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Effect of Forage and Grain Pearl Millet on *Pratylenchus penetrans* and Potato Yields in Quebec[1]

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Abstract: Rotation crop experiments were conducted from 1998 to 2000 to assess the impact of forage and grain pearl millet (*Pennisetum glaucum*) on *Pratylenchus penetrans* populations in three potato (*Solanum tuberosum* cv. Superior) fields in Quebec. These crops were compared to oats and(or) barley. Forage millet had a suppressive effect on *P. penetrans* populations after a 1 year rotation. The following year, marketable potato yields were negatively correlated with initial *P. penetrans* densities on two experimental sites ($r = -0.454$, $P = 0.044$; $r = -0.426$, $P = 0.017$). Average marketable and total yields were increased by 10% in plots previously grown in forage millet hybrid CFPM 101 when compared to oats ($P = 0.017$). Damage functions between preplant nematode density (Pi) and marketable yield ($y = 42.0 - 4.091 \log_{10} [Pi + 1]$) and total yield ($y = 43.9 - 4.039 \log_{10} [Pi + 1]$) of potato were established on pooled yield data. Forage pearl millet is an efficient and economically viable alternative for managing root-lesion nematodes and improving potato yields in Quebec.

Key words: pearl millet, *Pennisetum glaucum*, potato, *Pratylenchus penetrans*, root-lesion nematode, rotation crop, *Solanum tuberosum*.

The root-lesion nematode, *Pratylenchus penetrans,* is a serious pest of many crops in North America. In eastern Canada, this endoparasitic nematode causes substantial yield reductions in high-value crops such as potato (*Solanum tuberosum*) (Florina and Loria, 1990; Olthof, 1986, 1987, 1989; Olthof and Potter, 1973). In Quebec, damaging population densities have been recorded (Vrain and Dupré, 1982) but no potato yield losses have been reported.

In Quebec, oats (*Avena sativa*) and rye (*Secale cereale*) are commonly grown in rotation with potato. Unfortunately, both cereals are good hosts of the root-lesion nematode, which multiplies to high densities in the roots (Bélair et al., 2002a; Florini and Loria, 1990; MacDonald and Mai, 1963; Olthof, 1980). Thus, their use as rotation crops increases the nematode pressure on subsequent crops, thereby potentially decreasing yields. The reliance on soil fumigation with nematicides such as metham sodium is now a common practice in Quebec to control *P. penetrans* and increase potato yields. The use of crops that are unfavorable for the root-lesion nematode may help to reduce or eliminate use of the costly nematicide applications in these soils. Hybrids of pearl millet (*Pennisetum glaucum* L.) forage and grain types have been developed by Agriculture Environmental Renewal Canada (AERC Inc.) and are well adapted to the climatic and soil conditions of eastern Canada. Hybrids of grain pearl millet are dwarf and early maturing, and produce 5 to 10 head-bearing tillers/plant. Potential grain yields vary from 2.5 to 3.5 t/ha. Grain millet has several potential uses including use as feed for beef and dairy cattle and in poultry rations. In contrast, forage pearl millets are highly photoperiod sensitive and produce high levels of forage (4 to 7 t/ha of dry matter) beginning 50 days after planting. Generally two to three cuts are taken during a season. Forage also is used for silage and incorporated into the soil as organic matter. Both forage and grain millet hybrids are poor hosts of *P. penetrans* (Bélair et al., 2002a; Jagdale et al., 2000). In southern Ontario, Ball-Coelho et al. (2003) reported that a rotation with forage pearl millet suppressed *P. penetrans* populations and increased potato yields compared to rye.

The objective of our work was to assess the impact of forage and grain pearl millet on *P. penetrans* populations and their impact on subsequent potato yields in Quebec.

Materials and Methods

From 1998 to 2000, crop rotation experiments were conducted at three experimental sites in Quebec. These were located on two different commercial potato farms—one site in Val-Barrette (VB1y) and two other sites in Notre-Dame-de-la-Paix. At the latter location, the two experiments were established in the same potato field; the first was established in 1998 for 2 consecutive years with the same rotation crop (ND2y), and the second in 1999 (ND1y) for a 1-year rotation. On all sites, potatoes were grown prior to experimentation. Treatments were arranged in a randomized complete block design with four replications. At the ND1y and ND2y sites, the rotation crops were barley cv. Béluga, forage pearl millet hybrid CFPM 101, grain pearl millet hybrids CGPM H5 and CGPM H6, and oats cv. Ultima. At the VB1y site, the crops were CFPM 101, CGPM H5, and oats cv. Ultima. Seeds were obtained from local seed suppliers, and pearl millet hybrids were provided by AERC Inc., Ottawa, Ontario.

Plots were 6.1 m wide × 14 m long in all three experiments. In 1998, crops were sown on 2 June and received

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300 kg/ha 14-15-4 fertilizer the week before sowing. In 1999, crops were sown on 2 June in Val-Barrette and on 9 June in Notre-Dame-de-la-Paix and received 150 kg/ha 34-0-0 and 150 kg/ha 10-10-20 fertilizer the week before sowing. At Val-Barrette, poultry manure was added on 2 June 1999 into the soil at 16,850 liters/ha. At Notre-Dame-de-la-Paix, both sites were amended with biosolid (paper mill sludge) at 10 t/ha 1 week before sowing. Millet hybrids were sown 13.5 cm apart within a row and 15 cm between rows. Seeding rate of grain pearl millet hybrids was 7 kg/ha for about 420,000 plants/ha and forage type at 10 kg/ha for 388,000 plants/ha. Oats and barley were both sown at 120 kg/ha.

At both locations, herbicides were used to control weeds. At Notre-Dame-de-la-Paix, the herbicide pendimethalin at 1.25 kg a.i./ha was applied on 9 June 1999 as a pre-emergence treatment, and glyphosate was sprayed at Val-Barrette on 1 June 1999 at 2.47 kg a.i./ha 1 week prior to seed bed preparation.

In 2000, all sites were cropped with potato cv. Superior. In Val-Barrette, potato tubers were planted on 23 May 2000, 45 cm apart within a row and 100 cm between rows. All plots received 1,233 kg/ha 10-10-12, 616 kg/ha 10-0-17, and 56 kg/ha urea. On 19 September, potato tuber yields were estimated by harvesting a 10-m section of one row per plot. All potato tubers were graded as follows: J-size > 8.25 cm tuber diam., B-size < 4.8 cm tuber diam., and A-size between 4.8 and 8.25 cm tuber diam. Total tuber yield was expressed as weight in metric tons per hectare. At Notre-Dame-de-la-Paix, potato seeds were planted on 16 May 2000, 30 cm apart within a row and 90 cm between rows. All plots received 10 t/ha biosolid (paper mill sludge), 1,050 kg/ha of fertilizer (12-7-10) at planting, 112 kg/ha 34-0-0 before flowering, 336 kg/ha 16-0-12, and 101 kg/ha 27-0-0 during the growing season. On 19 September, potato tubers were harvested from two 10-m rows in each plot to assess potato yields. All tubers were graded as described.

Soil and root samples were collected at each site to assess *P. penetrans* population density. For the first samples, 12 soil cores (5-cm-diam. × 20-cm-deep)/plot were arbitrarily collected on the row or between rows. For the mid-season and at-harvest samples, both soil and roots were collected. Roots from 12 plants/plot were removed arbitrarily, and the soil surrounding roots was kept for soil extraction. Soil and roots were placed in plastic bags and stored at 4 °C until nematodes were extracted.

Nematode population density was estimated by processing two subsamples of 50 cm^3 for each plot by the modified Baermann pan method (Townshend, 1963). Roots were washed and two subsamples/plot were placed in a mist chamber for 2 weeks at 22 °C (Seinhorst, 1950). After nematode extraction, roots were oven-dried (65 °C) for 2 days and weighed. Nematodes were counted using a stereomicroscope and expressed as numbers per kg of soil and numbers per g of dry root weight.

Statistical analysis: Nematode counts were transformed using ($\log_{10}[x + 1]$) before statistical analysis. Data were analyzed by the analysis of variance, general linear model (GLM) and correlation procedures (SAS Institute Inc., Cary, NC). Waller's test was used to compare treatments when the analysis of variance showed significant differences among means ($P = 0.05$).

Results

Pratylenchus penetrans was the dominant plant-parasitic nematode species in all the experimental sites, but *P. crenatus* was occasionally observed in low numbers in less than 5% of the soil samples. Rotation crops influenced *P. penetrans* densities in the soil and the roots during the year of the rotation (Table 1). At the VB1y site, average initial nematode density was 266/kg soil with no difference among the plots. Based on mid-season and late-season root densities, nematodes were lower in CFPM 101 and CGPM H5 than in oats ($P = 0.0001$) (Table 1). At the ND1y site, average initial nematode density was 1,481/kg soil with no difference among the plots. Mid-season soil nematode densities were lower under barley and oats but were not different

TABLE 1. *Pratylenchus penetrans* populations in soil and roots under rotation crops at three sites in 1999, A/Val-Barrette 1-year rotation, B/Notre-Dame 1-year rotation, C/Notre-Dame 2-year rotation.

Crops		*P. penetrans*/kg soil			*P. penetrans*/ g dry root	
		Sampling dates			Sampling dates	
			A/VB1y			
		05/27	08/03	08/31	08/03	08/31
CFPM 101		265[a]	173[ab]	745[a]	47[c]	50[c]
CGPM H5		170[a]	380[a]	835[a]	181[b]	93[b]
Oats		275[a]	157[b]	690[a]	564[a]	255[a]
			B/ND1y			
		26/05	27/07	23/09	27/07	23/09
Barley		1290[a]	78[a]	943[a]	208[a]	51[a]
CFPM 101		2613[a]	190[a]	985[a]	27[c]	129[a]
CGPM H5		1053[a]	217[a]	815[a]	40[bc]	116[a]
CGPM H6		1148[a]	263[a]	1215[a]	84[ab]	141[a]
Oats		1303[a]	37[a]	1400[a]	128[ab]	103[a]
			C/ND2y			
	02/06/98	26/05	27/07	23/09	27/07	23/09
Barley	15508[a]	2203[b]	347[b]	1375[ab]	197[a]	68[a]
CFPM 101	7335[a]	1650[b]	393[b]	1375[ab]	24[b]	91[a]
CGPM H5	11740[a]	2455[ab]	883[a]	2265[a]	48[b]	258[a]
CGPM H6	9340[a]	1538[b]	552[ab]	1145[b]	50[b]	150[a]
Oats	10310[a]	4345[a]	383[b]	3130[a]	422[a]	104[a]

The logarithms of values in the same column followed by the same letter within each experimental site are not different ($P < 0.05$) as determined by Waller's test.

from CFPM101, CGPM H5, and CGPM H6 ($P = 0.073$). Based on mid-season root samples, nematodes were lower in CFPM 101 and CGPM H5 than in barley and oats ($P = 0.003$). No difference was detected based on the late-season root and soil samples. At the ND2y site, average initial nematode density was 10,847/kg soil in 1998 with no difference among the plots. In 1999 after a first year of rotation, preplant soil nematode densities were lower under CFPM 101, CGPM H6, and barley than under oats ($P = 0.042$). On the late-season soil sample date, nematode densities were lower under CGPM H6 than under oats and CGPM H5. Based on the mid-season root samples, nematodes were lower in CFPM 101, CGPM H5, and CGPM H6 when compared to barley and oats ($P = 0.0004$).

In 2000, *P. penetrans* densities in the soil or in potato roots were affected by the previous rotation crop except at the ND1y site (Table 2). Preplant soil nematode densities for each rotation crop followed a trend similar to that recorded the previous fall. At mid-season, soil nematode densities were lower in CFPM 101 plots in VB1y ($P = 0.004$) and in ND2y ($P = 0.055$). Root nematode densities on the same sample date were lower in CFPM 101 plots in VB1y ($P = 0.001$) and in ND2y ($P = 0.014$). At harvest, soil and root nematode densities remained lower in the plots previously planted with CFPM 101 at the VB1y ($P = 0.0001$ for soil; $P = 0.0004$ for roots), but no differences were observed at the other sites. At the ND1y site, soil and root nematode densities remained low at all sampling events and were not affected by the previous rotation crops.

Based on the average of all three sites, potato yields were affected by the rotation crops (Table 3). Marketable (grades A + J) and total yield were both increased by 10% ($P = 0.017$) following CFPM 101 when compared to oats and CGPM H5. Marketable and total potato yields were the highest following CFPM 101 on all experimental sites. In ND1y and ND2y, CGPM H6 consistently provided the second best potato yields although no difference was measured between rotation crops on each site. When comparing potato yields from a single year (ND1y) vs. 2 consecutive years of each rotation (ND2y), CFPM 101 plots provided greater yields (marketable, $P = 0.030$; total yield, $P = 0.045$) in the 2 consecutive years vs. single year but no change in yield was detected between the other rotation crops.

Potato yields were negatively correlated with initial *P. penetrans* densities (Table 4). Marketable fresh weight and total fresh weight of potato were correlated with initial population densities at both the VB1y and ND2y sites. The correlations were stronger at the ND2y site than at the VB1y site. No correlation was observed at

TABLE 2. *Pratylenchus penetrans* populations in soil and roots at three sites under the potato crop in 2000, A/Val-Barrette 1-year rotation, B/Notre-Dame 1-year rotation, C/Notre-Dame 2-year rotation.

Crops in 1999	Number of *P. penetrans*: Per kg soil, Sampling dates			Per g dry root, Sampling dates	
A/VB1y					
	05/27	08/03	09/19	07/25	09/19
CFPM 101	43[b]	290[b]	750[c]	1335[b]	33[c]
CGPM H5	175[ab]	1463[ab]	3100[ab]	3633[a]	121[bc]
Oats	328[a]	2629[a]	5175[a]	7214[a]	270[ab]
B/ND1y					
	05/26	07/27	09/23	07/27	09/23
Barley	0[a]	3[a]	63[a]	40[a]	0[a]
CFPM 101	10[a]	23[a]	171[a]	64[a]	6[a]
CGPM H6	35[a]	13[a]	50[a]	51[a]	27[a]
CGPM H5	15[a]	0[a]	38[a]	18[a]	2[a]
Oats	5[a]	3[a]	63[a]	37[a]	57[a]
C/ND2y					
	06/14	07/26	09/20	07/26	09/20
Barley	185[a]	336[ab]	400[a]	659[a]	51[a]
CFPM 101	8[a]	39[b]	450[a]	167[b]	23[a]
CGPM H6	8[a]	531[a]	363[a]	812[a]	99[a]
CGPM H5	15[a]	576[a]	788[a]	390[a]	206[a]
Oats	13[a]	268[ab]	588[a]	754[a]	133[a]

The logarithms of values in the same column followed by the same letter within each experimental site are not different ($P < 0.05$) as determined by Waller's test.

TABLE 3. Potato yields at three sites in 2000, A/Val-Barrette 1-year rotation, B/Notre-Dame 1-year rotation, C/Notre-Dame 2-year rotation.

Treatment	Fresh weight of tubers (t/ha): Grade A[a]	Grade J	Grade B	Grade A + J	Total
A/VB1y					
CFPM 101	24.7[a]	8.0[a]	1.5[a]	32.7[a]	34.3[a]
CGPM H5	24.6[a]	6.4[a]	1.1[a]	31.0[a]	32.1[a]
Oats	24.7[a]	4.9[a]	1.3[a]	29.6[a]	30.9[a]
B/ND1y					
Barley	35.9[a]	3.9[a]	4.0[a]	39.8[a]	41.1[a]
CFPM 101	36.8[a]	6.6[a]	1.7[a]	43.3[a]	45.0[a]
CGPM H6	36.0[a]	6.6[a]	1.6[a]	42.5[a]	44.1[a]
CGPM H5	33.0[a]	6.4[a]	1.6[a]	39.4[a]	41.0[a]
Oats	37.4[a]	4.9[a]	1.4[a]	42.3[a]	43.7[a]
C/ND2y					
Barley	36.7[a]	7.1[a]	1.4[a]	43.8[a]	45.2[a]
CFPM 101	40.5[a]	8.8[a]	1.2[a]	49.3[a]	50.4[a]
CGPM H6	38.1[a]	8.6[a]	1.3[a]	46.7[a]	48.0[a]
CGPM H5	37.4[a]	5.2[a]	1.2[a]	42.6[a]	43.8[a]
Oats	35.7[a]	7.1[a]	1.3[a]	42.8[a]	44.1[a]
Average yields of the 3 sites[b]					
CFPM 101	33.7[a]	7.7[a]	1.5[a]	41.5[a]	42.9[a]
CGPM H5	31.3[a]	5.9[a]	1.3[a]	37.6[a]	38.5[b]
Oats	31.9[a]	5.7[a]	1.3[a]	37.6[b]	38.9[b]

[a]Tuber classification: Grade A between 4.8- and 8.25-cm tuber diameter; Grade J 8.25 cm; Grade B < 4.8 cm. Values in the same column followed by the same letter are not different ($P < 0.05$) as determined by Waller's test.

[b]Each site treated as a block effect.

TABLE 4. Pearson's correlation coefficient (r) between the numbers of *Pratylenchus penetrans* at sowing and potato yield data at two experimental sites in 2000.

Potato data	Number of *P. penetrans* at sowing (log[x + 1]/kg soil)		
	VB1y	ND2y	Both sites
Fresh weight of Grade A[a]	−0.316	−0.477**	0.523****
Fresh weight of Grade B	0.117	0.2189	−0.149
Fresh weight of Grade J	−0.130*	−0.218	−0.222
Fresh weight of Grade A + J	−0.454**	−0.426**	−0.540****
Total fresh weight	−0.364*	−0.425**	−0.536****

[a] Tuber classification: Grade A between 4.8- and 8.25-cm tuber diameter, Grade J > 8.25 cm.; Grade B < 4.8 cm.
* $P \leq 0.10$, ** $P \leq 0.05$, *** $P \leq 0.01$, **** $P \leq 0.001$.

the ND1y site. Regression analyses between the log [x + 1] transformation of Pi and the marketable yield showed a negative correlation at both the VB1y (r = −0.454; P = 0.044) and ND2y (r = −0.426; P = 0.017) sites. When pooling the data from both sites, the total yield showed a highly significant (r = −0.536, P = 0.0004) negative correlation (Table 4). The slopes were −3.92 (P = 0.0004) and −4.09 (P = 0.0003) for total yield and marketable yield, respectively.

Discussion

These results demonstrated that *P. penetrans* reduces potato yields under Quebec's growing conditions. It has showed that a 1-year crop rotation with forage pearl millet hybrid CFPM 101 reduces *P. penetrans* populations and provides an increase in potato yields the following year. Thus, our work confirms results obtained in Ontario, Canada (Ball-Coelho et al., 2003). Traditionally, Quebec's potato growers have used barley, oats, and rye as rotation crops. These crops have been reported to be good hosts of the root-lesion nematode (Bélair et al., 2002a; MacDonald and Mai, 1963; Thies et al., 1995). From our field data, forage pearl millet hybrid CFPM 101 would be an efficient and economically viable alternative to these crops for controlling root-lesion nematodes and improving potato yields. Currently, the total area planted with CFPM 101 as a rotation crop in potato fields was estimated at 400 ha for 2004, which is a 160% increase compared to the previous year (G. Michaud, Semico Inc., pers. comm.). Based on other potato yields recorded in 2002, a single year of pearl millet hybrid CFPM 101 reduced nematode populations and increased marketable yields by nearly 40% (Bélair et al., 2002b). Such potato yield response confirms the earlier work done by Olthof and Potter (1973), which measured a 43% loss in marketable yields of potato at preplant densities of 18,000 nematodes/kg of soil.

Based on our field data, it was possible to calculate damage functions or linear relationships between preplant *P. penetrans* density (Pi) and marketable yield ($y = 42.0 - 4.091 \log_{10} [Pi + 1]$) and total yield ($y = 43.9 - 4.039 \log_{10} [Pi + 1]$) for potato cv. Superior. When nematode populations are high, a curvilinear relationship may be more appropriate but, practically, the relationships are linear. The functions reported here are similar to those reported by Olthof (1986) between *P. penetrans* and potato cv. Russet Burbank from Ontario commercial fields, where total yield = $43.9 - 4.059 \log_{10} [Pi + 200]$. This latter relationship was established with initial population densities ranging from 100 to 18,320 *P. penetrans*/kg soil, whereas the functions in the current study were calculated with nematode densities ranging from 10 to 710 *P. penetrans*/kg soil. It should be stressed that determination of field nematode densities are relatively imprecise, especially for endoparasitic species such as *P. penetrans* where an unknown proportion of the population is located in the roots or organic fraction of the soil samples. Also, plant damage caused by nematodes can be influenced by various factors such as soil type, pathogens, pests, and weather. Further studies are needed to validate these functions and to determine the relative susceptibility of various potato cultivars to *P. penetrans* under Quebec's production system.

In Quebec, potato growers would prefer growing grain pearl millet to forage if it performs as well as oats or barley used as a rotation crop to generate an income from the rotation year. Based on our data and previous reports (Ball-Coelho et al., 2003; Jagdale et al., 2000), the grain pearl millet used so far has performed less well than CFPM 101 under field conditions. Currently, we are evaluating more than 200 pearl millet parental lines for their ability to suppress *P. penetrans* reproduction under greenhouse conditions. Grain pearl millet hybrid CGPMH 1 is currently being evaluated in the field. The level of *P. penetrans* suppression achieved with this hybrid is similar to the level achieved with forage millet CFPM 101 and marketable potato yield response the following year (Bélair et al., 2002b).

Forage pearl millet CFPM 101 has a return potential as a rotation crop due to its high forage value. Millet is readily marketed although soil characteristics and integration into or proximity to livestock operations will dictate whether millet has greater value harvested as forage or left on the field as green manure. Pearl millet is well adapted to Quebec's potato soils, which are light textured with low fertility and low water-holding capacity. Because forage pearl millet needs warm temperatures for establishment in the spring, it is recommended to sow in late May and(or) early June when the probability of frost is low. In a single growing season, forage pearl millet provides up to 15 t/ha of dry matter. In Quebec, CFPM 101 is mowed twice with residues returned as green manure each time. Mowing is important because mature pearl millet residues can be difficult to incorporate and slow to decompose. Such crop residues may cause problems during planting and variability in subsequent crop growth. On fragile, low-organic-matter soils or areas within fields, millet residues help to improve soil structure, retain moisture, and maintain crop productivity.

Future investigations should consider evaluating the number of years of rotation required for obtaining optimum suppression of the root-lesion nematode. Data reported here do not clearly answer if it is beneficial to have more than 1 year of rotation with this crop. Breeding of high-yielding, early-maturing, and nematode-suppressing grain pearl millet hybrids is being pursued. In some potato-growing areas, the fungus *Verticillium dahliae* is responsible for the early-dying disease and causes severe yield losses. Because the interaction with *P. penetrans* is well known, it would be worthwhile to investigate the impact of forage pearl millet on this disease complex. In addition, forage millet could be an interesting crop to work with to investigate the mechanisms and compounds involved in the suppression of *P. penetrans*.

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