THE PATHOGENICITY AND POPULATION MANAGEMENT OF PRATYLENCHUS PENETRANS ON POTATO

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ABSTRACT

THE PATHOGENICITY AND POPULATION MANAGEMENT OF

PRATYLENCHUS PENETRANS ON POTATO

By

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Pratylenchus penetrans (Cobb) Filipjev and Schuurmans-Stekhoven significantly decreased the tuber yields of potato cultivars Katahdin, Kennebec, and Superior, had no observed effects on Russet Burbank, and stimulated an increase in tuber yield in Onaway. All initial population densities (P_i) of *P. penetrans* (P_i = 38, 81, 164, and 211/100 cc soil) decreased tuber yields of Superior; a moderate P_i (81/100 cc soil) decreased yields of Kennebec; and a moderate P_i increased yields of Katahdin, followed by a marked decline at higher P_i's.

In general, yields were related to tolerance of the cultivars to nematode colonization. Highest nematode populations in roots were found in Russet Burbank, followed by Kennebec, Katahdin, and Superior. Symptoms of nematode colonization were confined to reductions in tuber weight and root weight.

Ernest C. Bernard

An estimate of the economic thresholds for root-lesion nematode colonization was made using P_i, cultivar grown, anticipated yield, and value of yield. Each cultivar exhibited a different threshold value. For instance, maximum feasible treatment costs for cultivars at a P_i of 100/100 cc soil are: $38 for Katahdin, $70 for Kennebec, $10 for Russet Burbank, and $160 for Superior.

Field studies demonstrated that fumigation may inhibit the emergence of sprouts if climatic conditions are not within acceptable ranges. Heavy rainfall may seal the soil and prevent fumigant dispersal. Greenhouse nematicide trials using 1,3 D-MIC and PHENAMIPHOS reduced nematode populations 90-95% and increased yields of Russet Burbank 20% and 40%, and Superior 35% and 80%, on treated-infested and treated-noninfested soil, respectively.

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INTRODUCTION

Root-lesion nematodes (*Pratylenchus* spp.) are among the most ubiquitous of phytoparasitic nematodes, occuring in most of the world's agricultural areas (11). Most cultivated crops are susceptible to attack from one or more species of root-lesion nematodes. Most species of this genus are capable of parasitizing a wide range of plant species. The potential economic importance of this genus in Michigan is supported by examination of Cooperative Extension Service samples submitted for nematode analysis from 1963-1973. *Pratylenchus* is distributed throughout the state (10), and is the most frequently encountered phytopathogenic nematode genus in potato (*Solanum tuberosum* L.) fields, often occuring in high numbers (Tables 1 and 2). *Pratylenchus penetrans* (Cobb 1917) Filipjev and Schuurmans-Stekhoven 1941 is the predominant species of root-lesion nematode recovered from potato roots and associated soil in Michigan (N. A. Knobloch, personal communication).

Nematode-incited losses to potato tuber crops are estimated at ten percent annually (35), giving a potential loss of productivity in Michigan of 45,000 metric tons, or \$2.8 million (15). A better understanding of the pathogenic

TABLE 1. Occurrence of plant-parasitic nematode genera in samples submitted from potato fields to the Cooperative Extension Service from 1963-1973.

		Percent of samples containing:							
COUNTY	Total No. Samples	*Meloidogyne*	*Pratylenchus*	*Tylenchorhynchus*	*Heterodera*	*Helicotylenchus*	*Paratylenchus*	*Trichodorus*	*Xiphinema*
Allegan	14	33%	93%	13%	-	-	-	-	-
Bay	15	7	29	21	86%	64%	57%	21%	7%
Berrien	2	-	50	-	-	-	-	-	50
Calhoun	7	-	100	14	-	-	-	-	-
Clinton	30	17	77	-	-	-	-	-	-
Ingham	15	13	60	-	-	-	-	-	-
Lapeer	8	50	87	-	-	-	13	-	-
Lenawee	1	-	100	-	-	-	-	-	-
Luce	1	-	100	-	-	-	-	-	-
Macomb	5	100	80	100	-	-	20	-	-
Manistee	2	-	100	-	-	-	-	-	-
Missaukee	2	-	100	-	-	-	-	-	-
Montcalm	3	-	100	-	-	-	-	-	-
Newaygo	1	100	100	-	-	-	-	-	-
Tuscola	3	-	67	-	-	-	-	-	-
Washtenaw	4	25	100	-	-	-	-	-	-
TOTAL	113	21	75	13	11	8	15	3	2

TABLE 2. Relative abundance of *Pratylenchus penetrans* in samples submitted from potato fields to the Cooperative Extension Service from 1963-1973.

County	No. infested samples	No. from mineral soil	No. from organic soil	% of samples at rating:[1]				
				1	2	3	4	5
Allegan	14	8	6	36%	-	-	9%	55%
Bay	4	4	0	-	50%	50%	-	-
Berrien	1	1	0	-	-	-	-	100
Calhoun	7	7	0	-	29	-	15	56
Clinton	23	9	14	4	13	30	4	49
Ingham	9	9	0	33	-	-	-	67
Lapeer	7	5	2	14	14	14	-	58
Lenawee	1	1	0	100	-	-	-	-
Luce	1	1	0	-	-	-	-	100
Macomb	4	4	0	-	-	-	25	75
Manistee	2	2	0	-	50	50	-	-
Missaukee	2	2	0	-	-	-	-	100
Montcalm	3	2	1	33	33	-	-	33
Newaygo	1	0	1	-	-	-	-	100
Tuscola	2	2	0	50	50	-	-	-
Washtenaw	4	4	0	50	25	-	-	25

1 Rating: 1 = 1-10 nematodes/100 cc soil; 2 = 11-20; 3 = 21-40; 4 = 41-70; 5 = more than 70.

potential of *P. penetrans* and an increased awareness of proper control alternatives should enable workers to make more accurate control recommendations.

The objectives of this study were: 1) to determine the population density of *P. penetrans* necessary to incite an economic decrease in potato tuber yields; 2) to investigate the tolerance of selected potato varieties to *P. penetrans*; 3) to study the influence of fumigant and non-fumigant nematicides on potato growth and tuber yield in both nematode-infested and non-infested soil.

LITERATURE REVIEW

The first species of root-lesion nematode was described in 1880 by DeMan. The generic names _Tylenchus_ Cobb 1893 and _Anguillulina_ Cobb 1893 were used until Filipjev established the genus _Pratylenchus_ in 1934. Cobb reported _P. penetrans_ in 1917 from potato and cotton plants (3).

P. penetrans is a migratory endoparasite. Sontirat _et al_. (36) reported that late larval and adult stages invaded roots more readily than 2nd-stage larvae. Ferris (5) reported that _P. penetrans_ could survive for at least six months in moist, fallow soil at room temperature, and even increased its numbers in refrigerated soil (1-4 C), probably due to the hatching of eggs. Dunn (unpublished research) found that _P. penetrans_ could survive for up to two years at 4 C, but only 1-4 days at -4 C.

A wide range of soil types are suitable for the maintenance and reproduction of _P. penetrans_. Mountain and Boyce (19) found that gravelly sand and sand were most suitable, while clay loam was least suitable for nematode survival and reproduction; whereas Kleyburg and Oostenbrink (9) found approximately equal numbers in clay, sandy peat soil, and sandy soil. _P. penetrans_ appears to survive well in both mineral and organic soils in Michigan (Table 2).

Root and soil population densities of *P. penetrans* often fluctuate during the growing season. Mountain and Boyce (20) noted that the number of root-lesion nematodes per gram of peach root declined during the summer and rose again in autumn. They postulated that the suberization of roots and decay of tissue suitable for nematode colonization led to this decrease in density. Miller and Edgington (16) found a similar natural decline on potatoes, from a high of 90/100 g soil in spring to 45/100 g soil in late summer. Late summer population densities increased over spring populations in other herbaceous vegetables, according to Olthof and Potter (25), except in potatoes and onions.

Hastings (6) estimated that the life cycle of *P. penetrans* required 54-65 days: 25-31 days for egg and larval development, and 29-34 days for maturation of the adult, but he did not give an experimental temperature. Dunn (unpublished data) and Mamiya (12) similarly observed that at 30 C only 30 days were required for complete development. Dickerson *et al*. (4) observed that a soil temperature range of 16-20 C gave the fastest increase in *P. penetrans* populations. Hastings (6) calculated an average rate of egg-laying for *P. penetrans* at 0.8 eggs/day for 30-40 days, while Mamiya (12) estimated the mean rate at between 0.8 and 1.1 eggs/day for 35 days.

P. penetrans has a wide host range, including members of the families Poaceae, Fabaceae (8), Asteraceae and Brassicaceae (38). Oostenbrink *et al*. (30) determined that

P. penetrans was able to survive and reproduce on 164 plant species and varieties (the total number tested).

Root-lesion nematode parasitism can cause the production of hyperplastic, hypoplastic, or necrotic symptoms. Affected plants may exhibit increased secondary root proliferation above the invasion site (37), but more commonly, hypoplastic symptoms, such as reduced shoot and root growth, reduced plant yields, chlorosis, and reduced plant vigor, are seen (4, 18, 37). Necrotic symptoms on the roots consist of lesions of variable size composed of dead cortical cells (20).

Hastings and Bosher (7) reported an average growth reduction of 59.6% for potato seedlings infested with *P. penetrans*. Oostenbrink confirmed the pathogenicity of this nematode on potato, demonstrating that *P. penetrans* could reduce tuber yields 20-50% (26) and total plant weight 50% (27).

The initial population density of nematodes at planting (P_i) is a consistent parameter for estimating yield reductions, Oostenbrink (28) demonstrating a significant negative linear regression between initial density of *P. penetrans* and tuber weight of potato. Olthof *et al.* (23) and Olthof and Potter (25) showed that initial nematode density is related to yield loss in tobacco, potato, and other vegetable crops.

Minimum nematode population levels necessary to incite damage on potato have been established by several authors. Seinhorst (32) stated that 1.0 *P. penetrans*/g soil produced damage on potato plants. Oostenbrink, in a synthesis of earlier work, gave a range of 0.4-1.0/g soil on sandy soil and 0.7-2.0/g soil on loam and organic soils as the minimum number necessary to decrease potato tuber yields (29). Olthof and Potter (25) established the threshold level for economic damage to potatoes at 2.0 nematodes/g soil.

MATERIALS AND METHODS

1. Pathogenicity Studies

Greenhouse Cultivar Trials

Five initial population densities (P_i) of *P. penetrans* and potato cvs. 'Onaway' and 'Russet Burbank' were used to investigate the influence of *P. penetrans* on the growth and development of potatoes. Initial inoculum densities of 0, 51, 84, 137, and 270 *P. penetrans*/100 cc soil were prepared by mixing a steam-sterilized sandy clay loam greenhouse soil with infested soil grown to Navy beans (*Phaseolus vulgaris* L.) for six months in greenhouse benches. Soils of different infestation levels were placed in plastic-lined metal cans 25 x 30 cm, and planted with a seed piece of one of the varieties on November 22, 1972. Each infestation level was replicated ten times in a completely randomized design. Onaway and Russet Burbank were grown for 117 and 134 days, respectively. Plants were maintained under greenhouse conditions at 21 $\pm$ 4 C. One nitrogen treatment was made 45 days after planting using urea at a rate of 250 kg/ha. The appearance and growth of each variety was monitored throughout the trials. At harvest, the tubers of each plant were weighed.

Bioassays to determine P_i's were prepared by planting four 500 ml pots from each infestation level with Navy bean. After 30 days, the roots of each bioassay plant were removed, washed free of soil, cut into 1 cm lengths, and placed in a mist chamber (31). Roots were sprayed with a solution of dihydrostreptomycin sulfate (50 ppm) and ethoxyethyl mercuric chloride (10 ppm) for 45 seconds every 20 minutes (2) for five days. The extracted nematodes were concentrated on a 400-mesh screen, washed into a grated dish of 100 squares and numbers recorded. Twenty randomly chosen squares were counted and the sum multiplied by five to estimate the number of nematodes present.

Field Microplot Cultivar Trials

Microplots similar to those described by Olthof and Potter (24) were used to study the effects of different P_i's on the growth and yield of five potato cultivars. Cylindrical clay drainage tiles 20 x 30 cm were covered at one end with 1.19 mm mesh nylon screen and placed screen down in a 30-cm deep hole. Excess field soil was packed around the outside of each tile. Microplot sites were centered at 0.9 m intervals. Nematode-infested soil containing 0, 38, 81, 164, or 211 *P. penetrans*/100 cc soil was prepared as previously described. These P_i's were determined by the bioassay method described earlier. Soils for all five P_i's were put into tiles on April 25, 1973, at the Michigan State University Entomology Experiment Farm and planted with five potato cultivars ('Katahdin', 'Kennebec', 'Norchip', 'Russet Burbank', and 'Superior') in a completely randomized design with each inoculation level replicated ten times per cultivar. Superior and Russet Burbank were planted as whole seed, the others as cut seed. All cultivars were planted at a depth of 6 cm. During the summer, samplings of each cultivar-infestation combination were examined at three intervals to study the nematode population dynamics. One set of plants was removed 83 days after planting, and two sets each were removed 95 and 105 days after planting. The remaining microplots were removed when each variety had reached its maximum growth. When plants of a given cultivar exhibited signs of dieback, all the plants of that cultivar were removed, washed free of soil, and the tops and root systems and tubers weighed separately. Superior, Kennebec, Katahdin, and Russet Burbank were harvested 116, 122, 133, and 147 days after planting, respectively. The cultivar 'Norchip' was excluded because of unhealthy seed and plants.

Final nematode population densities (P_f) were determined by processing 2 g root samples from each plant using the previously described mist chamber and counting techniques. Additional root samples of cv. 'Superior' were stained with acid fuchsin in a 1:1 solution of 95% ethanol and glacial acetic acid, modified from McBryde (13), and destained with chloral hydrate to determine the position of nematodes in the roots. These destained samples, and additional root samples of Superior preserved in 4% formalin, were also used to count the number of secondary roots. Five 1-cm sections of each preserved root sample were examined.

2. Population Management Studies

Field Soil Fumigation

A study of the effects of soil fumigation on five potato cultivars was initiated at the Montcalm Experimental Farm, Entrican, Michigan, in the spring of 1973. The purpose of this study was to observe differences between fumigated and non-fumigated plants.

On April 30, a mixture of methyl isothiocyanate and chlorinated C3 hydrocarbons (1,3 D-MIC) was applied to one-half of a 31 x 15 m plot arranged as a randomized block design with five replications. Fumigant was injected 20 cm beneath the surface with a broadcast eleven-shank pump-driven applicator at a rate of 142 l/ha. Fumigant was applied to the west 31 x 6.1 m and not applied to the east 31 x 6.1 m, leaving a 31 x 3 m buffer between the two test strips. The entire plot was double-disked 12 and 15 days after soil fumigation. Five potato cultivars ('Katahdin', 'Kennebec', 'Russet Burbank', 'Norchip', and 'Superior') were planted 19 days after fumigation. Russet Burbank and Norchip were planted in 0.9 m rows at 30-cm intervals, the others in 0.9 m rows at 25-cm intervals. Guard rows were planted between blocks and rows were extended beyond treatment boundaries to provide guard plants. Nutrient treatments consisted of 672 kg/ha of 20-10-10 NPK fertilizer at planting, and sidedresses of 78 kg/ha nitrogen 26 and 34 days after planting.

The number of plants for each cultivar-treatment combination was counted 49 days after planting. All five cultivars were harvested with a one-row mechanical harvester 126 days after planting. Tubers were hand-graded and weighed. The buffer zone was not included in the data.

Greenhouse Nematicide Studies

A greenhouse experiment was used to observe the effects of a fumigant nematicide, 1,3 D-MIC, and a non-fumigant nematicide, ethyl 3-methyl-4-(methylethyl) phosphoramidate (PHENAMIPHOS) on the tuber yield of Russet Burbank and Superior potatoes. The following treatments were used:

1. *P. penetrans*-infested soil;
2. 1,3 D-MIC + steam-sterilized soil;
3. PHENAMIPHOS + steam-sterilized soil;
4. 1,3 D-MIC + infested soil;
5. PHENAMIPHOS + infested soil.

Soil for infested treatments was obtained from a greenhouse culture of *P. penetrans* grown on broadbean (*Vicia faba* L.). All treatments except those involving the fumigant were mixed in a cement mixer and placed in cylindrical 25 x 30 cm metal cans. PHENAMIPHOS was mixed with soil in the cement mixer before being placed in cans. The soil for each can received 0.4 g PHENAMIPHOS 15G, equivalent to a treatment of 4.5 kg ai/ha. Soil to be fumigated was treated by dispensing fumigant with a pipet at a soil depth of 20 cm. The injection hole was covered and the soil surface watered to prevent premature fumigant loss. Each fumigant-treated can received 0.5 ml, the equivalent of 142 l/ha. This soil was mixed five days after treatment to release any remaining fumigant. Bioassays, prepared as described earlier, revealed P_i's in treatments 1, 4, and 5 of 45, 4, and 2 nematodes/100 cc soil, respectively.

Cultivars were planted in the treatment cans January 4, 1974. Each cultivar was arranged as a randomized complete block design with ten replicates. All replicates were oriented in an east-west direction in a greenhouse. Russet Burbank was planted as whole seed, Superior as cut seed. Both cultivars were planted at a depth of 6 cm.

Cultivars were harvested when the majority of the vines began to die back. Superior and Russet Burbank were harvested 126 and 143 days after planting, respectively. Tubers were recovered and weighed. Due to the loss of fresh vine weight during dieback, it was not possible to weigh foliage.

RESULTS AND DISCUSSION

1. Pathogenicity Studies

Greenhouse Cultivar Trials

Pratylenchus penetrans had no significant influence on the yield of Russet Burbank, but Onaway showed increased tuber yield at a moderate P_i (Table 3). These results indicate that potato cultivars respond to nematode colonization in different ways.

Field Microplot Cultivar Trials

The initial population density of *P. penetrans* (P_i) influenced tuber weights of three cultivars (Fig. 1). Yields of Superior were reduced 20-30% at all P_i's, while Russet Burbank yields were unaffected by increasing densities. Katahdin demonstrated a yield increase at a P_i of 81/100 cc soil, followed by large decreases. Kennebec was unaffected up to 81/100 cc soil. These results indicate that the degree of yield reduction is directly related to the cultivar as well as the P_i. Olthof and Potter (25) found that *P. penetrans* reduced tuber yields of cv. Sebago at a P_i of 60/100 g soil. In this study, only Superior exhibited yield decreases at a P_i below 60.

TABLE 3. Effect of initial population density (P_i) of *Pratylenchus penetrans* on tuber yield of two potato cultivars grown under greenhouse conditions.[1]

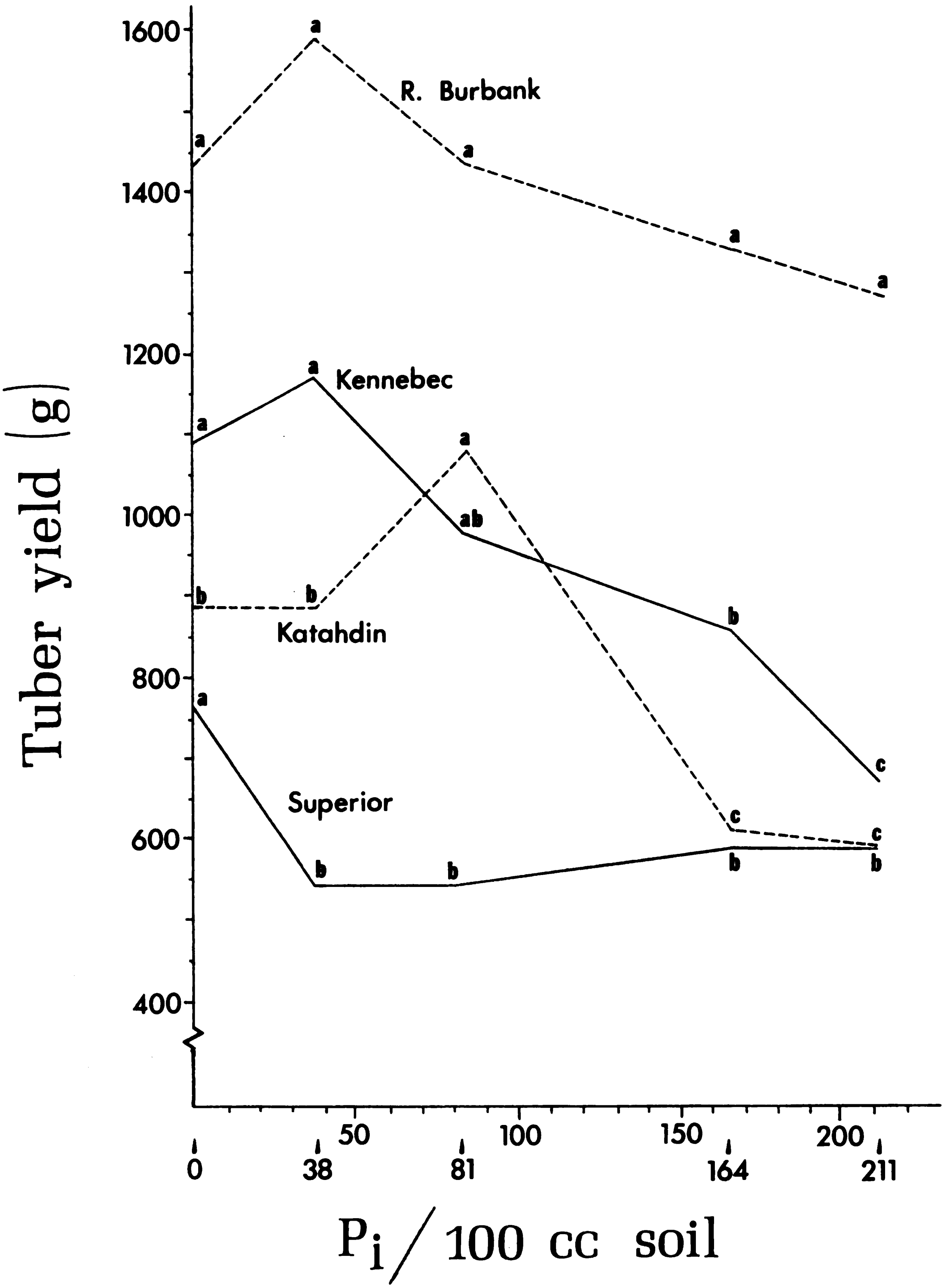
	Tuber weight (g)	
P_i/ 100 cc soil	Onaway	Russet Burbank
0	330 b	358 a
51	398 ab	392 a
84	499 a	396 a
137	462 a	331 a
270	435 ab	373 a

1 Numbers are means of ten replications. Column means followed by the same letter are not significantly different according to Duncan's Multiple Range Test ($P = 0.05$).

FIG. 1. Effect of initial population level (P_i) of <u>Pratylenchus penetrans</u> on the tuber yield of selected potato cultivars.

Points are the means of five replicates. Points with the same letter for a given variety are not significantly different according to Duncan's Multiple Range Test (P = 0.05)

(⬇ = experimental P_i's.)



1600
1400
1200
1000
800
600
400
Tuber yield (g)
R. Burbank
Kennebec
Katahdin
Superior
a
a
a
a
a
a
a
ab
b
c
a
b
b
c
c
a
b
b
b
b
50
100
150
200
0
38
81
164
211
Pi / 100 cc soil

No consistent relationship was found between Pi and Pf for the cultivars in this study, similar to the results of Olthof and Potter (25). P_f's in this study fluctuated considerably. Microplots with the highest P_i possessed a smaller P_f than those with the lowest P_i. This might be explained by Seinhorst's concept of "equilibrium density" (33): i.e., at a certain nematode density the available food is just sufficient to maintain the population. When population density is too large to be supported by the available root tissue, the nematode density falls to some supportable point. This fall can be brought about by several factors: population increase, decrease of suitable feeding sites (competition), or plant physiological changes (e.g. suberization of roots). This hypothesis is supported by examination of microplots sampled during the growing season (Table 5). Densities fluctuated widely between sampling dates, indicating cycling around an equilibrium level.

Nematode equilibrium densities varied between cultivars. They are estimated at 2000/g root for Kennebec and Katahdin, 3000/g root for Russet Burbank, and 1200/g root for Superior. Olthof and Potter (25) estimated the equilibrium density of P. penetrans on cv. 'Sebago' to be 1200-1300/g root.

These data also indicate that P_f's were highest in the highest-yielding cultivar, Russet Burbank (Fig. 1), lowest in the lowest-yielding, Superior, and intermediate in Katahdin and Kennebec. Tolerance to nematode colonization

TABLE 4. Effect of selected potato cultivars on the final population density (Pf) of *Pratylenchus penetrans* in microplots.[1]

	Pf/ g root			
Pi/ 100 cc soil	Katahdin	Kennebec	R. Burbank	Superior
38	2538 ab y	2506 ab y	5814 a x	1937 b z
81	2048 bc y	1780 bc y	2697 c x	907 c z
164	2732 a y	3440 a x	4004 b x	2909 a y
211	1461 c y	1161 c yz	2249 c x	925 c z

1 Numbers are means of five replications. Column means followed by the same letter a, b, or c, and row means followed by the same letter x, y, or z are not significantly different according to Duncan's Multiple Range Test ($P = 0.05$).

TABLE 5. Effect of four potato cultivars on the population dynamics of four initial population densities (P_i) of *Pratylenchus penetrans* at selected intervals during the growing season.[1]

	P. penetrans/ g root							
	Katahdin				Kennebec			
P_i/ 100 cc soil	83[a]	95	105	133	83[a]	95	105	122
38	361	1335	2906	2538	1470	378	1343	2506
81	405	1490	1472	2048	41	423	732	1780
164	2680	1670	4424	2732	905	2230	2272	3440
211	483	633	1860	1460	1240	520	887	1161
	Russet Burbank				Superior			
	83[a]	95	105	147	83[a]	95	105	116
38	1655	1043	3285	5814	----[b]	1033	1114	1937
81	113	665	3307	2697	688	421	1488	907
164	1955	2000	2012	4004	346	348	682	2909
211	469	469	595	2249	1050	933	640	925

1 First-column values are for one plant; 2nd and 3rd-column values are the means of two plants; 4th-column values correspond to the final population density figures of TABLE 4 and are the means of five replicates.

a: days after planting
b: indicates a dead plant

appears to be directly related to tuber yield.

Above-ground symptom expression to root-lesion nematode colonization by these cultivars was not as definitive as reported by other workers. No nematode-induced chlorosis, wilt, or differences in fresh weight of foliar growth were observed. Tuber weights were reduced (Fig. 1) and significant differences in final root weight among cultivars Kennebec and Superior were noted (Table 6). Katahdin was not harvested at the proper time of dieback and results for it may not be accurate. Differences between non-infested and infested root systems for Kennebec are illustrated in Fig. 2.

Roots of plants in this experiment rarely demonstrated signs of necrosis or discoloration. Occasionally, a general tanning of the entire root system was observed, possibly attributable to either nematode colonization or suberization of the roots. In this study, *P. penetrans* was recovered infrequently from stolons and tubers, at densities of 1-4/g fresh weight tissue.

Dickerson *et al*. (4) reported that *P. penetrans* caused lesions on the roots of potato cv. 'Antigo'. Mountain and Patrick (21) discovered that lesions on peach roots infested with *P. penetrans* were caused by hydrolysis of the glycoside amygdalin. A peach cultivar with low amounts of amygdalin supported a high nematode population without noticeable symptoms, whereas a cultivar high in amygdalin was severely stunted in the presence of a lower *P. penetrans* population.

TABLE 6. Effect of initial population density (P_i) of *Pratylenchus penetrans* on fresh root weights of selected potato cultivars.

	Fresh root weight (g)[1]			
P_i/100 cc soil	Katahdin	Kennebec	R. Burbank	Superior
0	11.2 a	29.8 a	8.2 a	12.6 a
38	6.6 a	16.2 b	7.4 a	6.6 b
81	9.8 a	16.4 b	8.0 a	5.8 b
164	8.2 a	12.4 b	5.8 a	5.2 b
211	8.8 a	12.0 b	7.0 a	5.8 b

1 Numbers are the means of five replicates. Column means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (P = 0.05).

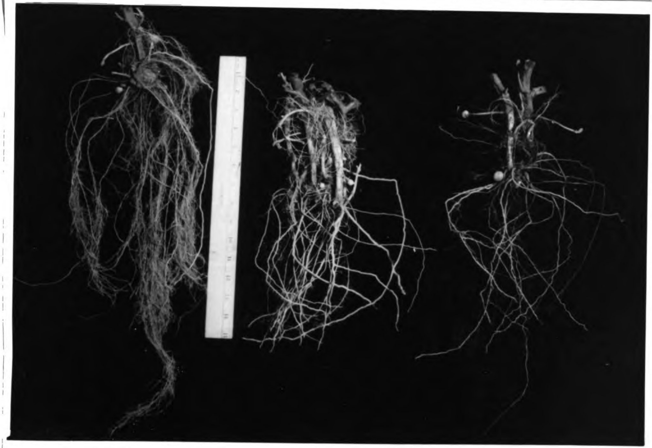


FIG. 2. Effect of initial population level (P_i) of <u>Pratylenchus</u> <u>penetrans</u> on the appearance of Kennebec potato root systems.

(Left to right, P_i = 0, 81, 211 nematodes/100 cc soil)

The absence of root lesions in the cultivars of the present study and their presence in Dickerson's cultivar indicate that a similar process may function in potato.

The nematode population studied in these trials may also be a distinct physiological race from Dickerson's population. Slootweg (34) suggested the possibility of "different races or even species at present indistinguishable morphologically from *P. penetrans*." Olthof (22) differentiated two races of *P. penetrans* in Ontario on the basis of their reproductive potential and pathogenicity on tobacco and celery. In culture pots at Michigan State University, the experimental population of *P. penetrans* caused moderate lesioning of Navy bean roots, and heavy lesioning, blackening and necrosis of broadbean roots.

Examination of stained roots of Superior revealed a varying number of apparently necrotic secondary roots. An analysis of the number of healthy secondary roots versus final tuber yield gave a significant positive correlation (Fig. 3). Generally, more nematodes clustered near these than elsewhere in the root. Possibly this root-lesion nematode population reduces yields by feeding partially upon the bases of secondary roots, reducing total plant nutrient uptake. Further work will be required to determine precisely the role *P. penetrans* plays in secondary root reduction and alteration of other morphological structures and physiological activities.

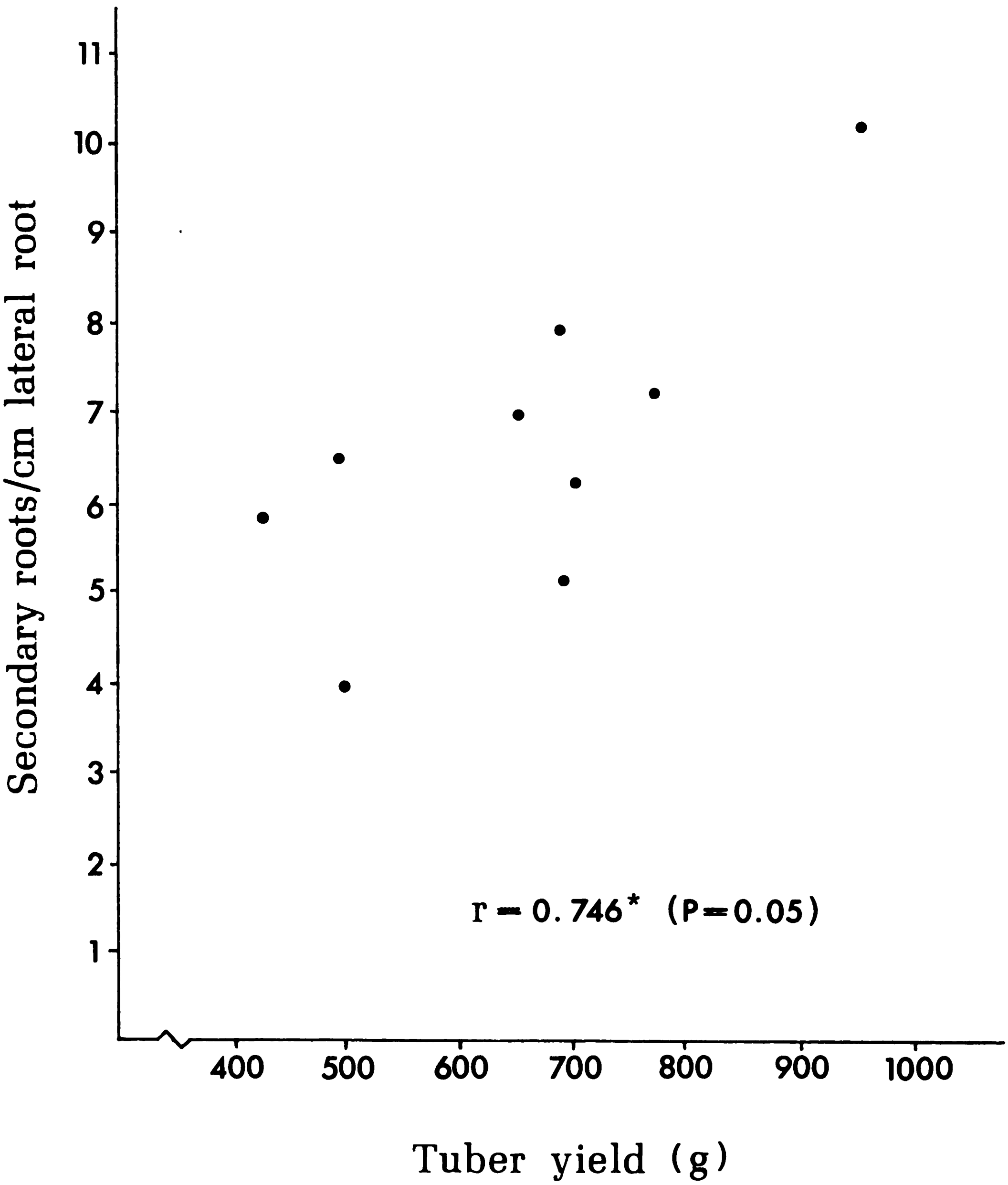


FIG. 3. Correlation of tuber yield with number of secondary roots/cm lateral poot for Superior potatoes.

Using Michigan Department of Agriculture data (14), it is possible to estimate the economic loss threshold for nematode damage (i.e. the minimum yield loss at which treatment becomes feasible). The approximate economic loss thresholds for four cultivars are shown in Figs. 4-7. When the dollar value of the lost yield becomes greater than the cost of control treatment, a grower should seriously consider nematode control.

A simple method was used to predict economic loss thresholds. Three parameters are necessary: 1) anticipated loss in yield due to a known nematode P_i (obtained from Fig. 1); 2) anticipated value of the crop in \$/cwt; 3) anticipated yield/acre. The cost of treatment should be less than the anticipated dollar loss, and a maximum feasible cost for treatment can be calculated by multiplying these three parameters. Several points for a cultivar can be plotted on a graph of cost for treatment versus P_i/100 cc soil to form an economic threshold value. All points below a line connecting experimental points indicate treatment feasibility, while points above indicate treatment unfeasibility. The calculation method for Figs. 4-7 follows:

For the years 1969-1971, the average value of the Michigan potato crop was \$2.70/cwt, with an average yield of 225 cwt/acre (14). The calculation is:

Anticipated yield loss (fraction of yield)
x cwt yield/acre
x \$ value/cwt = maximum feasible cost of treatment.

For a P_i of 80/100 cc soil in a Kennebec field, the maximum feasible treatment cost is, for an anticipated loss of 0.10 (obtained from Fig. 1):

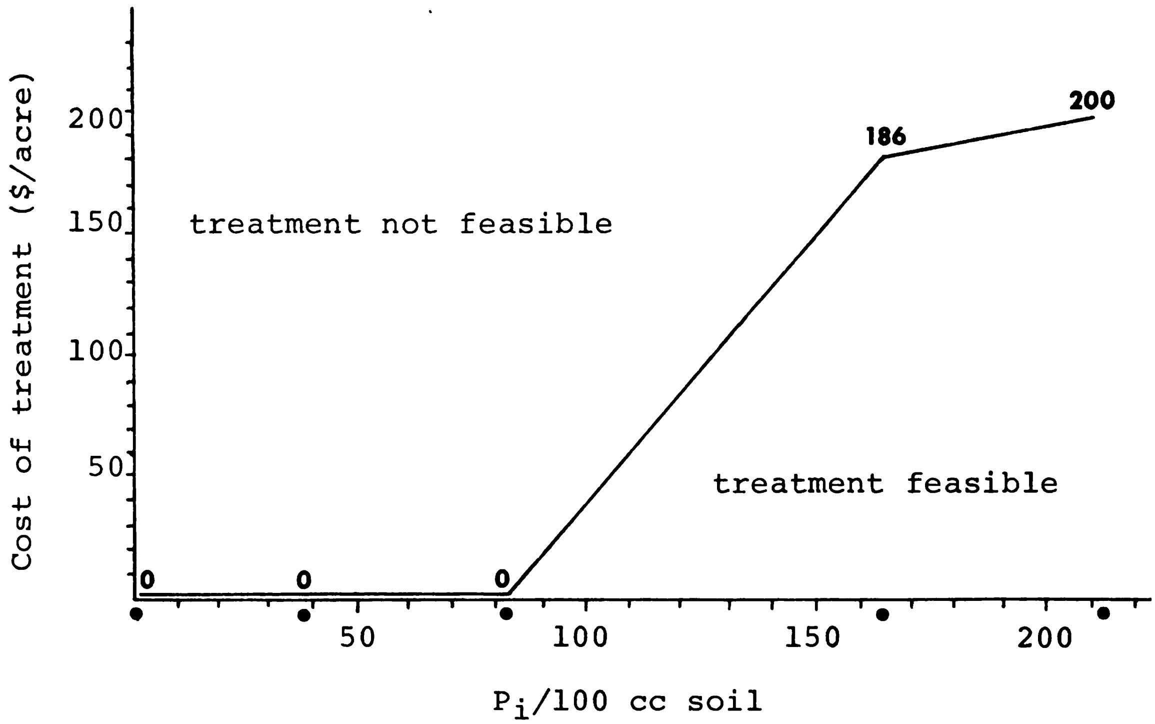
$$0.10 \times 225 \text{ cwt/a} \times \$2.70/\text{cwt} = \$60/\text{a}.$$

Therefore, a control treatment would be profitable for a grower anticipating a 10% loss if treatment costs were below $60/acre. Furthermore, using figures for his own farm or locale, a farmer can reach a more precise estimation of the need for control.

FIG. 4. Feasibility of treatment based on initial population densities (P_i) of *Pratylenchus penetrans* for Katahdin potato tuber yield of 225 cwt/a valued at $2.70/cwt.

FIG. 5. Feasibility of treatment based on initial population densities (P_i) of *Pratylenchus penetrans* for Kennebec potato tuber yield of 225 cwt/a valued at $2.70/cwt.

• = experimental P_i's.


Cost of treatment ($/acre)
200
150
100
50
treatment not feasible
treatment feasible
0
0
0
186
200
50
100
150
200
Pi/100 cc soil

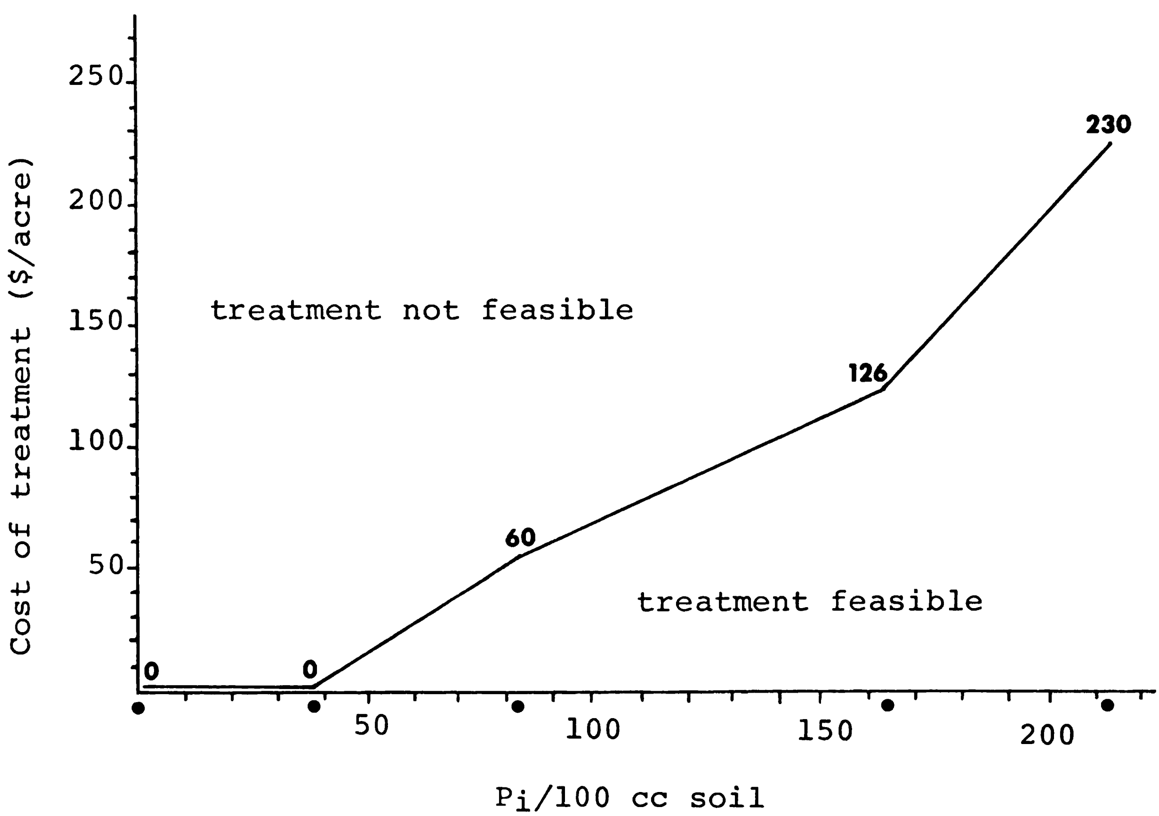
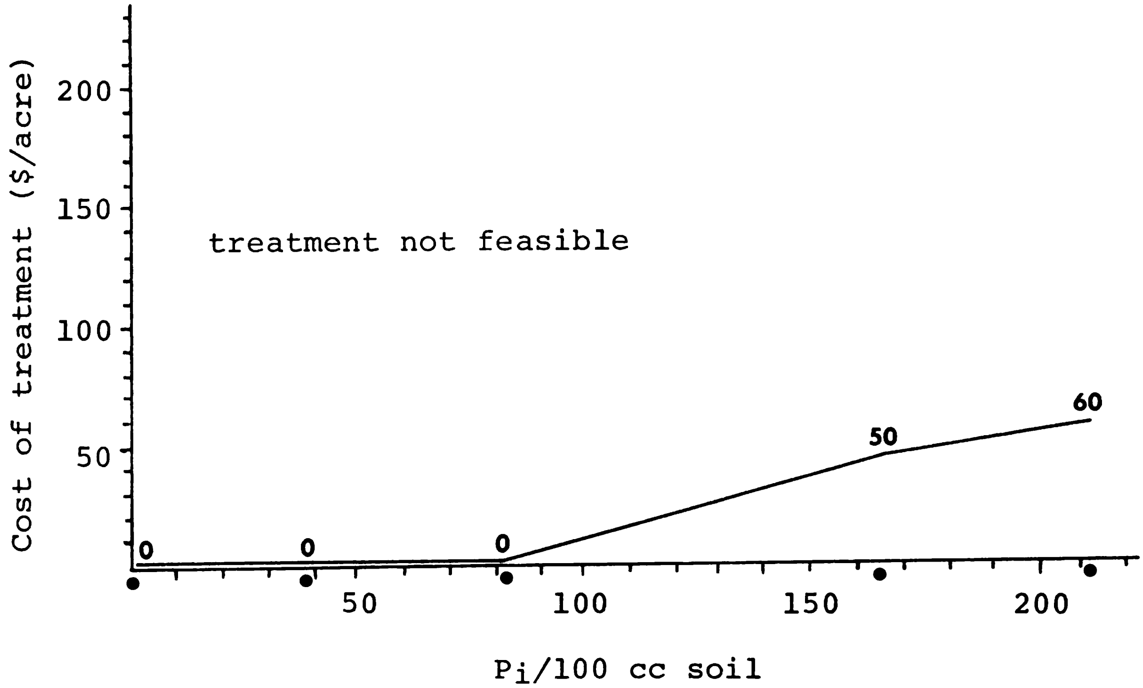

Cost of treatment ($/acre)
250
200
150
100
50
treatment not feasible
treatment feasible
0
0
60
126
230
50
100
150
200
Pi/100 cc soil

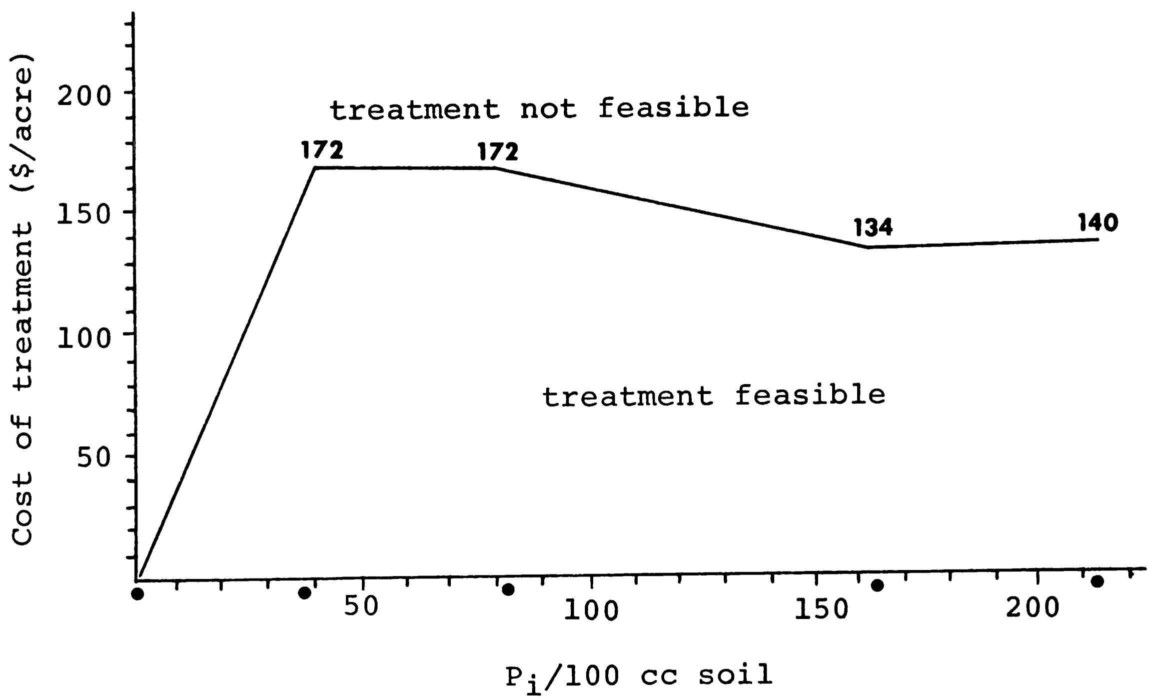
FIG. 6. Feasibility of treatment based on initial population densities (P_i) of *Pratylenchus penetrans* for Russet Burbank potato tuber yield of 225 cwt/a valued at $2.70/cwt.

FIG. 7. Feasibility of treatment based on initial population densities (P_i) of *Pratylenchus penetrans* for Superior potato tuber yield of 225 cwt/a valued at $2.70/cwt.

• = experimental P_i's.



Cost of treatment ($/acre)
200
150
100
50
treatment not feasible
0
0
0
50
60
50
100
150
200
P_i/100 cc soil



Cost of treatment ($/acre)
200
150
100
50
treatment not feasible
172
172
134
140
treatment feasible
50
100
150
200
P_i/100 cc soil

2. Population Management Studies

Field Soil Fumigation

Spring fumigation showed no significant stimulatory effects on the emergence of potato cultivars and gave reduced emergence on Kennebec and Norchip (Table 7). These results may have been confounded by at least two separate factors. Rainfall for April and May were much above average (17): April, 3.25 inches (5 year mean, 2.39), and May, 3.91 inches (mean, 2.91). These heavy rainfalls may have sealed the soil surface too tightly to release fumigant, even with two diskings. In addition, Kennebec and Norchip seed pieces were rotted and not fit for planting. Other varieties were healthy. Weakened seed may have been affected more severely by fumigation. These results suggest that the length of time between fumigation and planting should be varied with regard to the amount of rain. Fall fumigation is less likely to be phytotoxic than spring, due to the length of time between treatment and planting.

Total yields for the field fumigation study are presented in Table 8. As in emergence data, these results indicate that Kennebec and Norchip yields were significantly lower in treated plots. Fumigation had little effect on yields of the other cultivars.

TABLE 7. Effect of spring fumigation on the emergence of selected potato cultivars.

	Percent emergence[1]	
Cultivar	Fumigated	Not fumigated
Katahdin	79 a x	91 ab x
Kennebec	56 b x	75 bc y
Norchip	45 b x	73 c y
R. Burbank	86 a x	96 a x
Superior	78 a x	83 abc x

1 Numbers are the means of five replicates. Column means followed by the same letter a, b, or c and row means followed by the same letter x or y are not significantly different according to Duncan's Multiple Range Test ($P = 0.05$).

TABLE 8. Effect of spring fumigation on the tuber yield of selected potato cultivars.

	Tuber yield (kg)[1]	
Cultivar	Fumigated	Not fumigated
Katahdin	27.4 a x	28.6 a x
Kennebec	18.9 a x	25.2 ab y
Norchip	10.1 b x	15.3 c y
Russet Burbank	20.6 a x	22.7 b x
Superior	22.2 a x	21.1 b x

1 Numbers are the means of five replications. Column means followed by the same letter a, b, or c and row means followed by the same letter x or y are not significantly different according to Duncan's Multiple Range Test ($P = 0.05$).

TABLE 9. Effect of spring fumigation on the mean tuber yield per plant of selected potato cultivars.

	Tuber yield (kg)[1]	
Cultivar	Fumigated	Not fumigated
Katahdin	1.56 a x	1.34 a y
Kennebec	1.45 a x	1.43 a x
Norchip	1.12 a x	1.05 a x
R. Burbank	1.19 a x	1.18 a x
Superior	1.20 a x	1.08 a x

1 Numbers are the means of five replicates. Column means followed by the same letter a, b, or c and row means followed by the same letter x or y are not significantly different according to Duncan's Multiple Range Test (P=0.05).

Using data in Tables 7 and 8, the average yield/plant was calculated (Table 9). A significant difference was observed between fumigated and non-fumigated Katahdin plants. The other cultivars exhibited no significant differences, although each had a slightly higher yield in fumigated areas.

Fumigation decreased plant emergence, but did not decrease yields except in plants grown from weakened seed. Rainfall, temperature, and seed condition made all of these results equivocal at best and difficult to interpret. Because of uncertain climatic and planting conditions, fall fumigation should be favored over spring fumigation.

Nematicide Greenhouse Studies

The nematicide greenhouse studies indicated that 1,3 D-MIC and PHENAMIPHOS similarly affected nematode populations and tuber yields (Table 10). Both materials reduced a P_i of 45/100 cc soil to 4 and 2/100 cc soil, respectively. Yields were increased substantially in both cultivars. Both chemicals applied to infested soil raised yields about 35% on Superior and 20% on Russet Burbank. Applied to non-infested soil, both materials increased tuber yields 80% on Superior and 40% on Russet Burbank.

Using variety trial data it appeared that Russet Burbank was not susceptible to yield loss at these P_i's of *P. penetrans*, while Superior was highly susceptible. However, both cultivars exhibited the same pattern of yield increase

TABLE 10. Effects of nematicides and initial population density (P_i) of Pratylenchus penetrans on tuber yield of two potato cultivars.

Treatment	P_i/100cc sl.	Tuber yield (g)[1] R. Burbank	Superior
Nematode-infested soil	45	243 c	159 c
1,3 D-MIC + infested soil	4	288 bc	217 b
PHENAMIPHOS + infested soil	2	304 ab	213 b
1,3 D-MIC + sterile soil	0	343 a	283 a
PHENAMIPHOS + sterile soil	0	331 ab	289 a

1 Numbers are the means of ten replicates. Column means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (P = 0.05).

when treated with nematicides. The greatest increases occured with treatment of steam-sterilized soil, while smaller increases occured with treatment of infested soil. Differences in cultivar response to treatments may be partially due to effects of nematicides on potential plant nutrients. Altman and Tsue (1) reported an increase in available nitrogen following fumigation with dichloropropane-dichloropropene. It is possible that both types of nematicides in this experiment mobilized nutrients useful to the plants.

The reaction of Russet Burbank to treated-infested soil may be due to the effect of the remaining nematode population. However, from previous pathogenicity trial data it was determined that *P. penetrans* did not appear to affect Russet Burbank yields. Thus it is more probable that 1,3 D-MIC and PHENAMIPHOS had a stimulatory effect in addition to the reduction of nematode populations. A control of sterile soil, however, is needed to prove such a point.

SUMMARY AND CONCLUSIONS

1. Potato cultivars differed in their response to different initial nematode population densities (P_i). Russet Burbank showed no reduction in tuber yield, while Onaway and Katahdin demonstrated increased tuber yield at a P_i of 80 *P. penetrans*/100 cc soil. Kennebec had reduced yields at 80/100 cc soil, and Superior suffered 20-30% losses at all infestation levels.
2. Final nematode populations (P_f) could not be correlated with P_i's or other factors studied here. Variations in mid-season populations probably indicated fluctuations about the equilibrium density for a specific cultivar. It appears that Russet Burbank can support a higher nematode density than Katahdin or Kennebec, with Superior supporting the lowest density.
3. Symptoms attributable to nematode colonization included decreased tuber yields, and in Kennebec and Superior, decreased root weights. Superior demonstrated a positive correlation between yields and the number of secondary roots. Tubers and stolons did not serve as food sources for *P. penetrans*. Root lesions were not seen, lending support to the hypothesis that different physiological races exist in this nematode species.

4. A system for determining economic loss thresholds was established for potatoes using four parameters: 1) cultivar grown; 2) initial density of *P. penetrans*; 3) anticipated yield/acre; 4) anticipated dollar value/cwt. Using these parameters, a grower can predict a need for treatment before the crop is planted.
5. Field fumigation studies indicated that fumigation may inhibit the emergence of sprouts if other conditions are not within acceptable ranges. Rainfall between treatment and planting was greater than normal and this factor may have prevented escape of the fumigant from the soil. The planting of weakened seed may have also contributed to the inconclusive emergence and yield data.
6. Nematicide trials using 1,3 D-MIC and PHENAMIPHOS demonstrated that both nematicides produced about the same results on Russet Burbank and Superior. Application to infested and non-infested soil increased yields 20% and 40%, respectively, on Russet Burbank. On Superior, yields increased 35% and 80% on infested and non-infested soil, respectively. This effect may be partially due to soil nitrogen mobilization by the nematicides and the presence of a residual nematode population in treated-infested soil. However, neither alternative satisfies the yield increase in Russet Burbank from treated-infested to treated non-infested soil, since previous tests indicated a high tolerance to *P. penetrans*.

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