Nematodes Associated with Carrot Production in Tasmania, Australia, and the Effect of *Pratylenchus crenatus* on Yield and Quality of Kuroda-Type Carrot

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ABSTRACT

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A survey for nematodes in carrot crops in northern Tasmania detected lesion nematode (*Pratylenchus* spp.) in 28 of 33 crops, with *P. crenatus* occurring most frequently and *P. neglectus*, *P. thornei*, and *P. penetrans* occurring infrequently. Root-knot nematode was detected in five of 33 carrot crops, with *Meloidogyne fallax* present in two crops. The effect of *P. crenatus* on yield and quality of Kuroda-type carrot was assessed in 42 plots arranged in a 6 × 7 lattice in each of two commercial crops. High numbers of *P. crenatus* were recovered from fine roots at 58 days after sowing (DAS). However, following formation of the taproot, low numbers were recovered. In both crops, there was a significant negative correlation between numbers of *P. crenatus* per gram dry weight of root at 58 DAS and the dry weight of root and shoot at 58 DAS. However, the low numbers of *P. crenatus*/g dry weight of root recovered at subsequent sampling times, and the lack of an increase in the number of *P. crenatus* in the soil during the season, suggested that Kuroda-type carrot became resistant to *P. crenatus* following taproot formation. In both crops, *P. crenatus* populations were significantly negatively correlated with plant density and in one crop with average carrot weight. Regression analysis predicted potential yield penalties of 12.1 to 22.3 t/ha between plots with the highest number of *P. crenatus* and those with none. There was no significant correlation between *P. crenatus* populations during the season and carrot defects. Spatial analysis using Spatial Analysis by Distance Indices determined that *P. crenatus* in soil were significantly aggregated at all times and in roots at 58 DAS were aggregated in one of two trials, with indices of aggregation (I_a) ranging from 1.27 to 1.64.

Carrot is an important vegetable crop in Australia, with some 330,000 tonnes produced annually from approximately 7,500 ha, with a farm-gate value of A\$150 M. In Tasmania, carrot production has increased rapidly in recent years, with 35,000 tonnes produced from 616 ha in the 1999–2000 season (10). Approximately 3,770 tonnes of carrots were exported from Tasmania to other countries in 2000–2001 (13), mainly of Kuroda types to Japan.

Worldwide, plant-parasitic nematodes are a significant constraint to carrot production. More than 90 species from several genera have been associated with umbelliferous crops, including *Meloidogyne*, *Pratylenchus*, *Longidorus*, *Paratylenchus*, *Belonalaimus*, *Paratrichodorus*, *Rotylenchus*, and *Ditylenchus* (5). Recently, *Hemicycliophora saueri* was also associated with carrot defects (31). Diseases caused by root-knot nematode (*Meloidogyne* spp.) have been traditionally considered to be the most damaging. This genus has been

associated with forking of the taproot, galls, proliferation of fibrous roots, and stunting (1). *Meloidogyne hapla* has been shown to cause losses in marketable yield of up to 77% (2). The main nematodes affecting carrot production in Australia are root-knot (*M. hapla* and *M. javanica*) and lesion nematodes (*Pratylenchus* spp.) (10). Root-knot nematode is recognized as a sporadic but serious problem in carrot production in Tasmania and lesion nematode (*Pratylenchus* spp.) as a potential problem.

The effect of *Pratylenchus* spp. on carrot in Tasmania is not well known; moreover, there has been little work published on the effect of *P. crenatus* on carrot yield and quality. Potter and Olthof (22) reported *P. crenatus* to cause branched and shortened taproots, death of root tips on side roots, and foliage to be thin and chlorotic. *P. crenatus* has also been associated with “carrot sickness”, exhibited as patches of poorly growing, chlorotic plants with small and often branched main and secondary roots with lesions and dead tips (12). Moreover, Weischer and Brown (32) reported that 600 *P. crenatus* per liter of soil were necessary to cause damage to carrots. Other *Pratylenchus* spp. have also been implicated with reduced yield and quality of carrot. For example, *P. penetrans* has been associated with forking and

plant death (4) and reduced size and branching of the taproot (30). *Pratylenchus mediterraneus* has also been reported to cause seedling death and splitting of the taproot. The application of nematicides for the control of *P. mediterraneus* increased marketable carrot yield by 38 to 45% (16).

Spatial depiction of nematode populations and temporal changes in density provide basic information on the pathogen dissemination and epidemic structure. Quantifying this information is useful for predicting losses associated with diseases caused by nematodes and the design of effective management strategies. Spatial processes can be visualized on two different scales: at the level of the sampling unit or below by point-pattern based analyses and at the level of sampling unit or above by correlation or geostatistical based analyses (27,28). Several methods of correlation-based analyses have been used to describe the spatial patterns of plant-parasitic nematodes as either aggregated or random at specific points in time, while others may also quantify and describe aggregation. Two-term local variance analysis (7) and geostatistics (23,26) are examples of techniques that depict spatial pattern and quantify scale. Both methods have been used for spatial analysis of nematode densities of soybean cyst nematode (7,8). However, spatial patterns have also recently been depicted using the Spatial Analysis by Distance Indices (SADIE) method developed by Perry (17,19). SADIE has been used to describe spatial patterns of data based on counts such as weeds (18), insects (19,34), predator–prey relationships (6), and foliar disease (21,24,25,27).

The objectives of this research were to: (i) characterize the plant-parasitic nematodes associated with carrot in Tasmania, Australia, (ii) quantify the relationship between *P. crenatus* and yield and quality of Kuroda carrot varieties, and (iii) quantify spatial patterns of *P. crenatus* in soil and carrot roots.

MATERIALS AND METHODS

Prevalence and incidence of plant-parasitic nematodes. The prevalence and incidence of plant-parasitic nematodes associated with carrot production in 33 fields across northern Tasmania was assessed. Soil samples were gathered within 1 month after emergence of carrots between November 2000 and early February

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2001. All fields were located within a 60-km radius. Each field received similar standard production practices including irrigation, fertilizer, fungicide, and herbicide applications. In each field, a soil and root sample was taken at approximately 30-m intervals along every tenth bed. Samples were collected with a trowel to a depth of 20 cm. Soil samples were bulked, crumbled to a fine tilth, and mixed. Nematodes were extracted by Whitehead tray method (33) from a 400 cm³ sample and from weighed quantities of roots cut into 1-cm lengths. Soil or roots were placed on tissue suspended in a wire basket in a tray (30 cm long by 20 cm wide by 3 cm deep). The tray was filled with water to halfway up the depth of the sample and incubated at room temperature (15 to 20°C) for 72 h. The basket was removed from the tray and nematodes retrieved by passing the suspension through a 20-µm sieve. Material retained on the sieve was rinsed into a 60-ml container. Water that passed through the sieve was sieved for a second time. Nematodes were allowed to settle overnight (5°C), and the supernatant was drawn off to leave a suspension of 20 to 30 ml. A 4-ml aliquot was placed in a counting dish and nematodes counted and identified to genus at ×50 to ×100 magnification. The number in the total volume of suspension was then calculated and expressed per 200 cm³ of soil or per gram dry weight of root. Roots were oven dried at 100°C for 24 h following nematode extraction and dry weight recorded.

Subsamples of nematodes from the *Pratylenchus*, *Meloidogyne*, and *Merlinius* genera from 17 crops were sent to Jackie Nobbs of the South Australian Research and Development Institute for identification to species. At least 10 individuals of *Pratylenchus* spp. from each site were identified to species.

Effect of *P. crenatus* on yield and quality. One field trial was established in each of two seasons (2001 and 2001–2002), hereafter referred to as 2001 and 2002, respectively. At both sites, *P. crenatus* was dominant, comprising 90 to 95% of the *Pratylenchus* population. Trials were located in fields of carrot on a commercial farm in Penguin, Tasmania (41° 11' S, 146° 07' E) with a long history of vegetable cropping. Carrots had not been grown in either field for 5 years prior to the current crop. The fields were cultivated by

deep ripping and plowing, and the seed bed prepared by rotary hoe and bed formation. Seed was sown with a precision air seeder. Pesticides and fertilizer were applied as per commercial industry practice and crops watered by overhead traveling gun-type irrigator at 10- to 14-day intervals.

Field trial – 2001. In the first season, the field was sown on 1 January 2001 with a Kuroda-type carrot (var. Koyo II), and the trial was established shortly after emergence on 1 February. The trial consisted of 42 plots arranged in a 6 × 7 lattice, each 7 m long by three beds wide (approximately 5.25 m) with each bed having two double rows of carrots. Soil and root samples were obtained on 27 February, 3 April, and 26 April at 58, 93, and 123 days after sowing (DAS), respectively. Samples collected during the season consisted of three carrot plants taken from each of six locations from 2-m sections at each end of the plots. The middle 3-m section of the 7-m-long plots was left unsampled for harvest purposes. Foliage was removed, blotted dry, and fresh weight recorded. Dry weight of foliage was calculated after drying for 24 h at 100°C. Roots were washed, blotted dry, and the fresh weight also recorded prior to nematode extraction. For samples collected at 58 DAS, fine roots were chopped into 2-cm sections for extraction, while for those samples collected at 93 and 123 DAS, taproots were halved longitudinally and chopped into 4- to 5-cm lengths for extraction. Nematodes were extracted from roots or a 200 cm³ subsample of soil from each plot by the Whitehead tray technique (33) described previously. Following extraction, roots were oven dried (100°C for 24 h) and weighed.

On 3 May (130 DAS), approximately 1 week prior to commercial harvest, the density of plants was assessed in the center 3-m section of each plot by counting the number of plants in 1-m transects taken along three beds. Plots were harvested by digging up 20 plants from each of five double rows from within the 3-m center section of each plot (100 plants per plot). Foliage was removed and discarded. Taproots were washed and graded into categories (0 to 5) using a scale adapted from Belair and Boivin (3): 0 = no lateral protrusions or stunting; 1 = taproot with one to two lateral protrusions <1 cm long; 2 =

taproot with two to three lateral protrusions 1 to 3 cm long, no stunting; 3 = taproot with three or more lateral protrusions >3 cm long, no stunting; 4 = taproot with three or more lateral protrusions >3 cm long, moderate stunting; and 5 = taproot with three or more lateral protrusions >3 cm long, severe stunting. Carrots in categories 0 or 1 were considered first grade, suitable for export. Carrots were also further graded into categories of small (<10 cm long, <2.5 cm wide), forked, twisted, short cracks (<2 cm), long cracks (>2 cm), constricted, and other damage (e.g., insect). Estimated plant density (carrots per ha) was calculated as (mean no. carrots/m row × m of row per plot)/plot size (m²) × 10,000. Carrot yield (t/ha) was calculated as (weight of carrots in a 100-carrot sample/100 carrots) × carrots/ha.

Field trial – 2002. The second field trial was established with Kuroda var. Coral II on 23 September 2001. A trial area was selected within an area found to have high numbers of *Pratylenchus* spp. from soil samples 8 weeks earlier (results not shown). The trial consisted of 42 plots arranged in a 6 × 7 lattice. Each plot was 7 m long by four carrot beds wide (approximately 6.65 m), and each bed contained three double-rows of carrots. Soil and plant samples were collected from six positions in each plot on 20 November (58 DAS). Samples consisted of one trowel depth (20 cm) of soil and two carrot plants taken at six locations and bulked. Samples were collected from a 2-m section at each end of the plot. The central 3-m section of each plot was left intact for harvest purposes. Nematodes were extracted from a 200 cm³ subsample of soil or roots by the Whitehead tray technique (33) described above. Following extraction, roots and foliage were oven dried (100°C for 24 h) and weighed.

Soil and root samples consisting of a trowel depth of soil and one carrot were collected at 116 DAS from six arbitrarily chosen locations at the ends of each plot as described previously. Nematodes were extracted from soil as described above. Carrots were washed and cut in half longitudinally. Half of each carrot was discarded. Carrots were then cut transversely into pieces approximately 0.5 to 2 cm long × 0.2 to 1 cm wide with a food processor (Sunbeam Maestro Pro) fitted with a coarse cutting blade. These pieces were then weighed and nematodes extracted by the Whitehead tray technique (33) and recovered by sieving as described previously. After extraction, root tissue was dried (100°C/24 h) and weights recorded.

The trial was harvested on 17 January 2002 (116 DAS), 4 days before commercial harvest. Plant density was recorded by counting the number of carrots in 1-m sections of rows at four arbitrarily chosen locations in the center 3-m section of plots. Twenty carrots were removed from each of

Table 1. Mean, minimum, and maximum numbers of nematode genera per 200 cm³ soil and prevalence from 33 Tasmanian carrot crops up to 5 weeks in age (November 2000 to February 2001)

	<i>Pratylenchus</i>	<i>Paratylenchus</i>	Stunt ^a	<i>Heterodera</i>		
				<i>trifolii</i>	<i>Meloidogyne</i>	<i>Helicotylenchus</i>
Mean ^b	62.5	7.8	10.6	4.7	3.8	2.9
Minimum	0	0	0	0	0	0
Maximum	313.5	20.0	38.0	8.9	8.9	2.9
Prevalence	28	8	14	3	5	1

^a Includes *Tylenchorhynchus* spp. and *Merlinius brevidens*.

^b Mean number of nematodes over sites at which a particular genus occurred.

five arbitrarily chosen locations in the center 3-m section of each plot, bagged, and kept in a coolroom (5°C) overnight. Carrots were washed and graded into the following categories: forked, carrots with taproot in two sections of approximately equal size; twisted, cracks >5 mm wide and >20 mm long; splits <5 mm wide and >20 mm long; bolters, carrots that had formed a seed head; bent; and a 0 to 5 scale adapted from Belair and Boivin (3), as described previously. Carrots in categories 0-1 were again considered first grade. The length and diameter of these carrots were measured. The weight and number of carrots in each category was also recorded.

Statistical analysis. The relationship between nematode numbers and measured variables was calculated using the Pearson's correlation coefficient (r) and a t test conducted for significance of association. For variables with a significant correlation, linear regression analysis was conducted to describe predictive relationships. All statistical analyses were conducted using Genstat for Windows (Version 5.4.2).

Spatial distribution of *P. crenatus* in carrots fields. The spatial distribution of *P. crenatus* extracted from soil and roots from each of the plots at each time were analyzed using the SADIE program (Version 1.22) (20). The theory underlying SADIE has been previously described (17,19) and implications discussed (35,36). Briefly, this technique calculates the shortest distances needed to move spatially referenced data to depict "regular" and "crowded" spatial patterns using the same number of sampling units as calculated by a transportation algorithm. For all simulations, the maximum number of 5,967 randomizations was used. These distances are then summed to calculate the overall "distance to regularity, D " and "distance to crowding, J " values. The null hypothesis of no spatial dependence was tested using a one-sided test for aggregation. This is expressed as the index of aggregation, which is equal to the ratio of expected and observed distances to regularity. Values equal to one indicate a random spatial pattern, values less than one suggest a regular pattern, and values greater than one suggest an aggregated pattern (17,19).

RESULTS

Prevalence and incidence of plant-parasitic nematodes. *Pratylenchus* spp. were the main species associated with carrot crops in northern Tasmania (Table 1). *Pratylenchus* spp. were present in 28 of 33 carrot crops surveyed and occurred at a mean population density of 62.5/200 cm³ of soil in crops in which it was detected (Table 1). Stunt nematodes (*Tylenchorhynchus* spp. and *Merlinius brevidens*) occurred in 14 crops in small numbers, at an average density of 10.6/200 cm³ of soil (Table 1). Other genera occurred at low densities, on average less than 5/200 cm³

of soil in those crops in which they were detected (Table 1). These included *Pratylenchus* spp. and *Helicotylenchus* spp. Second-stage juveniles of clover cyst nematode (*Heterodera trifolii*) were detected in soil from three crops. Low numbers of root-knot nematode (*Meloidogyne* spp.) were also found in five crops. *P. crenatus*, *P. neglectus*, *P. thornei*, and *P. penetrans* were confirmed from 14, 4, 2, and 1 of 17 crops, respectively (Table 2). A stunt nematode from one farm was identified as *Merlinius brevidens*. Second-stage juveniles of *Meloidogyne* were identified as *M. fallax* from two crops.

Effect of *P. crenatus* on carrot yield and quality in 2001. The number of *P. crenatus* extracted from soil remained similar throughout the season (Table 3). The average number of *P. crenatus* extracted from roots was highest at 58 DAS,

but declined at later samplings, with less than one *P. crenatus*/g dry weight of root extracted at 93 and 123 DAS (Table 3). The number of *P. crenatus*/g dry weight root at 58 DAS was significantly negatively correlated with the dry weight of roots per plant ($r = -0.48$, $P = 0.01$) and foliage per plant (g) at 58 DAS ($r = -0.43$, $P = 0.01$). The regression equation (Table 4) demonstrated that mean root weight of plants in plots with the highest number of *P. crenatus* (260.6/g dry weight root) was less than half that predicted when no *P. crenatus* were present. At 58 DAS, *P. crenatus*/200 cm³ of soil or in roots or soil at 93 and 123 DAS was not significantly correlated with the dry weight of roots or shoots at 58 DAS.

P. crenatus in roots or soil at any time (58, 93, or 123 DAS) was not significantly correlated with the fresh weight of carrots

Table 2. Identification of nematode species in 17 carrot fields in Tasmania (2000 to 2001)

Location	<i>Pratylenchus crenatus</i>	<i>P. neglectus</i>	<i>P. thornei</i>	<i>P. penetrans</i>	<i>Meloidogyne fallax</i>	<i>Merlinius brevidens</i>
Burnie	+					
Cressy	+					
Forth		+				
Heybridge	+					
Kindred	+					
Kindred	+					
Penguin		+	+			
Penguin	+		+			
Unknown	+					
Sassafras	+					
Sassafras	+					
Somerset	+			+		
Sprent		+			+	
Sulphur Creek	+	+			+	+
Preservation Bay	+					
Thirlstane	+					
Wesley Vale	+					
Total fields	14	4	2	1	2	1

Table 3. Mean numbers of *Pratylenchus crenatus* in soil and roots, carrot yield, and plant density (2001)

	Average	Minimum	Maximum	Standard deviation
<i>P. crenatus</i> /200 cm ³ soil				
58 days after sowing (DAS)	86.9	19.9	223.1	46.3
93 DAS	75.6	9.2	258.4	53.2
123 DAS	80	14.8	245	59.3
<i>P. crenatus</i> /g dry weight root				
58 DAS	99.3	0	260.6	75.8
93 DAS	0.02	0	0.2	0.04
123 DAS	0.02	0	0.36	0.06
Plant density (/m ²)	42.2	32.8	52.2	4.7
Yield of carrot (t/ha)	53.1	39.6	70.4	7.7
First-grade carrot (% by weight)	71.8	51.8	86.9	9.4

Table 4. Linear regression analysis between numbers of *Pratylenchus crenatus* extracted from tissue and soil at 58 days after sowing (DAS), and from soil at 123 DAS and yield and quality of Kuroda carrot (2001)

<i>P. crenatus</i> /g dry weight root at 58 DAS			
Dry weight of roots/plant (58 DAS)	$Y = 0.2469 - 0.0005X$	$P = 0.002$, adjusted $R^2 = 0.21$	
Dry weight of foliage/plant (58 DAS)	$Y = 0.7669 - 0.0008X$	$P = 0.08$, adjusted $R^2 = 0.15$	
<i>P. crenatus</i> /200 cm ³ soil at 58 DAS			
Carrots/ha (123 DAS)	$Y = 44.75 \times 10^6 - 388.91X$	$P = 0.01$, adjusted $R^2 = 0.14$	
Yield (t/ha) (123 DAS)	$Y = 55.976 - 0.0542X$	$P = 0.02$, adjusted $R^2 = 0.10$	

($n = 100$) from each plot, weight in categories 0-1, 2-5, or any of the abnormal categories, or in the average weight of a carrot, or average weight of a carrot in categories 0-1, 2-5 at harvest (130 DAS). This suggested that *P. crenatus* had not contributed to stunting of carrot or abnormalities in this trial.

P. crenatus extracted from soil at 58 DAS was significantly correlated with plant density at harvest ($r = -0.42$, $P = 0.01$), and with estimated yield potential

(t/ha) ($r = -0.39$, $P = 0.05$). A regression between numbers of *P. crenatus* extracted from soil at 58 DAS and potential plot yield (t/ha) at harvest (Table 4) predicted yields of 56.0 and 43.9 t/ha at population densities of zero and the maximum density recorded (223 *P. crenatus*/200 cm³ soil), respectively, a difference of 12.1 t/ha. *P. crenatus* in roots or shoots at other times was not significantly correlated with plant density or estimated yield potential at harvest.

Table 5. Mean numbers of *Pratylenchus crenatus* in soil or roots, carrot yield, and plant density (2002)

	Average	Minimum	Maximum	Standard deviation
<i>P. crenatus</i> /200 cm ³ soil				
58 days after sowing (DAS)	119.2	10.1	354.4	73.4
116 DAS	76	0	220	51.3
<i>P. crenatus</i> /g dry weight root				
58 DAS	734.0	200.8	1,455.0	352.2
116 DAS	0.11	0	0.61	0.17
Plant density (/m ²)	55.3	44.3	72.3	6.2
Yield of carrot (t/ha)	62.6	42.2	83.4	10.1
First-grade carrot (% by weight)	80.7	64.4	90.8	6

Table 6. Pearson's correlation coefficients (r) and probability levels in parentheses (P) between *Pratylenchus crenatus* populations at 58 days after sowing (DAS) and yield and quality attributes of Kuroda carrot at two sampling dates in 2002

	<i>P. crenatus</i> /200 cm ³ soil	<i>P. crenatus</i> /g dry weight root
58 DAS		
Dry weight of foliage/plant (g)	ns ^a	-0.45 (0.05)
Dry weight of root/plant (g)	ns	-0.48 (0.05)
116 DAS		
Fresh weight (all categories)	ns	-0.4 (0.01)
Fresh weight (categories 0-1)	ns	ns
Fresh weight (categories 2-5)	-0.36 (0.05)	-0.31 (0.05)
Fresh weight (abnormal ^b)	ns	ns
Average individual carrot weight (categories 0-1)	ns	-0.36 (0.05)
Average individual carrot weight (categories 2-5)	ns	ns
Average individual carrot weight (all categories)	ns	-0.36 (0.05)
Average carrot length (categories 0-1)	ns	-0.47 (0.05)
Plant density (/ha)	-0.44 (0.05)	-0.38 (0.05)
Yield (t/ha)	-0.35 (0.05)	-0.53 (0.01)
Yield (categories 0-1) (t/ha)	ns	-0.43 (0.01)
Yield (categories 2-5) (t/ha)	-0.41 (0.01)	-0.36 (0.05)

^a ns = not significant.

^b Abnormal categories include forked, twisted, cracks of at least 5 mm, bolters, and bent.

Table 7. Linear regression analysis between numbers of *Pratylenchus crenatus* extracted from roots and soil at 58 days after sowing (DAS), and soil at 116 DAS, and yield and quality of Kuroda carrot (2002)

<i>P. crenatus</i> /200 cm ³ soil at 58 DAS		
Yield (t/ha) (116 DAS)	$Y = 65.09 + -0.045X$	$P = 0.002$, adjusted $R^2 = 0.19$
<i>P. crenatus</i> /g dry weight root at 58 DAS		
Dry weight (g) of foliage/plant (58 DAS)	$Y = 0.226 + -0.0001X$	$P = 0.008$, adjusted $R^2 = 0.15$
Dry weight (g) of roots/plant (58 DAS)	$Y = 0.040 + -1.41 \times 10^{-5}X$	$P = 0.002$, adjusted $R^2 = 0.21$
Fresh weight (g) of 100 carrots (116 DAS)	$Y = 12,058.88 + -1.29X$	$P = 0.01$, adjusted $R^2 = 0.13$
Mean length (cm) of a carrot in first grade categories (116 DAS)	$Y = 160.36 + -0.008X$	$P = 0.002$, adjusted $R^2 = 0.19$
Mean weight (g) of carrot in first grade categories (116 DAS)	$Y = 117.6 + -0.01X$	$P = 0.03$, adjusted $R^2 = 0.10$
Mean weight (g) of all carrots (116 DAS)	$Y = 117.32 + -0.01X$	$P = 0.03$, adjusted $R^2 = 0.10$
Potential plot yield (t/ha) (116 DAS)	$Y = 73.802 + -0.0153X$	$P = 0.0003$, adjusted $R^2 = 0.267$

Effect of *P. crenatus* on carrot yield and quality in 2002. Similar numbers of *P. crenatus* were recovered from soil at 58 and 116 DAS (Table 5). However, greater numbers of *P. crenatus*/g dry weight of root were extracted at 58 DAS in comparison to 116 DAS (Table 5). Low numbers of *Paratylenchus* sp. were also present in soil (results not shown). The number of *P. crenatus* in roots, but not soil, at 58 DAS was negatively correlated with the dry weights of foliage and roots per plant at 58 DAS (Table 6). Regression analysis (Table 7) demonstrated that the average weight of roots per plant at the maximum number of *P. crenatus* (1,455/g dry weight of root) was less than half the weight of roots predicted in the absence of *P. crenatus* (Table 7). *P. crenatus* in roots at 58 DAS were negatively correlated with the fresh weight of 100 carrots sampled from each plot, weight of carrots in categories 2-5, and average carrot weight and length (Table 6). *P. crenatus* in soil at 58 DAS was negatively correlated with the weight of carrots in categories 2-5 (Table 6).

P. crenatus in roots and soil at 58 DAS were negatively correlated with plant density at harvest, estimated yield of carrots (t/ha), and estimated yield of carrots in category 2-5 (t/ha) (Table 6). In addition, numbers of *P. crenatus* in roots at 58 DAS were negatively correlated with estimated yield (t/ha) in category 0-1 (Table 6). Linear regression analysis predicted total yields of 65.1 and 49.2 t/ha at zero and 354.4 *P. crenatus*/200 cm³ soil, respectively (the maximum number recorded in this trial), a difference of 15.9 t/ha (Table 7). Similarly, linear regression analysis predicted yields of 73.8 and 51.5 t/ha at zero and 1,455 *P. crenatus*/g dry weight of root, respectively, a difference of 22.3 t/ha (Table 7). *P. crenatus* in soil or roots at 116 DAS was not significantly correlated with any of the measured yield or quality variables listed (Table 6).

Spatial distribution of *P. crenatus* in carrot fields. According to SADIE, the distribution of *P. crenatus* extracted from soil in fields in both seasons was significantly aggregated at all times after planting (Table 8). The distribution of *P. crenatus* extracted from roots at 58 DAS was random in the trial conducted in 2001, while in the trial conducted the following year, it was significantly aggregated (Table 8).

DISCUSSION

This research has provided new quantitative information concerning the distribution of plant-parasitic nematodes associated with carrot production and the effect and spatial distribution of *P. crenatus* on commonly used carrot varieties in Tasmania. *Pratylenchus* spp. (especially *P. crenatus*) was the most common lesion nematode occurring in carrot crops in northern Tasmania. This species is also common in pyrethrum crops in Tasmania (9). Root-

knot nematode occurred infrequently in carrot crops. *Meloidogyne hapla* and *M. arenaria* have been reported from Tasmania (14); however, this is the first report of *M. fallax*. *M. fallax* was first described from the Netherlands (11,29) and has recently been reported from South Australia (15). It is thought this nematode has been in Australia for many years and is likely to be widespread. The nematode can be particularly damaging to carrot and potato crops at high population densities (15).

In this study, numbers of *P. crenatus* were not associated with defects of the taproot in either trial. This may indicate that Kuroda types of carrot have a different response to feeding by lesion nematode than that described for other carrot types in other studies (22,32). The main impact of *P. crenatus* on Kuroda carrot was at the early stages of seedling emergence and growth. In both trials, high numbers of *P. crenatus* were recovered from roots at 58 DAS and were correlated with reduced foliage and root growth at this stage. The significant negative relationship between *P. crenatus* populations at 58 DAS and plant density at harvest in both trials suggested that *P. crenatus* contributed to seedling death, as was noted by Orion et al. (16) for *P. mediterraneus*. Beyond 58 DAS, there was poor recovery of *P. crenatus* from roots in either year. The rapid growth of the taproot later in the season would have reduced the number extracted per gram of root. However, the finding that *P. crenatus* populations in the soil did not increase over the life of the crop suggested poor multiplication of *P. crenatus* during the season, and that Kuroda carrot may become resistant to nematode feeding with age. Further work is required to assess the multiplication rate of *P. crenatus* on different carrot varieties. *P. crenatus* at 58 DAS were negatively correlated with average carrot weight in 2002 (but not in 2001), suggesting that nematode feeding early in the season could reduce carrot size at harvest. The discrepancy between the two trials is probably due to the greater range of nematode population densities of *P.*

crenatus per gram roots at 58 DAS in the trial in 2002 in comparison to 2001. *P. crenatus* at 58 DAS extracted from either soil or roots was negatively correlated with potential plot yield and yield of first-grade carrots in both trials. Linear regression analysis determined potential yield differences between those plots with the highest number of *P. crenatus* in comparison to those with none ranging from 12.1 t/ha (2001) to 22.3 t/ha (2002).

The strong spatial dependence of *P. crenatus* extracted from soil and roots demonstrated in both trials is typical of the patchy distribution of nematodes described by several investigators (7,8) and emphasizes the need for intensive sampling of fields to gain a reliable measure of nematode numbers prior to planting. Identifying areas where nematode numbers are high may also give growers flexibility for the application of nematicides in high risk areas.

We have been able to describe the spectrum of plant-parasitic nematodes associated with carrot production in Tasmania, Australia, and attribute the main effect of *P. crenatus* on Kuroda types of carrot to seedling death. Future research will aim at identifying resistant carrot varieties and alternative crops that can be used in rotation to reduce nematode numbers and hence the risk of disease.

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Table 8. Analysis of the spatial distribution of *Pratylenchus crenatus* extracted from soil and roots in carrot fields in 2001 and 2002 using SADIE^a

	<i>I</i> _a	<i>P</i>
2001		
Root 58 DAS	1.213	0.104
Soil 58 DAS	1.528	0.008
Soil 93 DAS	1.643	0.002
Soil 123 DAS	1.595	0.003
2002		
Root 58 DAS	1.446	0.018
Soil 58 DAS	1.268	0.07
Soil 116 DAS	1.629	0.003

^a SADIE = spatial analysis by distance indices; *I*_a = index of aggregation derived from SADIE analysis; DAS = days after sowing.

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