root-knot nematode, *Meloidogyne hapla*, is a major pest of carrots in the northern United States and in eastern Canada (Berney and Bird, 1992; Vrain, 1978). The infective second-stage juveniles disrupt the normal formation of the taproot and induce symptoms such as galling, forking, and stunting (Vrain, 1982). In the organic soils of southwestern Quebec, Canada, carrot monoculture is a common practice, and reduction in marketable yields from root-knot nematode infection can reach 100% in heavily infested fields (Vrain et al., 1981). Soil fumigation with 1,3-dichloropropene nematicide at the high rate of 300 liters·ha⁻¹ is the standard chemical treatment used for nematode control. The low efficacy and high cost of soil fumigation in organic soil, the pressure of environmental concerns, and the threat of possible withdrawal from the market of the remaining fumigant nematicides have created a sense of urgency in the search of alternative nematode management tactics.

Crop rotation has been recommended for reducing nematode populations and limiting crop damage in many cropping systems (McSorley et al., 1994; Nusbaum and Ferris, 1973; Raymundo, 1985). In the carrot production system, introducing small grains, nonhost crops to *M. hapla*, has provided large increases in marketable carrots (Bélair, 1992; Brzeski and Bodja, 1974; Wilson, 1962). Under small microplot conditions, the cropping sequence, onion–small grain–carrot, reduced *M. hapla* population densities below the detectable level and provided a 282% increase in marketable yield compared to the yield obtained in monoculture plots (Bélair, 1992). This cropping sequence has good potential for managing root-knot nematode in organic soils,

but a more extensive evaluation or a field validation of this cropping sequence was required before it could be recommended to growers.

Our objective was to assess the influence of various cropping sequences, including an onion–barley–carrot sequence, on *M. hapla* population densities and carrot yields under field conditions.

Materials and Methods

The trial was conducted at Sherington, Quebec, Canada, in a 1.2-ha commercial carrot field on organic soil with a severe root-knot nematode problem. This peaty soil had a 80% to 85% organic content with a pH of 5.5. Plots (15 × 11 m) were arranged in a randomized complete-block design with six replications. Crops included in the sequences were 'Sixpak' carrot (C), 'Flame' onion (O), weedy fallow (F), and 'Birka' barley (B). Three-year cropping sequences of C–O–C, B–C–C, F–F–C, C–B–C, B–O–C, O–B–C, and C–C–C were investigated from 1989 to 1991. Each experimental plot was surrounded by a 3-m band of barley that was mowed regularly during the growing season. Cultural practices were conducted according to Quebec's agricultural recommendations for each crop (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 1987). In 1991, all plots were planted to carrot. At harvest, carrots were removed from four rows (1 m long) from each plot, graded for marketability, weighed, and rated on a root-gall index as follows: 0 = no galling, no forking, no stunting, marketable; 1 = one to 10 galls on secondary roots, taproot not affected, marketable; 2 = 11 to 50 galls, none coalesced, taproots with light forking, no stunting, unmarketable; 3 = 51 to 100 galls with some coalesced, forking, no stunting, unmarketable; 4 = more than 100 galls with some coalesced, severe forking and moderate stunting, unmarketable; 5 = more than 100 galls, mostly coalesced, severe stunting, unmarketable (Fig. 1). Based on this root-gall index, an economic threshold of 0.65 (60% marketable roots) has been established on the average production return and soil fumigation costs in muck-grown carrots (Bélair and Boivin, 1988). Soil samples for nematode as-

Fig. 1. Root-knot nematode galling and nematode damage index (on a scale from 0 to 5): 0 = no galling, no forking, no stunting, marketable; 1 = one to 10 galls on secondary roots, taproot not affected, marketable; 2 = 11 to 50 galls, none coalesced, taproots with light forking, no stunting, marketable; 3 = 51 to 100 galls with some coalesced, forking, no stunting, unmarketable; 4 = more than 100 galls with many coalesced, severe forking, moderate stunting, unmarketable; 5 = more than 100 galls, mostly coalesced, severe stunting, unmarketable.

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says were collected each year before planting and after harvest. Each sample consisted of eight to 10 soil cores (5 cm in diameter × 20 cm deep) collected randomly on each row. *Meloidogyne hapla* second-stage juvenile (J2) population densities in each plot were assayed by processing a 100-cm³ soil subsample using a modified Baermann pan method (Townshend, 1963).

Nematode counts were transformed using log₁₀ (x + 1) before statistical analysis. Data were analyzed by general linear model procedures (SAS institute, Cary, N.C.). Waller-Duncan k-ratio *t* test was used to compare treatments when analysis of variance showed significant differences among means.

Results

In 1989, when the experiment was established, J2 preplant densities ranged from 5 to 360/100 cm³ soil, with no significant differences among treatments (Table 1). At harvest, J2 densities were significantly higher in carrot plots than in all other crops.

In 1990, J2 preplant densities were high in plots previously planted with carrot and plots that were weedy fallow; densities were low in all other treatments (Table 1). At harvest, J2 densities were low in all plots except those in weedy fallow and carrot monoculture. In the B-C-C and C-C-C sequences, carrot yields were recorded as previously mentioned and were estimated at 88% (55 t·ha⁻¹) and 8% (4 t·ha⁻¹) marketable roots, respectively.

In 1991, the J2 preplant densities were significantly lower following O-B, B-O, and C-B cropping sequences than all other treatments (Table 1). At harvest, J2 densities were significantly lower following O-B-C, B-O-C, and C-B-C than in the other cropping sequences. The percentage of marketable carrots was above the economic threshold in the O-B-C, B-O-C, and C-B-C cropping sequences (Table 2). The highest weights of marketable carrots were recorded in the B-O-C and O-B-C cropping sequences, with yields of marketable carrots more than 20 times that for the carrot monoculture, where yield was the lowest. The root-gall index of carrots was high following F-F-C and C-C-C; intermediate after C-O-C, B-C-C, and C-B-C; and low after B-O-C and O-B-C cropping sequences.

Discussion

The B-O and O-B cropping sequences were the most effective in reducing *M. hapla* population densities and providing profitable carrot yield increases the subsequent year under field conditions. Based on root-gall indices at harvest, carrot could be grown economically for a second year following both sequences. These results confirm earlier observations in small microplots in southwestern Quebec (Bélair, 1992). In terms of monetary returns, the B-O and O-B sequences provide a profit (in Canadian dollars) of \$2200/ha over the 3-year sequence (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation, 1990). For all other sequences, the net losses range from (in Canadian dollars) \$1294 to \$6779/ha. For economic reasons, growers cannot extend the number of years in rotation without their primary crop (carrot) for more than 2 years. An integrated pest management (IPM) program to manage *M. hapla* is being used by carrot growers in Quebec based on an assessment of nematode damage potential (root damage indices) obtained from the previous carrot crop (Bélair and Boivin, 1988). The program provides for a mapping of the nematode distribution in each field and optimizes *M. hapla* management decisions by subdividing the field and practicing a rotation only in the areas where the nematodes are located.

A single year of barley, a resistant crop, significantly reduced *M. hapla* population densities near or below the detectable level but provided only a single profitable carrot crop in the B-C-C and C-B-C cropping sequences. Thus, under a severe nematode infestation, a single crop of small grain would not be an economically viable alternative in carrot production. A good preventive practice, however, would be to introduce a small grain as a rotating crop in all carrot fields every 3 to 5 years to reduce the potential of nematode infestation and thus provide long-term management of *M. hapla*. The introduction of a small grain in the cropping system also would be economically justifiable by its other positive effects, such as increasing the soil fiber content and, thus, reducing loss from wind erosion. Using a small grain would improve weed control via efficacious herbicides against specific weed problems that cannot be managed in carrot and

Table 2. Effect of cropping sequences on carrot yields in the last year of the cropping sequence under large field-plot conditions in organic soil.

Cropping sequences	Marketable roots ^a		Root-gall index
	%	t·ha ⁻¹	
1989-90-91 ^b			
B-O-C	88.9 a	56.8 a	0.1 e
O-B-C	83.4 ab	47.4 b	0.1 e
C-B-C	72.6 bc	34.0 c	0.4 de
B-C-C	64.5 c	33.1 c	0.8 cd
C-O-C	49.1 d	23.0 d	1.2 c
F-F-C	45.5 d	15.3 e	1.8 b
C-C-C	7.3 e	2.2 f	3.5 a

^aMeans followed by different letters in columns are different at *P* ≤ 0.05 according to the Waller-Duncan k-ratio *t* test.

^bC = carrot, F = weedy fallow, O = onion, B = barley.

onion production (D.L. Benoit, personal communication).

Onion is an intermediate host of *M. hapla* and reduces populations of this nematode when compared to carrot (Bélair, 1992; Brzeski and Bodja, 1974; Kotcon et al., 1985; Wilson, 1962). In our study, a single crop of onion did not provide a useful level of root-knot nematode control in carrot production. The efficiency of onion could have been lessened by the presence of many common weeds, such as oak-leaved goosefoot (*Chenopodium glaucum* L.), green smartweed (*Polygonum scabrum* Moench), and marsh yellow cress [*Rorippa islandica* (Oeder) Borb.] (Leroux et al., 1996). These weeds have been good hosts of *M. hapla* in organic soil (unpublished observations). High *M. hapla* population densities and the high level of culls recorded in weedy fallow plots also emphasize the importance of an effective weed management program for the successful use of crop rotation.

Our study demonstrated that B-O and O-B cropping sequences are efficacious and cost-effective rotations for managing *M. hapla* in carrot production. These results may contribute to the introduction of such control practices in the IPM program and, thus, reduce the dependence on nematicides in the carrot cropping system of southwestern Quebec.

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Table 1. Effect of cropping sequences on *Meloidogyne hapla* population densities under large field-plot conditions in organic soil.

Cropping sequence	No. <i>M. hapla</i> second-stage larvae/100 cm ³ soil ^a					
	1989		1990		1991	
	Preplant	Harvest	Preplant	Harvest	Preplant	Harvest
1989-90-91						
O-B-C ^b	46 a	31 b	39 b	0 b	17 b	1 c
B-O-C	40 a	15 b	3 b	1 b	0 b	1 c
C-B-C	35 a	1236 a	232 a	3 b	0 b	4 c
B-C-C	13 a	3 b	1 b	4 b	121 a	245 a
C-O-C	9 a	1206 a	265 a	33 b	52 a	81 b
F-F-C	98 a	55 b	329 a	335 a	242 a	320 a
C-C-C	46 a	1601 a	331 a	1458 a	140 a	89 b

^aMeans followed by different letters in columns are different at *P* ≤ 0.05 according to the Waller-Duncan k-ratio *t* test.

^bC = carrot, F = weedy fallow, O = onion, B = barley.

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