Yield of 'Superior' potatoes (*Solanum tuberosum*) and dynamics of root-lesion nematode (*Pratylenchus penetrans*) populations following "nematode suppressive" cover crops and fumigation

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Studies were conducted at Simcoe, Ontario from 1992 to 1996 to evaluate various cover crop species as possible alternatives to fumigation prior to potatoes (*Solanum tuberosum*). Cereal rye (*Secale cereale*), a common overwinter cover crop in vegetable production systems, is an excellent host for the root-lesion nematode (*Pratylenchus penetrans*) and provides a suitable overwintering host on coarse sandy soils. Vorlex Plus CP and Telone IIB fumigants were compared to 'Domo' mustard (*Brassica juncea*) for the 1993 and 1994 potato crop years. Rye plus red clover (*Trifolium pratense*) was included as a known host cover crop system. Cyanogenic plants including 'Domo' mustard (1994) or 'Cutlass' mustard (1995, 1996), 'Forge' canola (*Brassica rapa*), 'Sordan 79' and 'Trudan 8' sorghum-sudangrass hybrids (*Sorghum bicolor*), and flax (*Linum usitatissimum*) were compared to Vorlex Plus CP fumigant and 'NK557' sorghum (*Sorghum vulgare*) for effects on potato yield and nematodes. Shallow (15 cm) and deep (45 cm) fumigation with Vorlex Plus CP were also compared prior to potatoes for the 1994 to 1996 crop years. There was little detectable difference in percent or days to 50% emergence of potatoes following any treatment. Highest total and marketable yields resulted from Telone IIB fumigation, then Vorlex Plus CP fumigation and 'Domo' mustard, followed by control and rye plus red clover cover. Populations of nematodes surpassed the threshold of 1000 kg^{-1} soil in all treatments and were highest in potatoes following rye plus red clover. Yield and nematode control following sorghum-sudangrass hybrids and mustards appeared to be intermediate between fumigated and not fumigated. All of the cover crops appeared to be root-lesion nematode hosts in the field, and reduction of population levels appeared to result after incorporation or nematode winterkill. Nematode mortality was excellent with fumigation and next best from kill over the winter after 'Sordan 79' incorporation. 'Sordan 79' grown over at least part of the summer followed by incorporation was an alternative to fumigation prior to potatoes. Deep chiselling appears to reduce nematode population,

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possibly by physical action. Where nematode populations warrant, deep fumigation prior to potatoes appears to be of merit.

[Rendement de la pomme de terre (*Solanum tuberosum*) 'Superior' et dynamique des populations du nématode des lésions racinaires (*Pratylenchus penetrans*) à la suite de cultures de couverture « répressives de nématodes » et de fumigation]

De 1992 à 1996, des études ont été menées à Simcoe, Ontario, pour évaluer diverses espèces de cultures de couverture comme alternatives possibles à la fumigation précédant la culture de la pomme de terre (*Solanum tuberosum*). Le seigle (*Secale cereale*), une culture de couverture hivernante fréquente dans les systèmes de production de légumes, est un excellent hôte pour le nématode des lésions racinaires (*Pratylenchus penetrans*) et lui procure un hôte convenable pour hiverner dans les sols sableux grossiers. Les fumigants Vorlex Plus CP et Telone IIB ont été comparés à la moutarde 'Domo' (*Brassica juncea*) pour les années 1993 et 1994 de production de pommes de terre. Le seigle mélangé au trèfle rouge (*Trifolium pratense*) a été inclus en tant que système connu de culture de couverture hôte. Les plantes cyanogénétiques telles la moutarde 'Domo' (1994) ou la moutarde 'Cutlass' (1995, 1996), le canola 'Forge' (*Brassica rapa*), les hybrides sorgho/sorgho herbacé 'Sordan 79' et 'Trudan 8' (*Sorghum bicolor*) et le lin (*Linum usitatissimum*) ont été comparées au fumigant Vorlex Plus CP et au sorgho 'NK557' (*Sorghum vulgare*) quant à leurs effets sur les rendements de la pomme de terre et sur les nématodes. Une fumigation superficielle (15 cm) et une en profondeur (45 cm) avec le Vorlex Plus CP ont aussi été comparées pour les années 1994 à 1996 de production de pommes de terre. Il y avait peu de différence de décelable entre tous les traitements en pourcentage ou en jours pour atteindre 50 % d'émergence des pommes de terre. Les rendements totaux et vendables les plus élevés ont été obtenus avec la fumigation au Telone IIB, puis avec la fumigation au Vorlex Plus CP et la moutarde 'Domo', suivis du traitement témoin et de la couverture de seigle et de trèfle rouge. Les populations de nématodes ont dépassé le seuil de 1000 kg^{-1} de sol pour tous les traitements et étaient les plus élevées pour les pommes de terres qui suivaient la couverture de seigle et de trèfle rouge. Les rendements et la répression des nématodes avec les hybrides sorgho/sorgho herbacé et les moutardes semblaient intermédiaires entre la fumigation et la non-fumigation. Toutes les cultures de couverture semblaient être des hôtes au champ pour le nématode des lésions racinaires et la réduction des niveaux des populations n'apparaît que lorsque intervient la destruction par l'hiver. La mortalité des nématodes était excellente avec la fumigation et n'était surpassée que par la mortalité hivernale après incorporation de 'Sordan 79'. L'emploi du 'Sordan 79' pendant au moins une partie de l'été suivi de son incorporation a été une alternative à la fumigation précédant la culture de la pomme de terre. Le passage en profondeur d'un chisel semble réduire les populations de nématodes probablement par un effet physique. Là où les populations de nématodes le justifient, une fumigation en profondeur avant la culture de la pomme de terre semble de mise.

INTRODUCTION

An overwinter cover crop of cereal rye, *Secale cereale* L., planted in autumn after harvest is an important component of potato *(Solanum tuberosum* L.) and other vegetable production systems in Ontario. Rye is winterhardy and establishes quickly to form a soil cover but, unfortunately, is a good to excellent host for the northern root-lesion nematode *Pratylenchus penetrans* Cobb (Dunn and Mai 1973; Olthof 1980), but not for *Meloidogyne hapla* Chitwood (Potter and Olthof 1993). Thus a rye-host crop rotation contributes to root lesion nematode problems. Many weed, agronomic and vegetable species grown in Ontario, including potatoes, are good to excellent hosts for the root-lesion nematode (Potter and Olthof 1993; Townshend and Davidson 1960). Furthermore, sandy soils where potatoes are typically grown provide an ideal physical environment for *P. penetrans* (Potter and Olthof 1993) over other related species (Florini *et al.*1987; Huettel *et al.*1990). Combining an ideal physical environment and wide host range with a well-adapted pest creates a crop management dilemma in any cropping system. The potato cv. Superior is very susceptible to root-lesion nematodes (Olthof 1986), making it suitable as an assay plant for studies to evaluate remedial treatments or systems.

Soil fumigation for nematode control is usually applied only for high value crops, as the cost outweighs the returns on many crops. Non-chemical, relatively inexpensive remedial options for other crops or organic systems would be valuable. Fumigation is typically applied to the top 15 cm of soil but, because root-lesion nematodes may inhabit soil to the depth of rooting, reinfestation could easily occur. Even with suppressive cover crops, remedial effects are only to the zone of incorporation (Mojtahedi *et al*. 1993). Deeper fumigation may eliminate this possibility. Additionally, reduced soil compaction from chisel-style tillage increases potato yield (Pierce and Chase 1987; Sojka *et al.* 1993) and may provide an additional benefit. However, there is concern about loss of fumigants due to regulatory action. Thus, options other than fumigants for nematode management would be beneficial.

Crops that suppress plant-parasitic nematodes would be an asset in crop production systems for use as cover crops provided they were adapted to local climate, soils, and production systems, and were not phytotoxic to the subsequent crop. Some plants or plant parts can suppress various nematode species (Akhtar and Mahmood 1994; Chitwood 1993; Davis *et al.* 1989, 1991; Dunn and Mai 1973; Rodriguez-Kabana 1986). Selected high glucosinolate cultivars of *Brassica* spp. (Grossman 1993; Mojtahedi *et al.* 1991), and selected cyanogenic sorghum-sudangrass grass (*Sorghum bicolor* (L.) Moench) cultivars (Dunn and Mai 1973; Mojtahedi *et al.* 1993) appear interesting as potential cover crops to suppress nematodes. Mowing the cover crop was reported to enhance efficacy (Grossman 1993). Most of the reported works were on species other than *P. penetrans* and not in soils and climate/soil environment similar to Ontario. Asparagus (Potter and Olthof 1993), and several local native prairie plant species (McKeown *et al.* 1994) are non-hosts to *P. penetrans* but are more suitable as long term crops than as cover crops or short term rotational crops. Thus, there is a need to find adapted plant species/cultivars that fit into our production system, reduce nematode populations, and increase yield of subsequent crops.

Our objectives were to use the potato-cover crop system to : 1) compare efficacy of reputed nematode-suppressive cover-crop species to soil fumigation; 2) compare efficacy of shallow and deep fumigation on nematode populations; 3) assess the impact of cover crops and fumigation on emergence and yield of subsequent potato crops.

MATERIALS AND METHODS

Plots were located at the University of Guelph Simcoe campus, Ontario, Canada. Fields used were in a potato-rye-potato rotation. Prior to and including the spring of 1994, red clover (*Trifolium pratense* L.) was used in the rotation by frost-seeding into the rye. Treatment cover crops were planted in the summer previous to potato; however, for clarity, the data will be presented by calendar yr of potato. Cover crops were planted following turn-down at or near maturity of the preceding rye cover crop. No fertilizer was applied prior to turn-down of the rye except for the 1996 crop yr, when 25 kg ha^{-1} N as 34-0-0 was applied prior to incorporation of the rye. Plots were arranged in a randomized complete block design with six replications, unless otherwise stated.

Cover crops as "fumigants"

Series one

Initial comparisons of late-summer-planted cover crops to fumigants were made in 1993 and 1994. 'Domo' mustard (*Brassica juncea* L.) was compared to Vorlex Plus CP (methyl isothiocyanate/1,3-dichloropropene/chloropicrin; AgrEvo Canada Inc., Regina [*now* Aventis CropScience Canada, Regina]) or Telone IIB (1,3-dichloropropene; Dow-Elanco Canada Inc., Calgary [*now* Dow AgroSciences Canada Inc., Calgary]), rye plus under-seeded red clover (good host combination), or untreated bare soil (1993) or wheat (*Triticum aestivum* L.) (1994). 'Domo' mustard cover crops were sown at 10 kg ha^{-1} on 1 September 1992 and 10 September 1993. Fumigants were applied on 23 April 1993 and 7 October 1993.

Series two

Sorghum-sudangrass hybrids 'Sordan 79' and 'Trudan 8', high-glucosinolate mustards 'Domo' (1993 only, as the line was discontinued) and 'Cutlass' (sister line of 'Domo', substituted after 1993), 'Forge' canola (*Brassica rapa* L.) and 'Norlea' flax (*Linum usitatissimum* L.) were compared to 'NK557' sorghum (*Sorghum vulgare* L.) as a nematode host and Telone IIB (1994) or Vorlex Plus CP (225 L ha^{-1}) fumigants applied with a deep chisel applicator to 30 cm with a 45 cm tillage depth. Mow/no-mow treatments were included in a randomized complete block factorial design with eight treatments and six replications in the last 2 yr of this study. Sorghum/sorghum-sudangrass were planted at 14 kg ha^{-1}, brassicas at 10 kg ha^{-1} and flax at 45 kg ha^{-1} with a grain drill. Planting dates for cover crops were : 30 August 1993, 12 July 1994, and 28 June 1995. For the 1995/1996 cropping yr, one-half of the cover crop plots were mowed (17 August 1994 and 16 August 1995) and allowed to regrow. Sorghum and sudan-grass hybrids were flail mowed prior to plowing, brassicas were plowed under directly. Growth of mustard reached 15 cm in height for the 1993 crop but was in flower at time of incorporation. In all other trials, brassicas were at the green pod stage of growth when incorporated. Plots were rotovated to 15 cm deep on 4 November 1993 and mouldboard plowed to 15 cm on 3 November 1994 and 1995. Fumigation was applied on 8 October 1993, 16 August 1994 and 12 October 1995 when soil conditions were correct; plots were rolled with a cultipacker after treatment to seal the soil surface.

Fumigation studies

Treatments consisted of shallow fumigation using Vorlex Plus CP to 15 cm, deep fumigation to 30 cm with a 45 cm tillage depth, shallow and deep non-fumigated controls and an untreated check. Fumigants were applied with a modified subsoiler with tines 45 cm apart. Fumigant was applied at 225 L ha^{-1} on the same dates as the *series two* experiments. Plots were rolled immediately with a cultipacker after fumigation to seal the soil.

Potatoes

Cut, suberized seed pieces of cv. Superior potatoes weighing approximately 65 g were used in each yr. Plots consisted of three rows 10 m long with the centre row harvested. Between row spacing was 1.0 m and the in-row spacing 0.25 m. Planting dates were : *Series one*, 7 May 1993, 3 May 1994; *Series two*, 29 April 1994, 4 May 1995, and 15 May 1996. Fumigation trials were planted on 28 April 1994, 29 April 1995, and 16 May 1996. Shoots were counted three times per wk, and days to 50% emergence and percent emergence calculated. Plots were harvested as follows : *Series one*, 18 August 1993, and 19

August 1994; *series two*, 9 August 1994, 22 August 1995, and 27 August 1996.

Fumigation studies plots were harvested on 9 August 1994, 24 August 1995, 28 August 1996. After harvest, potatoes were held in storage at 10° C until grading. Potatoes were graded on a Treeways (Treeways Engineering, Hastings, New Zealand) computerized weight grader. Marketable tubers were greater than 45 mm using the Ontario Summer #1 size (O.M.A.F.R.A. grade standards).

Soil types

Series 1, Wilsonville sand 1993, Scotland /Wilsonville sand 1994. *Series two*, Scotland sand, Fox/Watford sand; Scotland/Wilsonville sand in 1994 - 1996 respectively. Soils in the fumigation studies were Scotland /Wilsonville sand 1994, Fox/Watford sand 1995, and Scotland sand 1996. Fertility was based on soil tests and fertilizer applied (kg ha^{-1}) as follows : *series 1,* 1993, 1994, 45 N, 30 P preplant followed by 45 N sidedress; *series two*, 1994, preplant incorporated 45 N, 30 P, 43 K, topdressed twice with 45 N as 34-0-0; 1995, preplant incorporated 90 N, 33 P, 208 K, sidedress : 40 N, 25 N; 1996, preplant : 102 N, 34 P, 85 K; sidedress: 60 N. Fertilization in the fumigation studies (kg ha^{-1}) was as follows : 1993, 45N , 30P, 33 K followed by 2 sidedressings of 45 N as 34-0-0; 1994, 90 N, 33 P, 208 K preplant followed by 40, 20 N as sidedresses; 1995, 102 N, 34 P, 85 K preplant followed by 60 N as a sidedressing.

Weed control was attained using herbicides as follows : 1993, 1994 : preplant incorporated metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide], Novartis Canada, Mississauga, at 1.92 kg a.i. ha^{-1} followed by metribuzin [4-Amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one], Dupont Canada, Mississauga, at 1.2 L a.i. ha^{-1} post emergence; 1995 and 1996, Eptam (s-ethyl dipropylthiocarbamate), Syngenta Canada, Calgary, 4.25 L a.i.ha^{-1} preplant incorporated followed by 1.2 L a.i. ha^{-1} post emergence. Pest management practices for potatoes followed Ontario recommendations. Plots were irrigated as required.

Nematodes

Nematode population density was estimated prior to planting potatoes (25 April 1993, 21 April 1994), during the season (23 June 1993, 13 July 1994) and near harvest (23 August 1993, 8 August 1994) for *series one*. Soil samples for nematode analysis were collected with a 2.5 cm x 45 cm Oakfield sampler, taking soil cores 15 cm deep in the middle row of each plot. Ten cores were collected from each plot to provide a 0.5 kg bulk sample. For *series two* and the fumigation studies, samples for nematode analysis were collected near potato planting dates in spring (21 April 1994, 19 May 1995 and 28 May 1996) and just prior to harvest (8 August 1994, 22 August 1995, 22 August 1996) in each yr. Nematodes were recovered from 50 g sub-samples by the Baermann pan method (Townshend 1963) and counted at 50X magnification with a stereoscopic microscope. Data were transformed using $\sqrt{(x+200)}$ prior to analysis; data presented are retransformed. Data were analysed using PC-SAS (SAS Institute, Cary, NC) using a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

Emergence and plant growth

Cover crop or fumigant had no observable effect on emergence or growth of cv. Superior potatoes in 1994 (data not shown). There was no consistent practical effect on percent emergence in any trial. Fumigated crops emerged one to 2 d earlier in 1995 and 1996 compared to some cover crops. Emergence was less than 5% lower in unfumigated, unchiselled plots in 1994 and 1996. No visual evidence attributable to deleterious effects of treatments on crop growth was observed in any yr.

Yield and nematodes

Series one

Yields were lower in 1993 than in 1994. For both yr, highest total and marketable yields followed Telone IIB fumigation (Table 1), with Vorlex Plus CP and 'Domo' mustard being similar, suggesting that 'Domo' mustard could have a positive effect on yield. There was no difference among spring populations of root-lesion nematodes in 1993 or 1994 with spring populations much higher in 1994 (Table 2). Highest post harvest nematode populations followed potatoes grown in the rye plus red clover plots in 1993. Telone IIB-treated plots had the least increase in population over the summer. High populations in the spring of 1994 were above the threshold of 1000 kg^{-1} soil (in pure cultures in sterilized soil) for injury (Potter and Olthof 1977), but there were no differences among treatments. Evidently, the 1993 winter and 1994 growing seasons were very favourable to root-lesion nematodes. The gain in population over the summer of 1994 was lower than 1993. Rye plus red clover rotations should probably not be used on sands infested with root-lesion nematodes prior to nematode sensitive vegetables.

Series two

Mowing was reported to increase efficacy of cover cropping (Grossman 1993) but had no effect in our study on emergence, yield or nematode populations; consequently the data for mowed and no-mowed treatments were pooled. Fumigation, followed by 'Domo' mustard and 'Sordan 79', resulted in the highest yields compared to 'NK557', 'Trudan 8', and flax cover crops (Table 3) in 1994. Fumigation resulted in higher yields in 1995 and there was no difference among cover crops. In 1996, lowest total yield among the cover crops was observed for 'Sordan 79', 'Cutlass' mustard and 'Norlea' flax. There was no difference among treatments in marketable yields.

Table 1. Effect of fumigation and cover crops on the yield of cv. Superior potatoes (1993-1994)[a]

	Yield (t ha^{-1})					
	1993			1994		
Treatments	Total	Marketable	Non-Marketable	Total	Marketable	Non-Marketable
Telone IIB	15.4 a	11.3 a	4.0 bc	25.9 a	23.7 a	2.1 a
Vorlex Plus CP	13.0 ab	9.7 ab	3.4 b	24.5 ab	22.6 ab	1.9 a
'Domo' mustard	12.7 ab	9.5 ab	4.2 b	22.7 abc	20.8 abc	1.9 a
Rye plus red clover	10.2 b	4.6 c	5.6 a	16.8 c	14.5 c	2.3 a
Bare soil 1993, Wheat (1994)	11.1 b	7.4 bc	3.7 b	19.1 bc	16.7 bc	2.4 a

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

Table 2. Effect of fumigation and cover crops on *Pratylenchus penetrans* populations (number kg^{-1} soil)[a]

	1993			1994		
Treatment	Spring	Aug.	Aug.- Spring[b]	Spring	Aug.	Aug.- Spring[b]
Telone IIB	173 a	977 b	804 b	2360 a	2983 a	623 a
Vorlex Plus CP	467 a	1713 ab	1246 ab	2100 a	2037 a	-63 a
'Domo' mustard	427 a	2210 ab	1783 ab	2018 a	2197 a	179 a
Rye plus red clover	393 a	2227 a	1834 a	3407 a	3697 a	290 a
Untreated	463 a	1693 ab	1230 ab	2547 a	3517 a	970 a

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

[b] Increase in nematode density from spring to August.

Table 3. Effect of various cover crops or fumigation on yield of cv. Superior potatoes [a]

	Yield (t ha^{-1})						
	1994			1995		1996	
Treatments	Total	Marketable	Non-Marketable	Total	Marketable	Total	Marketable
Fumigation	19.7 a	16.9 a	2.8 ab	35.0 a	28.9 a	35.8 a	31.5 a
Sorghum 'NK557'	12.3 b	9.9 b	2.4 ab	23.4 b	18.1 b	35.1 ab	31.4 a
'Sordan 79'	14.2 ab	11.7 ab	2.5 ab	22.1 b	17.6 b	29.0 b	24.7 a
'Trudan 8'	11.9 b	9.8 b	2.2 b	20.5 b	15.3 b	33.2 ab	28.6 a
'Domo' mustard	16.0 ab	13.0 ab	3.0 a	-	-	-	-
'Forge' canola	-	-	-	21.1 b	16.5 b	29.4 ab	25.1 a
'Cutlass' mustard	-	-	-	20.9 b	16.3 b	28.6 b	24.9 a
'Norlea' flax	11.2 b	8.7 b	2.5 ab	23.2 b	17.7 b	28.9 b	24.7 a

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

Cover crops were sampled in August of the cover crop planting yr to obtain overwintering nematode populations (Table 4). Highest nematode populations in the fall of 1993 (pre fumigation) were recorded in 'Domo' mustard treatment suggesting that it is a host for *P. penetrans*. All cover crops tested appear to be hosts under local field conditions for root-lesion nematodes. It may be that the crop has to be incorporated for any effect on the pests. Populations decreased over winter in 1993-1994 with the greatest loss in fumigated plots; however populations increased in 'Trudan 8' plots. The largest spring/summer increase came from potatoes in the fumigated plots with lower increases following cover crops suggesting some residual cover crop effect.

Fall 1994 populations were high and did not differ among treatments. There was a large overwinter drop in populations, without statistical differences among treatments. However, populations exceeded the threshold of 1000 kg^{-1} soil in all treatments in spring 1995, indicating that single fumigation or these cover crop treatments grown for one-season only do not provide control to below threshold levels if populations are high enough.

Populations declined precipitously for the fall 1995 and the subsequent 1996 crop yr. There were no differences in the fall, but fumigated plots had the lowest populations by spring, with little recovery of the populations during growth of the potato crop. This may explain the higher yields and lack of effect of treatments observed in 1996. In previous work at this location, a similar overwinter situation was observed with *Meloidogyne hapla* Chitwood followed by a slow increase in population (McKeown *et al.* 1998). We suspect these declines are at least in part a result of winter kill and, while beneficial for crop production, make comparison between treatments difficult. Nematode populations appear to be quite dynamic over time. Looking at percent population change from fall to spring following fumigation, winter mortality resulted in 92.3, 79.4, and 81.2% kill for 1994 to 1996 respectively. The next best winter population reductions were following 'Sordan 79' cover crops.

Fumigation methods

Highest yields followed deep chisel, deep and shallow fumigation in 1994 (Table 5). Yields were much higher in 1995 and both fumigation treatments had the highest total yields with deep fumigation resulting in the highest marketable yields. In 1996, shallow chisel+fumigation resulted in the highest yields. Lowest marketable yields were from control plots in all 3 yr. This indicates that the physical shattering of the soil was beneficial, and is consistent with our previous findings (McKe-

Table 4. Populations of *Pratylenchus penetrans* over time, following cover crops, fumigation and potatoes

	Nematode populations[a] (number kg^{-1} soil)														
	1994					1995					1996				
Treatments	Fall 1993	Spring 1994	Fall - Spring[b]	August 1994	Aug. - spring[c]	Fall 1994	Spring 1995	Fall - spring[b]	August 1995	Aug. - spring[c]	Fall 1995	Spring 1996	Fall- spring[b]	August 1996	Aug. - sping[c]
Fumigation	1217 ab	93 b	1124 a	1120 a	1027 a	4910 a	1010 a	3900 a	1556 a	546 a	168 a	32 b	136 a	212 a	180 ab
Sorghum 'NK557'	1557 ab	943 a	614 abc	797 a	-146 b	5370 a	2786 a	2584 a	4028 a	1242 a	173 a	77 ab	96 a	373 a	296 ab
'Sordan 79'	1523 ab	483 ab	1040 ab	1003 a	520 ab	4340 a	1706 a	2634 a	3670 a	1964 a	338 a	267 a	71 a	225 a	-42 b
'Trudan 8'	667 b	1133 a	-466 c	1277 a	144 b	4922 a	1944 a	2978 a	4500 a	2556 a	223 a	100 ab	123 a	147 a	47 ab
'Domo' mustard	1897 a	1043 a	854 abc	1460 a	417 ab	-	-	-	-	-	-	-	-	-	-
'Forge' canola	-	-	-	-		5645 a	2593 a	3052 a	3804 a	1211 a	257 a	40 b	217 a	525 a	485 a
Cutlas mustard	-	-	-	-	-	5407 a	1687 a	3720 a	4464 a	2777 a	170 a	83 ab	87 a	188 a	105 ab
'Norlea' flax	1013 ab	1270 a	-257 bc	1067 a	-203 b	4036 a	1856 a	2180 a	2208 a	352 a	193 a	53 b	140 a	123 a	70 ab

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

[b] Difference in nematode population from fall to spring.

[c] Increase in nematode population from spring to August.

Table 5. Yield (t ha^{-1}) of cv. Superior potatoes following deep or shallow fumigation [a]

	Year					
	1994		1995		1996	
Treatments	Total	Marketable	Total	Marketable	Total	Marketable
Untreated	10.5 b	7.2 c	31.1 b	27.2 c	21.1 b	16.2 b
Deep Chisel	14.3 a	9.7 ab	32.4 b	28.8 c	27.9 ab	22.9 ab
Deep Chisel + Fumigation	14.7 a	11.6 a	41.2 a	36.4 a	24.8 ab	20.2 ab
Shallow Chisel	10.9 b	7.4 b	35.2 b	31.1 bc	26.6 ab	22.3 ab
Shallow Chisel + Fumigation	14.1 a	9.2 bc	42.2 a	35.0 ab	29.3 a	24.6 a

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

own *et al.* 1998) and reported effects of zone tillage or chisel plowing to reduce soil compaction (Leach *et al.* 1993; Pierce and Chase 1987; Sojka *et al.* 1993). Additionally, diseases tend to be reduced in well structured soils and roots encountering compacted soils may become predisposed to infection (Leach *et al.* 1993). All treatments resulted in reduced root-lesion nematode populations compared to the untreated control in the spring of 1994 (Table 6), indicating that the physical action alone could reduce numbers of nematodes. Populations were much higher in 1995 but were lower in fumigation treatments. As with the *series two* above, populations declined to below threshold over the winter of 1995/1996 and there were no differences among treatments in 1996. Populations recovered slower in the plots that had been fumigated. The deep fumigation treatments in this work were essentially subsoiling and fumigation in one pass, and should be considered when fumigation is warranted.

Nematicidal chemistry including nitrogenous soil amendments has been reviewed by several authors (Akhtar and Mahmood 1994; Chitwood 1993; Rodriguez-Kabana 1986; Rodriguez-Kabana *et al.* 1987); however, many reports are on species other than *P. penetrans*. The possibility that *P. penetrans* is not controlled or is poorly controlled directly by the cover crops tested, is consistent with our results. In this work, control was probably from breakdown of cover crop residues, tillage, and winter conditions. Possibly, to improve action of similar cover crops, they need to be incorporated at peak content of the active ingredient so that sufficient active ingredient to achieve kill must be

Table 6. Effect of fumigation method on *Pratylenchus penetrans* populations[a].

	Nematode population [a] (number kg^{-1} soil)								
	1994			1995			1996		
Treatments	Spring	Aug.	Aug. - Spring	Spring	Aug.	Aug. - Spring	Spring	Aug.	Aug. - Spring
Untreated	1620 a	1543 bc	-77 c	3545 a	5953 ab	2408 a	188 a	368 ab	180 ab
Deep Chisel	707 b	2157 a	1450 a	3760 a	8463 a	4703 a	147 a	402 ab	255 ab
Deep Chisel + Fumigation	388 b	1007 c	619 abc	1907 b	4632 b	2725 a	118 a	203 b	85 b
Shallow Chisel	803 b	1212 bc	409 bc	3343 a	6770 ab	3427 a	103 a	506 a	403 a
Shallow Chisel + Fumigation	930 b	1643 ab	713 ab	1555 b	5008 b	3453 a	98 a	150 b	52 b

[a] Means of six replications. Means in the same column followed by the same letter are not different using Duncan's Multiple Range Test at the 5% level.

present. Rapid, inexpensive chemical tests for the active compound(s) would be an asset in management. Sufficient volume of crop residues would be required, along with time to decompose and kill the nematodes, and for the toxic byproducts to dissipate to prevent subsequent crop damage. Volume (1% v:v minimum) and a narrow C:N ratio around 20:1 of the amendment are crucial factors in the efficacy of organic amendments to control nematodes through general stimulation of soil microorganisms (Rodriguez-Kabana 1986; Rodriguez-Kabana *et al.* 1987).

Based on our experiments, use of the rye plus red clover combination is risky on sands where *P. penetrans* is present but may be successful in heavier soils where *P. penetrans* is less prevalent (Potter and Olthof 1993). The supposedly suppressive crops appear to be hosts *in situ*, and suppression occurs after incorporation. Suppression may be easier to demonstrate on heavier soils where the nematode is not well adapted (Potter and Olthof 1993). Interestingly, rye cover and rotation resulted in highest tomato yields on this site (McKeown *et al.* 1998), indicating that different cover or rotation patterns are needed for individual crops. While not as good as fumigation, 'Sordan 79' or one of the high glucosinolate *Brassica* spp. could be useful in soil/nematode management for potatoes and low value crops, for organic production, or where time permits as in the case of early vegetables or after grains. If fumigation usage were to be restricted, the cover crops used would become very attractive options compared with the alternative of no chemical control. Winter kill may be a major factor in nematode mortality, suggesting that treatments designed to weaken nematodes prior to winter would be beneficial. If the production system in the field could be managed to weaken the nematodes in the previous summer, winter kill might be enhanced. Yield increases resulting from deep fumigation or tillage indicate that the physical action of deep tillage adds to efficacy of treatments, thus summer subsoiling may be beneficial. The limitation of the cover crops system in the current work is that there was no overwinter cover crop for erosion control. Currently, we know of no winter-hardy covercrop which is not a host of *P. penetrans,* yet is adaptable for overwinter use in vegetable systems. A winter-hardy cover crop for late planting to replace rye is still required, as it was also pointed out by Dunn and Mai (1973). If nematode-suppressive factors could be added to winter rye or other crops, it would be an asset for vegetable management systems. There is potential to improve or maintain soil productivity and manage nematodes via certain cover crops, however, an integrated management approach is required for success.

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