D. P. Weingartner and J. R. Shumaker
University of Florida Agricultural Research Center, Hastings

G. C. Smart, Jr.
University of Florida, Gainesville

Why Soil Fumigation Fails to Control Pota

Potato (*Solanum tuberosum* L.) corky ringspot disease (CRS)—or spraing, as it is known in Europe—is caused by tobacco rattle virus (TRV) transmitted to potato tubers by stubby root or trichodorid nematodes (*Trichodorus* and *Paratrichodorus* spp.). The disease is widespread in Europe, where it is considered one of the more important virus diseases of potato, especially in seed production areas. In the United States, CRS has been reported in California, Colorado, Florida, Idaho, Indiana, Michigan, Oregon, and Washington. Aside from Florida, the disease is quite localized and confined to sandy locations.

Symptoms may differ according to cultivar, geographic location, and virus strain, but CRS is usually characterized by circular lesions on the surface of affected tubers (Fig. 1) and necrosis in the tuber flesh ranging from distinct arcs to diffused flecks (Fig. 2). Foliage symptoms (stem mottle) are rarely seen in the field in the United States but develop frequently in plants grown in the greenhouse from affected tubers (Fig. 3). Experimentally, the disease has been controlled effectively with both soil fumigants and certain nonvolatile nematicides in all areas of the world except Florida. In Florida, soil fumigation has consistently failed to control CRS.

The first report of CRS in the United States came from northeast Florida (Fig. 4) in 1946 (6). The similarity of CRS to spraing in Europe was recognized at that time, but the etiology of both remained an enigma until the discovery (19) and proof (2) of the ectoparasitism of nematodes and demonstration in 1958 that some of these could transmit viruses (11). Walkinshaw et al (20) demonstrated that TRV associated with CRS in northeast Florida potato fields was transmitted by stubby root nematodes (*Trichodorus christiei* Allen = *Paratrichodorus minor* [?]).

Although trichodorids have been found on 82% of the farms in northeast Florida (Table 1), CRS is estimated to occur to varying degrees on less than 30% of the 8,100 ha of potatoes grown in the area. Tubers severely affected by the disease are nonmarketable because of intense internal necrosis (Fig. 2). Because of CRS, many fields have been abandoned to potato production and used for other crops.

Other Nematode-Related Diseases

Trichodorids and CRS constitute but one portion of a nematode and soilborne disease complex found in northeast Florida potato soils; 11 other genera of plant-parasitic nematodes are also frequently found (Table 1). The sting (*Belonolaimus longicaudatus* Rau) and southern root-knot (*Meloidogyne incognita* (Kofoid & White) Chitwood) nematodes are the most important ones directly affecting tuber yields. Population densities of the other genera usually are below economic threshold levels. Trichodorids in northeast Florida are important in potato production only as vectors of CRS and do not themselves reduce yields.

The scenario is further complicated by early dying disease caused by *Verticillium albo-atrum* Reinke & Berth. and by bacterial wilt caused by *Pseudomonas solanacearum* E. F. Smith; both can be severe problems during some seasons in northeast Florida. Bacterial wilt is soilborne and endemic, whereas *Verticillium* is believed to enter the area annually in contaminated seed tubers. Both *Verticillium* spp. and *P. solanacearum* have been reported to interact with nematodes, such as *Meloidogyne* spp. and *Pratylenchus* spp. (7,21). Because of potential interactions with other control measures, any control program developed for CRS in northeast Florida must take the other problems into consideration.

Nematicides, Yield Increases, and Potential for CRS

Because of the widespread occurrence of pathogenic nematodes in northeast Florida, soil fumigation for nematode control resulted in dramatic increases in potato tuber yields, often double those of untreated plots (22). Thus it was apparent to us in 1970 that use of nematicides would become an integral part of potato production practices in northeast Florida. We were concerned, however, that CRS might become a more serious problem as more growers adopted soil fumigation, since trichodorid levels in other crops grown in Florida often increase after soil fumigation to many times the levels in untreated controls (17). Indeed, the incidence of CRS in tubers sampled from large fumigation demon-

Fig. 1. Circular lesions on surface of potatoes with corky ringspot disease.

Florida Agricultural Experiment Station Journal Series No. 3357.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. § 1734 solely to indicate this fact.

0191-2917/83/02013005/$03.00/0

orky Ringspot Disease in Florida

stration plots established by a chemical company during 1969–1970 suggested that the disease was not controlled by soil fumigation and may have been increased (Table 2). Data from some 40 replicated experiments performed on the Hastings Agricultural Research Center experimental farm and in farmers' fields during 1969–1981 have repeatedly confirmed these preliminary observations. Typical data are summarized in Table 3.

Soil fumigation, although providing effective control of CRS elsewhere (3,4,14,15), has failed consistently to control the disease in northeast Florida (23–25) and in many instances has resulted in significant increases in the disease. Certain nonvolatile nematicides, such as aldicarb (Temik), however, used either alone or in combination with soil fumigants, have provided effective economical control of CRS as well as effective nematode control (D. P. Weingartner, *unpublished*).

As anticipated, significant increases in average yields of potato tubers because of control of sting and other nematodes (and effective control of CRS after registration of aldicarb in 1975) stimulated rapid grower use of nematicides in northeast Florida (Fig. 5).

Fig. 2. Internal symptoms of corky ringspot disease on potatoes stored at 42 F for 2–3 months.

Solving the Riddle

Our early attempts using routine soil sampling procedures to correlate CRS incidence with population densities of trichodorids were mostly unsuccessful. This was due to several factors. First, population densities of trichodorids, even in untreated controls, were usually low. Second, many nonvolatile nematicides, including carbofuran and aldicarb, do not kill nematodes immediately after application; instead, population densities decline slowly (5), making statistical correlations with disease incidence or yield response of the host difficult, at best. Third, although the incidence of CRS in tubers from fumigated plots often exceeded that from untreated controls, there was no consistent corresponding increase in nematode population densities. We began to research this phenomenon in 1973.

Several reports in the European literature (12,13,18) indicated that some species of trichodorids were frequently found at soil depths exceeding a meter. A preliminary survey by R. E. Harrison during 1973 in the Hastings area confirmed that trichodorids in some fields were present throughout the soil profile. In a more detailed study, Harrison (8), using a 10-cm-diameter soil auger, took soil samples at 10-cm increments in a potato field on our research farm and showed that trichodorids occupied the entire soil profile down to the water table. The depth and densities of the population appeared more related to the level of the water table than to the month of the year or the cropping sequence. Subsequent studies have shown trichodorid populations to peak in some years during September following a sorghum summer cover crop (D. P. Weingartner, *unpublished*).

During 1973–1975, Harrison and Smart (8–10) demonstrated in experiments performed in the laboratory and growth room that: 1) trichodorids from northeast Florida potato fields multiplied on tomato but failed to reproduce on Sebago and Pungo cultivar potato plants; 2) when introduced at either the bottoms or tops of 175 × 10 cm plastic tubes, the trichodorids (*T. christiei* and *T. proximus*) were eventually found throughout the entire profile of the tubes; and 3) within 36 hours in a closed system, nematodes of both species migrated 25 cm horizontally from a point source to tomato roots.

Fig. 3. Stem mottle symptoms on plants grown in the greenhouse from tubers with corky ringspot disease.

Livingston et al (14) reported that although soil fumigation controlled CRS in Colorado, soil below the zone of fumigation (ie, deeper than 1 m) remained infective, suggesting that viruliferous trichodorids could persist at that depth. Evidence available in 1977, therefore, strongly implied that soil fumigation failed to control CRS in northeast Florida because viruliferous

Fig. 4. Potato production area in northeast Florida.

nematodes persisted in deeper soil after fumigation and that they migrated into the tubersphere during the potato season after the fumigant had dissipated. Direct proof of nematode migration in the field, however, was lacking.

Duplicating Harrison's procedures (8), we took soil samples at 10-cm increments to a depth of 70 cm at 4–6 week intervals during 1977–1979 after treatment of a potato field with 1,3D (Telone II), 56 L/ha in the row; aldicarb 15G (Temik), 22.4 kg/ha in the row; or 1,3D plus aldicarb. We also took samples of an untreated control. Incidence and severity of CRS were assessed at the end of each potato season. Population densities of trichodorids (Fig. 6) indicated clearly that incidence of CRS was related to changes in the densities during the potato season. Soil fumigation effectively reduced the initial population in the plant zone but not in deeper soil. As the season progressed, nematodes moved from the deeper soil into the tubersphere. Population densities in the aldicarb treatments continued to drop throughout the season. Similar observations were made in 1978 and 1979. Thus, it appeared that soil fumigants failed to control CRS simply because the nematodes moved from deeper soil after the fumigant had dissipated. Aldicarb, which was applied at planting, remained active during this period.

We further tested this hypothesis during 1979 by placing 122 × 10 cm plastic tubes containing sterilized field soil (Fig. 7) into soil treated previously with 1,3D. The tubes were open at the soil end and had six 25-cm^2 openings at the 30–60 cm soil depth, so that nematicide-treated soil was in direct contact with the sterile soil in the tubes. A single potato plant was planted in each tube. The tubes were removed from the field at various time intervals during the season and nematode population densities determined in 10-cm increments. The experiment was repeated in 1980 and 1981. During all three seasons, trichodorids were found in the sterilized soil inside the tubes within 35–45 days after placement, with considerable numbers (63–86/100 cm^3 soil) found by 45–50 days.

Timing Foliar Sprays

Oxamyl 2L (Vydate) is a short-lived (half-life, about 14 days) systemic

D. P. Weingartner

Dr. Weingartner is associate professor of plant pathology at the University of Florida Agricultural Research Center in Hastings. He received his Ph.D. in plant pathology from Michigan State University in 1969. His research program at Hastings has dealt principally with disease and nematode management in Irish potatoes and has included both foliage and soilborne diseases.

J. R. Shumaker

Dr. Shumaker is associate professor of horticulture at the Hastings Agricultural Research Center. He received an M.S. in horticulture from West Virginia University in 1959 and a Ph.D. in vegetable crops from the University of Minnesota in 1967. Since joining the staff at Hastings, his research responsibilities have included vegetable variety improvement, weed management, and vegetable crop production systems.

G. C. Smart, Jr.

Dr. Smart is a professor in the Department of Entomology and Nematology at the University of Florida in Gainesville. He received B.A. and M.A. degrees from the University of Virginia and a Ph.D. degree from the University of Wisconsin. He spent 4 years as a research nematologist at Virginia Polytechnic Institute and State University, Holland, Virginia, before moving to the University of Florida, where he is involved in teaching and research. His interests are in general nematology, morphology, and biological control of nematodes.

insecticide-nematicide. Some of the material is translocated to the roots after foliar applications, and such applications have reduced incidence of CRS in Scotland (1). In experiments performed in northeast Florida during 1970–1978, foliar applications of oxamyl were only moderately effective in reducing CRS, whether applied alone or in various combinations with soil-applied nematicides. We attributed the poor control to improper timing of applications (24).

Tuber symptoms of CRS in northeast Florida usually can be found as soon as tubers are formed (23), with over 70% of the total incidence often occurring by 68–75 days after planting. As noted, trichodorid migration from deeper soil can occur by 35 days after planting. To be effective, an adequate dosage of oxamyl must be present before the virus is transmitted. Using as guides our trichodorid population dynamics data from 1979 and 1980 and rates and spray schedules for oxamyl delineated from previous CRS control experiments, we applied oxamyl in three different schedules totaling 5.6 kg a.i. ha to potatoes grown in untreated soil and in soil previously treated with 1,3D, aldicarb, or 1,3D plus aldicarb. As shown in Table 4, oxamyl was effective when 5.6 kg a.i. was applied by 70 days (tuberization was late in 1980 owing to cool weather conditions). Incidence of CRS was 43% in 1,3D plots not treated with oxamyl but only 5–11% in 1,3D plots where the three schedules of oxamyl were applied to plants. When applied alone, the 5.6 kg a.i. rate of oxamyl was as

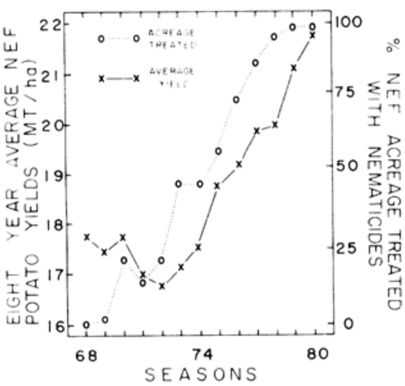

Fig. 5. Increase in use of nematicides and corresponding improvement in average potato yields in northeast Florida (NEF) during 1965–1979. Potato yields for each year are expressed as the average yields for the 8-year period ending in that year. Use of nematicides was the single major production practice to change in northeast Florida during this period, and most of the increase in average production is attributed to nematode control.

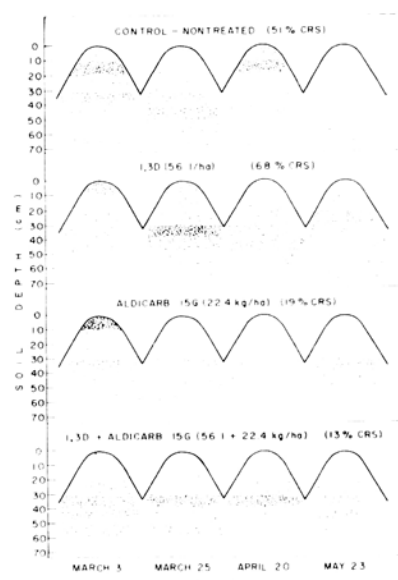

Fig. 6. Changes in trichodorid population densities in ridged rows during the 1977 season at different soil depths in an untreated control and after treatment with 1,3D, aldicarb 15G, or 1,3D plus aldicarb 15G. Each dot represents one nematode/100 cm^3 at each depth. Chemicals were applied in rows spaced on 102-cm centers. The fumigant was injected at about 25 cm on 25 January, the crop was planted and aldicarb applied on 17 February, vine desiccant was applied on 20 May, and the crop was harvested on 2 and 3 June.

Table 1. Plant-parasitic nematodes frequently found in northeast Florida potato fields[a]

Scientific name	Common name	Farms affected (%)
Belonolaimus longicaudatus	Sting	96
Meloidogyne incognita	Root-knot	85
Paratrichodorus minor	Stubby root	82
Trichodorus spp.	Stubby root	
Pratylenchus scribneri	Lesion	61
Tylenchorhynchus claytoni	Stunt	70
Criconemoides ornatus	Ring	99
Hemicycliophora sp.	Sheath	79
Hoplolaimus sp.	Lance	55
Hemicriconemoides sp.	Sheathoid	93
Helicotylenchus sp.	Spiral	26
Dolichodorus heterocephalis	Awl	23
Scutellonema bradys	...	27

[a]Based on 2,123 soil samples collected by the Florida Agricultural Extension Service from 82 northeast Florida potato farms during 1965–1979. Nematodes are listed in estimated order of importance in the area's potato production.

Table 2. Incidence of corky ringspot disease (CRS) in a grower demonstration trial in 1970

Soil fumigant	Application rate (L/ha)[a]	Tubers with CRS[b] (%)	Average no. lesions/tuber[b]
Ethylene dibromide (Dowfume W-85)	28	11.6	6.7
Ethylene dibromide	19	15.0	3.6
1,3D + ethylene dibromide (Dorlone)	?	5.1	2.9
1,3D (Telone)	56	1.0	3.3
Control	...	1.5	1.5

[a]Applied in the row (102-cm row spacing).
[b]Based on single 7.6-m plots sampled in each area. All plots were in the same large field; control plots, however, were > 0.40 km from the Dowfume W-85 area.

Table 3. Incidence of corky ringspot disease (CRS) in Sebago cultivar tubers after use of 1,3D (soil fumigant) or aldicarb (nonvolatile nematicide), or both, on the Hastings, Florida, Agricultural Research Center experimental farm during 1977–1981

		Tubers with CRS (%)[z]					
Treatment	Rate/ha[y]	1977	1978	1979	1980	1981	5-yr avg.
1,3D (Telone II)	56 L	17.6 c	57.6 c	40.3 b	16.2 b	43.0 c	34.9
Aldicarb 15G (Temik)	22.4 kg	0.4 a	2.4 a	3.4 a	1.8 a	7.5 a	3.1
1,3D + aldicarb	56 L + 22.4 kg	1.1 a	0.8 a	1.4 a	1.8 a	3.8 a	1.8
Control	...	10.8 b	28.5 b	27.2 b	19.0 b	20.0 b	21.3

[y]Applied in the row (102-cm row spacing).
[z]Based on 40 tuber samples from each replication of each treatment during all seasons. Values within a column followed by the same letter do not vary significantly according to Duncan's multiple range test.

Table 4. Incidence of corky ringspot disease (CRS) in Sebago cultivar tubers after foliar applications of oxamyl 2L (Vydate) superimposed on four soil treatments

Oxamyl schedule and application rates[w]				Tubers with CRS (%)[x]				
				Soil treatments[y]				
41 days	50 days	60 days	70 days	1,3D	Aldicarb	1,3D + aldicarb	None	Oxamyl mean
3.36	2.24	0	0	5 ab[z]	0 a	1 a	7 ab	3 A[z]
3.36	1.12	1.12	0	11 b	1 a	1 a	12 b	6 A
0	2.24	2.24	1.12	6 ab	1 a	1 a	4 ab	3 A
0	0	0	0	43 c	5 ab	5 ab	53 c	27 B
Soil treatment mean				16 B	2 A	2 A	19 B	

[w] Rates are kg a.i./ha overall; days are number from planting.
[x] Based on 40 tuber samples from each replication of each treatment. Values are rounded to the nearest whole percent.
[y] 1,3D (Telone II) at 56 L/ha and aldicarb 15G (Temik) at 3.36 kg a.i./ha applied in the row (102-cm spacing). Aldicarb was applied at planting and 1,3D, several weeks before.
[z] Means followed by the same lowercase letter or by the same capital letter do not differ significantly ($P = 0.05$) according to Duncan's multiple range test.

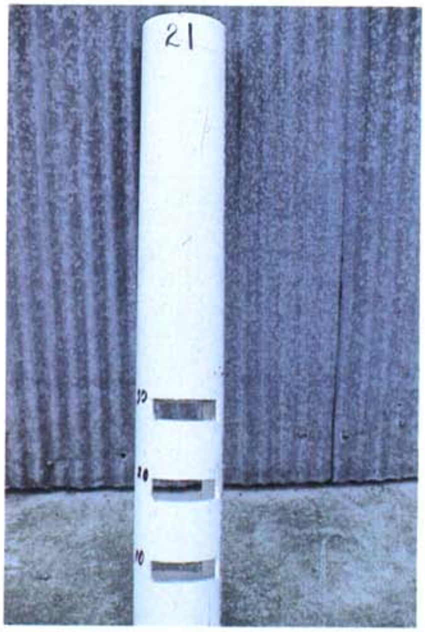

Fig. 7. Plastic tube used to demonstrate migration of trichodorids after soil fumigation. The tube was filled with sterilized field soil, a potato plant was planted in the tube, and the tube was placed into soil previously treated with 1,3D.

effective as the 3.36 kg a.i. rate of aldicarb alone.

Explanation Leads to Questions

Nematode migration, therefore, explains why soil fumigants fail to control CRS in northeast Florida. Soil fumigation reduces population densities of trichodorids early in the season, but nematodes from deeper soil migrate into the tubersphere after the fumigant has dissipated. Aldicarb applied at planting apparently remains effective during most of the season and prevents transmission of the virus to developing tubers, and oxamyl in adequate dosages applied before nematode migration effectively controls the disease.

Although migration of trichodorids and other nematodes in soil has been reported previously (16), to our knowledge this is the first work to show that nematode migration can play a significant role in disease expression in the field. Our observations raise many interesting questions related to nematode migration and attraction to roots and to control of these important pathogens. Some of these are currently being studied in Florida.

Acknowledgments

Portions of this research were supported by E. I. du Pont de Nemours & Company, Dow Chemical Company, Union Carbide Corporation, and HEW contract 223-76-2073.

Literature Cited

1. Alphey, T. J. W. 1978. Oxamyl sprays for the control of potato spraing disease caused by nematode transmitted tobacco rattle virus. Ann. Appl. Biol. 88:75-80.
2. Christie, J. R., and Perry, V. G. 1951. A root disease of plants caused by a nematode of the genus *Trichodorus*. Science 113:491-493.
3. Cooper, J. I., and Thomas, P. R. 1971. Chemical treatment of soil to prevent transmission of tobacco rattle virus to potato by *Trichodorus* spp. Ann. Appl. Biol. 69:23-34.
4. Dallimore, C. E. 1972. Control of corky ringspot in Russett Burbank potatoes by soil fumigation. Am. Potato J. 49:366.
5. Di Sanzo, C. P. 1973. Nematode response to carbofuran. J. Nematol. 5:22-27.
6. Eddins, A. H., Proctor, E. Q., and West, E. 1946. Corky ringspot of potatoes in Florida. Am. Potato J. 23:330-333.
7. Feldmesser, J. G., and Goth, R. W. 1970. Association of a root-knot nematode with bacterial wilt of potato. (Abstr.) Phytopathology 60:1014.
8. Harrison, R. E. 1976. The corky ringspot disease of potatoes: Biology of *Trichodorus christiei* and *Trichodorus proximus* and evidence for the existence of a stable tobacco rattle virus in corky ringspot infected potato. Diss. Abstr. Int. 36B 5886.
9. Harrison, R. E., and Smart, G. C., Jr. 1975. Movement of *Trichodorus christiei* and *Trichodorus proximus* through soil and towards roots of tomato plants. (Abstr.) J. Nematol. 7:323-324.
10. Harrison, R. E., and Smart, G. C., Jr. 1975. Vertical distribution of *Trichodorus christiei* and *Trichodorus proximus* relative to soil moisture. (Abstr.) J. Nematol. 7:324.
11. Hewitt, W. B., Raski, D. J., and Goheen, A. C. 1958. Nematode vector of soil-borne fan leaf virus of grapevines. Phytopathology 48:586-595.
12. Hijink, M. J., and Kuiper, K. 1966. Waarnemigen over de verdeling van aatjes in de grond. Meded. Rijksfac. Landbouwwet. Gent. 31:558-571.
13. Kuiper, K., and Loof, P. A. A. 1962. *Trichodorus flevensis* n. sp. (Nematoda: Enoplida). A plant nematode from new polder soil. Versl. Pl. Ziekt. Dienst. Wageningen 132:193-200.
14. Livingston, C. H., Lambert, R., Kaufman, M., and Knutson, K. 1976. Effects of soil fumigation with Telone-C on the field inoculum potential of tobacco rattle virus and potato yields. Am. Potato J. 53:81-86.
15. Maas, P. W. T. 1975. Soil fumigation and crop rotation to control spraing disease in potatoes. Neth. J. Plant Pathol. 81:138-143.
16. Pitcher, R. S. 1975. Factors influencing the movement of nematodes in soil. Pages 389-407 in: Nematode Vectors of Plant Viruses. F. Lamberti, C. E. Taylor, and J. W. Seinhorst, eds. Plenum Press, New York.
17. Rhoades, H. L. 1968. Re-establishment of *Trichodorus christiei* subsequent to soil fumigation in central Florida. Plant Dis. Rep. 52:573-575.
18. Richter, E. 1969. Zur vertiklen Verteilung von Nematoden in einem Sandboden. Nematologica 15:44-54.
19. Steiner, G. 1942. Plant nematodes the grower should know. Proc. Soil Crop Sci. Soc. Fla. IV B 72-177. (Issued 1 April 1949.)
20. Walkinshaw, C. H., Griffin, G. D., and Larson, R. H. 1961. *Trichodorus christiei* as a vector of potato corky ringspot (tobacco rattle virus). Phytopathology 51:806-808.
21. Weingartner, D. P., Dickson, D. W., and Dilbeck, J. D. 1974. Early dying disease on potatoes in north Florida. Plant Dis. Rep. 58:374-378.
22. Weingartner, D. P., Shumaker, J. R., and Littell, R. C. 1977. Sting nematode damage to potatoes in northeast Florida. (Abstr.) Am. Potato J. 54:505-506.
23. Weingartner, D. P., Shumaker, J. R., and Smart, G. C., Jr. 1975. Incidence of corky ringspot disease as affected by different fumigation rates, cultivars, and harvest dates. Soil Crop Sci. Soc. Fla. Proc. 34:194-196.
24. Weingartner, D. P., Shumaker, J. R., and Smart, G. C., Jr. 1975. Chemical control of corky ringspot disease on potatoes in Florida, U.S.A. Pages 443-444 in: Nematode Vectors of Plant Viruses. F. Lamberti, C. E. Taylor, and J. W. Seinhorst, eds. Plenum Press, New York.
25. Weingartner, D. P., Shumaker, J. R., Smart, G. C., Jr., and Dickson, D. W. 1976. A new nematode control program for potatoes in northeast Florida. Proc. Fla. State Hortic. Soc. 88:175-182.