Effect of Annual Sequence of Removing or Flaming Potato Vines and Fumigating Soil on Verticillium Wilt of Potato

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ABSTRACT

The effects of removing or flaming potato vines and soil fumigation on population density of *Verticillium dahliae* in soil, severity of Verticillium wilt, and tuber yield were studied in a field near Alliston, Ontario, between 1993 and 1996. Vines were physically removed or flamed using a propane flamer in September just before harvest and soil was fumigated with metam-sodium (Vapam) at 550 L/ha in October after harvest. Vine removal had no effect on soil populations of *V. dahliae*, area under the disease progress curve (AUDPC), or tuber yield. Flaming once (1993), twice (1993 and 1994), or three (1993, 1994, and 1995) times reduced the soil population density of *V. dahliae*, and flaming twice (1993 and 1994) reduced AUDPC compared to the nontreated control, but had no effect on tuber yield. Fumigation once (1993) or twice (1993 and 1994) reduced pathogen density in soil and AUDPC, but did not increase tuber yield. Fumigation once (1993) or twice (1993 and 1994), in combination with flaming twice (1993 and 1994), was equally and significantly effective in reducing both population density of *V. dahliae* in soil and AUDPC values and in increasing tuber yield in 1995. Annual flaming of vines in combination with soil fumigation once (1993) or twice (1993 and 1994) in the fall improved the control of Verticillium wilt of potato and realised the greatest profits.

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ADDITIONAL KEY WORDS: Disease control, potato early dying.

INTRODUCTION

Verticillium wilt of potato in Ontario, Canada, is caused primarily by *Verticillium dahliae* Kleb (McKeen and Thorpe 1973, 1981). This disease continues to have a considerable impact on the potato industry, worth about $44 million annually (Parker 1994). In the area near Alliston, which accounts for 25% of the total potato acreage in Ontario, *V. dahliae* was recovered from 80% or more of the plants in 17 of 36 potato fields (Lazarovits 1988) and was estimated to cause a 13% yield loss (Busch 1972).

In view of the economic impact of the disease, considerable effort has been devoted to developing control measures (Rowe et al. 1987). Most control measures are either inadequate or have undesirable effects on the environment. The most common rotation in Ontario is potato, rye/corn, potato. Such short rotations of two to three years have not reduced the population of *V. dahliae* in soil adequately (Joaquim et al. 1988; Mol et al. 1996) because of the long-term survival of microsclerotia in soil (Davis 1985; Wilhelm 1955) and because of the wide host range of the pathogen including some common weeds (Busch et al. 1978; McKeen and Thorpe 1981). Most widely grown potato cultivars are susceptible or moderately resistant to this disease. Soil fumigation can lower the population density of *V. dahliae* in soil, reduce disease incidence, and increase tuber yield (Ben-Yephet et al. 1983; Easton 1970; Easton et al. 1972, 1975; Kunkel and Weller 1965; Powelson and Carter 1973; Young 1956); however, the tactic is expensive and raises concerns related to human and environmental health (Munnecke 1972; Munnecke and Van Gundy 1979; Powelson and Rowe 1993; Rodriguez-Kabana and Curl 1980).

Microsclerotia are formed within dying infected plant tissues (Rowe 1985). When the dying plant tissues are plowed back into the soil the microsclerotia are slowly released into the soil as the crop residue is decayed. Control efforts, therefore, have focus on reducing the microsclerotia in stems and in soil.

Flaming kills the microsclerotia in stems. Over 95% of *V. dahliae* propagules were killed in mint and potato stems treated with a propane flamer (Horner and Dooley 1965; McIntyre and Horner 1973; Powelson and Gross 1962), and those that did survive did not persist long in soil (McIntyre and Horner 1973). Easton et al. (1972) examined the effect of vine flaming on *V. dahliae* populations in soil, Verticillium wilt incidence and tuber yield. In the first five years of the study (Easton et al. 1972), six different combinations of vine flaming and soil fumigation were tested in an unvarying annual sequence in which a given plot received the same treatment in each of the five years. Flaming of vines for two successive years increased tuber yield and after the third annual flaming, soil populations of *V. dahliae* were reduced. When soil fumigation was applied together with flaming of vines tuber yield was increased by 2% to 12% and soil populations of the pathogen were reduced by 14% to 100% compared to soil fumigation alone.

The effect of propane flaming in different temporal combinations with soil fumigation on disease suppression and tuber yield has not been reported. It is possible, for example, that yields following annual flaming in combination with biennial fumigation can equal or exceed those associated with annual fumigation. The objective of this study was to determine the effect of different annual sequences of removing or flaming vines and soil fumigation on populations of *V. dahliae* in soil, severity of Verticillium wilt, and tuber yield of potato.

MATERIALS AND METHODS

The experiment was conducted near Alliston, Ontario, between 1993 and 1996, in a commercial field, which had been cropped annually to potato for 20 years and had a history of Verticillium wilt. Each year rye was planted in the fall and plowed down in the spring. Three disease-management tactics, flaming, vine removal, and soil fumigation, were either applied singly or in combination with each other within a given year. The eight treatments for each of the three years were fallow (control), flaming or vine removal; flaming or fumigation in the first year and fallow for the next two years; fumigation in the first two years and fallow for the third year; flaming and fumigation in the first year and flaming in the next two years; flaming and fumigation in the first two years and flaming in the third year (Table 1). The treatments were arranged as a randomized complete block design with four replications. Plots were eight rows wide and 6 m long. Rows were spaced 1 m apart and each plot was separated by 3 m. Soil and plant samples and tuber yield were collected from the middle two rows of each plot. The chipping potato cultivar Atlantic, which is moderately resistant to Verticillium wilt, was sown in late April or early May each year. Plots were maintained by the grower. The soil was a loamy sand (sand 77.97%, clay 18%, silt 4%, and 0.03% organic matter) with a pH of 5.2. The crop was top killed in August with Reglone (diquat) (45 L/ha), except in 1995 due to early senescence. The crop was affected by the Colorado potato beetle in 1994, but in the following two years the insect pest was controlled with Admire (imadacloprid) (0.2 L/ha). Late blight (*Phytophthora infestans*) occurred in the plots in 1996.

TABLE 1—*Annual sequence of tactics evaluated for control of Verticillium wilt.*

Treatment[§]	1993	1994	1995
1	None	None	None
2	Flaming[α]	Flaming	Flaming
3	Fumigation[†]	Fumigation	None
4	Flaming and Fumigation	Flaming and Fumigation	Flaming
5	Flaming	None	None
6	Fumigation	None	None
7	Flaming and Fumigation	Flaming	Flaming
8	Vine removal[β]	Vine removal	Vine removal

[§] Vines were either removed or propane flamed in September 1993, 1994, and 1995. Soil was fumigated with metam-sodium in October 1993 and 1994.
fumigated with metam-sodium (Vapam) 550 L/ha
[α] ~ 99% of the vines were incinerated
[β] ~ 95% of the vines were removed

Vines (stems and attached leaves) were removed by hand or flamed with a propane flamer (ICG Propane, Inc., Markham, Ontario) in September, and soil was fumigated in October. The flamer was equipped with a boom bearing 25 burners that operated under hydraulic pressures of 133-600 kPa and produced temperatures up to 2 000 C. It passed over eight rows at 1.5 m/sec. Setting plots 3 m apart and removing vines trapped on tiller between plots minimized movement of vines or soil from one plot to another during cultivation. Soil and vine displacement was estimated to be approximately 1 m. Metam-sodium, at 550 L/ha in 1,100 L/ha of water, was shanked to a soil depth of 15 cm. The soil surface was compacted with a cultipacker to minimize escape of the fumigant into the atmosphere and facilitate its penetration deeper into the soil.

Soil samples were taken with a 2.5-cm-diameter soil probe from the top 15 cm in 10 sites in each plot. The 10 soil cores were mixed together and dried on a bench at room temperature (~ 21 C) for 2-12 wk. The soil was passed through a 2-mm mesh sieve to remove gravel and large pieces of organic matter. Three 2.174-g subsamples were each suspended in 10 ml of water containing 0.15% agar, which provided 2 g of soil per 10 ml of suspension. Aliquots of 0.25 ml were dispensed on each of five petri dishes containing soil pectate tergitol (SPT) medium (Hawke and Lazarovits 1994). The suspension was spread over the surface of the medium with an L-shaped metal rod with the aid of a turntable. Plates were incubated at room temperature (~21 C) for 2 to 12 wk and colonies of *V. dahliae* were counted with the aid of a stereo-microscope. A total of 15 dishes per soil sample provided a minimum detection level of 1.33 cfu/g of soil.

Severity of Verticillium wilt was assessed several times during each growing season on 20 potato shoots chosen arbitrarily from the middle two rows of each plot. Each shoot was scored for the extent of foliar chlorosis and necrosis on a scale of 1 to 10 where 1 = no chlorosis and necrosis, 2 = 1-6%, 3 = 7-13%, 4 = 14-25%, 5 = 26-50%, 6 = 51-75%, 7 = 76-88%, 8 = 89-94%, 9 = 95-99%, and 10 = dead shoot. Area under the disease progress curve (AUDPC) was calculated from the equation (1)

$$AUDPC = \sum_{i=1}^{n-1} [(x_{i+1} + x_i)/2]\,[t_{i+1} - t_i]$$

where x_i = the cumulative disease severity expressed as a proportion at the i^{th} observation, n = total number of observations, and t_i = time (days) at the i^{th} observation (Tooley and Grau 1984).

Tubers were harvested manually in the first two years and mechanically in the third year. The weight of marketable tubers (55 to 85 mm in diameter) was determined.

Data were analysed by one-way analysis of variance. When the F-test was significant ($P = 0.05$), means were separated using the least significant difference (LSD) test at $P = 0.05$ (Steel and Torrie 1980). To assess profitability of the treatments, we used costs of $148/ha to flame vines and $865/ha to fumigate soil and potato market prices of $19.13, $19.53, and $18.12 per 100 kg for 1994, 1995, and 1996, respectively.

RESULTS

Based on soil assays taken two months after flaming and one month after soil fumigation in 1993, none of the treatments significantly reduced the population density of the pathogen in soil (Table 2). When soils were assayed in July 1994 (nine to 10 months after treatments were applied), soil fumigation (treatments 3 and 6) and vine flaming combined with soil fumigation (treatments 4 and 7) significantly reduced soil populations of *V. dahliae*. No significant treatment effects on soil populations of *V. dahliae* were observed on 31 October 1994 (two months after vine flaming and one month after soil fumigation). All treatments, except treatments 5 (flaming vines 1993) and 8 (removing vines 1993 and 1994), significantly reduced *V. dahliae* populations in soil samples taken on 10 July 1995 (nine to 10 months after treatments were applied). Soil populations of *V. dahliae* at the beginning of the growing season taken 30 May 1996 were significantly reduced by all treatments, except vine removal. Treat-

TABLE 2—*Effect of vine removal, flaming of vines, and fumigation of soil on population density of* Verticillium dahliae *in a potato field soil.*

Treatment	Year 1			Year 2			Year 3		
	Tactic[x]	Fall 16/11/93	Spring 22/07/94	Tactic	Fall 31/10/94	Spring 10/07/95	Tactic	Fall	Spring 05/09/96
1	None	218a	203a[y]	None	113a	191a	None	-[z]	115a
2	FL	71a	157a	FL	73bc	45a	FL	-	63cd
3	FU	44a	89b	FU	72bc	60a	None	-	73bc
4	FL+FU	29a	80b	FL+FU	38c	55a	FL	-	41d
5	FL	60a	181a	None	92ab	54a	None	-	82bc
6	FU	30a	83b	None	68bc	112a	None	-	78bc
7	FL+FU	37a	57b	FL	47c	49a	FL	-	53cd
8	VR	69a	177a	VR	94ab	68a	VR	-	98ab

[x] Vines were either removed (VR) or propane flamed (FL) in September 1993, 1994 and 1995. Soil was fumigated (FU) with metam-sodium in October 1993 and 1994.
[y] Within a column, means followed by the same letter are not significantly different from each other according to a protected LSD test at $P = 0.05$.
[z] Data not collected

TABLE 3—*Effect of removal or flaming of vines, and fumigation of soil on area under the disease progress curve (AUDPC) for Verticillium wilt of potato.*

Treatment		AUDPC					
	Tactic[y]	1994	Tactic	1995	Tactic	1996
1	None	67.4a[z]	None	130.3a	None	138.5a
2	FL	59.9ab	FL	117.3bcd	FL	136.5a
3	FU	51.5bc	FU	115.8bcd	None	134.8a
4	FL+FU	49.4c	FL+FU	112.8cd	FL	131.0a
5	FL	63.4a	None	130.3a	None	131.3a
6	FU	51.3bc	None	123.3abc	None	138.3a
7	FL+FU	51.6bc	FL	105.0d	FL	137.0a
8	VR	66.8a	VR	126.8ab	VR	136.8a

[y]Vines were either removed (VR) or propane flamed (FL) in September 1993, 1994, and 1995. Soil was fumigated (FU) with metam-sodium in October 1993 and 1994.
[z] Within a column, means followed by the same letter are not significantly different from each other according to a protected LSD test at $P = 0.05$.

ment 4 (fumigating soil in 1993 and 1994 combined with flaming vines in 1993, 1994, and 1995) produced the lowest soil population density, but was not significantly different from treatment 7 (fumigating soil in 1993 combined with flaming vines in 1993 to 1995) and treatment 2 (flaming vines annually from 1993 to 1995).

Area under the disease progress curve (AUDPC) (Table 3) was reduced in year 2 (1994) by treatments 3, 4, 6, and 7 (fumigation with or without flaming in the previous year) and in year 3 (1995) by treatments 2, 3, 4, and 7 (flaming in the two previous years, fumigation in the two previous years, flaming and fumigation in the two previous years, and flaming in years 1 and 2 coupled with fumigation in year 1).

Marketable tuber yield was significantly increased only in 1995 when plots were flamed and fumigated in the previous two years or flamed and fumigated in year 1 and flamed in year 2 (Table 4). The greatest increases in profits compared to the check over three crop years (1994-1996) were with flaming plus fumigation in year 1 and flaming in years 2 and 3 and with flaming plus fumigation in years 1 and 2 and flaming in year 3 (Table 4).

DISCUSSION

Soil fumigation (Ben-Yephet et al. 1983) and flaming (Easton et al. 1972, 1975) or removal (Mol et al. 1995) of vines have been reported to reduce populations of *V. dahliae* in potato-field soil. In this study we tested the efficacy of different annual sequences of these treatments in lowering the population density of *V. dahliae* in soil, reducing the severity of Verticillium wilt of potato, and increasing tuber yield.

Flaming vines once, in the first year, significantly reduced soil population density of *V. dahliae* in the third year, but had no significant effect on disease severity or tuber yield in any of the three crop years. When vines were flamed in two consecutive years (treatment 2), soil population density of *V. dahliae* and AUDPC was significantly reduced, but this had no significant effect on tuber yield. When vines were flamed in three consecutive years (treatment 2), soil population density of *V. dahliae* was significantly reduced, but this had no significant effect on AUDPC or tuber yield. This is the first report that demonstrates a significant effect of flaming of potato vines on population density of *V. dahliae* in soil in the first few years after initiation of treatments, and the first demonstration of a residual effect of flaming–in this case, a reduction in population density in the second and third years after the treatment was applied.

In our study, flaming of vines either once or for three consecutive years significantly reduced soil populations of the pathogen compared to the check by the third year. However, the treatments did not differ. Neither treatment had an effect on AUDPC or marketable tuber yield in the third year. Easton et al. (1972) in his study on flaming of potato vines for Verticillium wilt control did not provide a statistical analysis of effects of flaming on population density of *V. dahliae* in soil. Examination of their Table 1 suggests that after three consecutive years of

TABLE 4—*Effect of vine removal, flaming of vines, and fumigation of soil on marketable yield of potato and profit ($/ha).*

	Marketable tuber yield (kg)						
Treatment	Tactic[y]	1994	Tactic	1995	Tactic	1996	Profit ($)
1	None	5.0a[z]	None	27.5c	None	28.3a	-
2	FL	6.9a	FL	29.2c	FL	30.3a	610
3	FU	5.9a	FU	33.5abc	None	35.2a	804
4	FL+FU	6.3a	FL+FU	38.3a	FL	35.5a	1485
5	FL	5.3a	None	28.5c	None	32.6a	875
6	FU	6.3a	None	32.1bc	None	30.4a	660
7	FL+FU	6.3a	FL	36.5ab	FL	32.8a	1509
8	VR	5.4a	VR	30.2c	VR	31.5a	958

[y] Vines were either removed (VR) or propane flamed (FL) in September 1993, 1994, and 1995. Soil was fumigated (FU) with metam-sodium in October 1993 and 1994.
[z] Within a column, means followed by the same letter are not significantly different from each other according to a protected LSD test at $P = 0.05$.

flaming (1966-1968), population densities were appreciably lower in the following spring in flamed compared to nonflamed plots, and this effect persisted after a fourth flaming. A significant reduction in percentage of stems infected by *V. dahliae* was first seen after three consecutive years of flaming and persisted with four consecutive years of flaming. Disease incidence was significantly reduced, and tuber yield was significantly increased after three and four flaming treatments. Thus, both the present study and that of Easton et al. (1972) indicate that flaming alone can reduce populations of *V. dahliae* in soil and incidence and severity of Verticillium wilt.

Easton et al. (1972, 1975) reported a significant 16% increase in tuber yield after two flaming treatments, and yields continued to be higher in annually flamed plots than unflamed plots, by 20% to 42%. Since they detected yield increases in the first year of the study, one year before seeing either reductions in soil population density of *V. dahliae* or in the incidence of infected stems and symptomatic plants, it is possible that flaming increased yield by mechanisms other than, or in addition to, reduction of soil populations of the pathogen. Flamed vines produce ashes rich in phosphorus and potassium that can increase tuber yield (Erich 1991).

In this study, a single fumigation in the fall (1993) significantly reduced soil populations of *V. dahliae* in 1994 (treatments 3 and 6). It significantly reduced AUDPC in 1994 (treatments 3 and 6), but did not affect marketable yield. Fumigation in fall 1993 and 1994 (treatment 3) reduced soil population density of *V. dahliae* in 1995 and 1996, reduced AUDPC in 1995 but did not affect tuber yield. These results confirm other reports on the efficacy of fumigation with metam-sodium on soil populations of *V. dahliae* (Ben-Yephet and Frank 1984, 1989; Ben-Yephet et al. 1983, 1988; Fravel 1996; Saeed et al. 1997; Subbarao 1999) and incidence or severity of Verticillium wilt of potato (Ben-Yephet et al. 1983; Easton et al. 1972, 1975). A single fumigation with metam-sodium (Powelson and Carter 1973) or with other products (Easton et al. 1975; Powelson and Carter 1973) has been reported to increase tuber yield in the following two crops, but without concomitant reductions in population densities or incidence of symptomatic plants (Easton et al. 1975). Conversely, we did not detect immediate or residual effects of fumigation alone on tuber yield but did observe residual reductions in soil population density of *V. dahliae* in treatment 3 in 1996 after fumigating last in fall 1994 and in treatment 6 in 1995 and 1996 after fumigating last in 1993.

Removing vines for three consecutive years (treatment 8) had no effect on soil populations of *V. dahliae*, AUDPC, or tuber yield. Vine removal was ineffective compared to propane flaming because it has no effect on pre-existing populations of microsclerotia in the soil. Propane flaming can raise temperature at the soil surface, thus reducing viability of microsclerotia in soil, and microsclerotia that survive flaming of the shoot are less able to survive in soil (McIntyre and Horner 1973). Sanitation was not complete with vine removal, and shattered portions of stems and leaves were left behind on the soil surface (<5% of the vines). In contrast, Mol et al. (1995) reported significant reductions in population density of *V. dahliae* in soil in microplots after removing vines, but did not specify how thorough the removal was.

A combination of flaming and fumigation was the most effective treatment in reducing both soil populations of *V. dahliae* and AUDPC and in increasing tuber yield. If vine flaming, vine removal, and soil fumigation reduce soil populations of *V. dahliae* by different mechanisms, they may have complementary effects on inoculum density, disease severity, and tuber yield. In the Columbia Basin of Washington the combination of fall flaming plus spring fumigation was more effective than a spring soil fumigation in lowering soil populations (Easton et al. 1972). This combination, however, was generally not more effective than fumigation alone in increasing tuber yield (Easton et al. 1972, 1975). In our study, the significant effects on yield in 1995 are perhaps the clearest evidence that combinations of fumigation and flaming can be more effective than either fumigation or flaming alone in managing Verticillium wilt of potato.

This is the first study to examine the effects of different temporal patterns of flaming and fumigation on disease, pathogen, and tuber yield parameters associated with Verticillium wilt of potato in the first three years after initiation of treatments. In 1994, yields were low due to excessive defoliation caused by the Colorado beetle and no significant effects of treatments were discerned. In 1995, yields were normal and significant treatment effects were obtained. Tuber yield of two treatments (2 fumigations + 2 flamings, 1 fumigation + 2 flamings) was significantly higher than in the control, an indication that frequency of fumigation and flaming has a direct bearing on final yield. Tuber yield in 1996 was normal, but treatment effects were not significant. It is possible that fumigation in 1995 may not have been effective due to partial degradation of crop residues resulting in some microsclerotia not being released into the soil. Effects of annual sequences of flaming and fumigation on AUDPC in the two years in which significant effects were realised (1994 and 1995) also indicated that greater effects were produced by increasing the frequency of both fumigation and flaming in a treatment sequence. Similar trends were seen in treatment effects on population density of *V. dahliae* in soil in 1994, 1995, and 1996. Effects of treatments over three years show that treatments 4 (flaming plus fumigation in 1993 and 1994, and flaming in 1996) and 7 (flaming plus fumigation in 1993 followed by annual flaming) were the most effective in reducing soil populations of *V. dahliae* and AUDPC and in increasing tuber yield. However, treatment 7 was the most profitable treatment. We conclude that combinations of flaming and fumigation are more effective and more profitable than either treatment alone. A comparison of treatments 7 and 4 shows that flaming can reduce fumigant use without compromising management of Verticillium wilt or profitability of the potato crop.

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LITERATURE CITED

Ben-Yephet, Y., and Z. Frank. 1984. Optimization of the metham-sodium dose in controlling *Verticillium dahliae* in potato. Phytoparasitica 12:203-205.

Ben-Yephet, Y., and Z.R. Frank. 1989. Factors affecting the efficiency of metham-sodium in controlling *Verticillium dahliae*. Acta Hortic 255:227-234.

Ben-Yephet, Y., J.M. Melero-Vera, and J.E. DeVay. 1988. Interaction of soil solarization and metham-sodium in the destruction of *Verticillium dahliae* and *Fusarium oxysporum* f. sp. *vasinfectum*. Crop Prot 7:327-331.

Ben-Yephet, Y., E. Siti, and Z. Frank. 1983. Control of *Verticillium dahliae* by metam-sodium in loessial soil and effect on potato tuber yields. Plant Dis 67:1223-1225.

Busch, L.V. 1972. Use of remote sensing in plant disease survey and loss assessment. Univ Guelph Notes on Agric 8:8-9.

Busch, L.V., E.A. Smith, and F. Njoh-Elango. 1978. The effect of weeds on the value of rotation as a practical control for Verticillium wilt of potato. Can Plant Dis Surv 58:61-64.

Davis, J.R. 1985. Approaches to control of potato early dying caused by *Verticillium dahliae*. Am Potato J 62:177-185.

Davis, J.R., J.J. Pavek, and D.L. Corsini. 1983. A sensitive method for quantifying *Verticillium dahliae* colonization in plant tissue and evaluating resistance among potato genotypes. Phytopathology 73:1009-1014.

Easton, G.D. 1970. Systemic insecticides, soil fumigation, and nitrogen fertilization for Verticillium wilt control. Am Potato J 47:419-426.

Easton, G.D., M.E. Nagle, and D.L. Bailey. 1972. Effect of annual soil fumigation and preharvest vine burning on Verticllium wilt of potato. Phytopathology 62:520-524.

Easton, G.D., M.E. Nagle, and D.L. Bailey. 1975. Residual effect of soil fumigation with vine burning on control of Verticillium wilt of potato. Phytopathology 65:1419-1422.

Erich, S.M. 1991. Agronomic effectiveness of wood ash as a source of phosphorus and potassium. J Environ. Qual 20:576-581.

Fravel, D.R. 1996. Interaction of biocontrol fungi with sublethal rates of metham-sodium for control of *Verticillium dahliae*. Crop Prot 15:115-119.

Hague, N.G.M., and S.R. Gowen. 1987. Chemical control of nematodes. *In*: Brown, R.H., and B.R. Kerry (eds), Principles and Practice of Nematode Control in Crops. Academic Press, New York. pp. 131-178.

Hawke, M.A., and G. Lazarovits. 1994. Production and manipulation of individual microsclerotia of *Verticillium dahliae* for use in studies of survival. Phytopathology 84:883-890.

Horner, C.E., and H.L. Dooley. 1965. Propane flaming kills *Verticillium dahliae* in peppermint stubble. Plant Dis Rep 49:581-582.

Joaquim, T.R., V.L. Smith, and R.C. Rowe. 1988. Seasonal variation and effects of wheat rotation on populations of *Verticillium dahliae* Kleb. in Ohio potato field soils. Am Potato J 65:439-447.

Kunkel, R., and M. Weller. 1965. Fumigation of potato soils in Washington. Am Potato J 42:57-69.

Lazarovits, G. 1988. Control strategies for early dying of potatoes. Agri-Book Mag 14:25-26.

MacGuidwin, A.E., and D.I. Rouse. 1990. Role of *Pratylenchus penetrans* in potato early dying disease of Russet Burbank potato. Phytopathology 80:1077-1082.

Martin, M.J., R.M. Riedel, and R.C. Rowe. 1982. *Verticillium dahliae* and *Pratylenchus penetrans*: Interactions in the early dying complex of potato in Ohio. Phytopathology 72:640-644.

McIntyre, J.L., and C.E. Horner. 1973. Inactivation of *Verticillium dahliae* in peppermint stems by propane gas flaming. Phytopathology 63:172-175.

McKeen, C.D., and H.J. Thorpe. 1973. Pathogenic species of *Verticillium* in horticultural crops and weeds in southwestern Ontario. Can J Plant Sci 53:615-622.

McKeen, C.D., and H.J. Thorpe. 1981. Verticillium wilt of potato in southwestern Ontario and survival of *Verticillium albo-atrum* and *V. dahliae* in field soil. Can J Plant Pathol 3:40-46.

Mol, L., and K. Scholte. 1995. Formation of microsclerotia of *Verticillium dahliae* Kleb. on various plant parts of two potato cultivars. Potato Res 38:143-150.

Mol, L., K. Scholte, and J. Vos. 1995. Effects of crop rotation and removal of crop debris on the soil population of two isolates of *Verticillium dahliae*. Plant Pathol 44:1070-1074.

Mol, L., J.M. Van Halteren, K. Scholte, and P.C. Struik. 1996. Effects of crop species, crop cultivar and isolates of *Verticillium dahliae* on the population of microsclerotia in the soil, and consequences for crop yield. Plant Pathol 45:205-214.

Mpofu, S.I. 1998. Population biology and management of *Verticillium dahliae* in potato fields in Ontario. Ph.D. thesis, Univ of Guelph. 249p.

Munnecke, D.E. 1972. Factors affecting the efficacy of fungicides in soil. Annu Rev Phytopathol 10:375-398.

Munnecke, D.E., and S.D. Van Gundy. 1979. Movement of fumigants in soil, dosage responses, and differential effects. Annu Rev Phytopathol 17:405-429.

Olthof, T.H.A., and J.W. Potter. 1973. The relationship between population densities of *Pratylenchus penetrans* and crop losses in summer-maturing vegetables in Ontario. Phytopathology 63:577-582.

Parker, A. 1994. Potato production in Prince Edward Island, Canada, and worldwide. Can J Plant Pathol 16:132-134.

Powelson, M.L., and R.C. Rowe. 1993. Biology and management of early dying of potatoes. Annu Rev Phytopathol 31:111-126.

Powelson, R.L., and G.E. Carter. 1973. Efficacy of soil fumigants for control of Verticillium wilt of potatoes. Am Potato J 50:162-167.

Powelson, R.L., and A.E. Gross. 1962. Thermal inactivation of *Verticillium albo-atrum* in diseased potato vines. Phytopathology 52:364.

Rodriguez-Kabana, R., and E.A. Curl. 1980. Nontarget effects of pesticides on soilborne pathogens and disease. Annu Rev Phytopathol 18:311-332.

Rowe, R.C. 1985. Potato early dying - a serious threat to the potato industry. Am Potato J 62:157-161.

Rowe, R.C., J.R. Davis, M.L. Powelson, and D.I. Rouse. 1987. Potato early dying: Causal agents and management. Plant Dis 71:482-489.

Rowe, R.C., R.M. Riedel, and M.J. Martin. 1985. Synergistic interactions between *Verticillium dahliae* and *Pratylenchus penetrans* in potato early dying disease. Phytopathology 75:412-418.

Saeed, I.A.M., D.I. Rouse, J.M. Harkin, and K.P. Smith. 1997. Effects of soil water content and soil temperature on efficacy of metham-sodium against *Verticillium dahliae*. Plant Dis 81:773-776.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and Procedures of Statistics: A Biometrical Approach. 2nd Edition. McGraw-Hill, Toronto. 633 pp.

Subbarao, K.V., J.C. Hubbard, and S.T. Koike. 1999. Evaluation of broccoli residue incorporation into field soil for Verticillium wilt control in cauliflower. Plant Dis 83:124-129.

Talboys, P.W. 1981. Chemical control of Verticillium wilts. In: Cirulli, M. (ed), Pathology of *Verticillium* Species. Pro 3rd Internat *Verticillium* Sympos, Bari, Italy. Mediterranean Phyopathological Union. pp. 69-81.

Tooley, P.W., and C.R. Grau, C.R. 1984. Field characterization of rate-reducing resistance to *Phytophthora megasperma* f. sp. *glycinea* in soybean. Phytopathology 74:1201-1208.

Wilhelm, S. 1955. Longevity of Verticillium wilt fungus in the laboratory and in the field. Phytopathology 45:180-181.

Young, R.A. 1956. Control of the early maturity disease of potatoes by soil treatment with Vapam. Plant Dis Rep 40:781-784.