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Control of *Globodera tabacum solanacearum* by Rotating Susceptible and Resistant Flue-Cured Tobacco Cultivars[1]

CHARLES S. JOHNSON[2]

Abstract: Alternate planting of flue-cured tobacco cultivars resistant (NC 567 or Speight G-80) or susceptible (K 326) to the tobacco cyst nematode (TCN) *Globodera tabacum* ssp. *solanacearum* on 1-year or 2-year intervals was investigated in Virginia in 1987–89. The TCN-resistant cultivars reduced TCN population densities compared with continuous planting of K 326. Initial TCN egg densities in soil tended to be lower and yields of K 326 without fenamiphos were consistently higher when a resistant cultivar had been planted the previous year. Planting NC 567 in 1987–88 reduced initial 1989 TCN densities to below 1,000 eggs/500 cm^3 soil. Use of NC 567 in 1987–88 also increased 1989 yields and net economic returns for K 326 above those of untreated plots continuously planted with K 326. Yields and net economic returns were similar from cultivar rotation strategies involving Speight G-80 or NC 567. Average yield and net economic returns for 1987–89, however, were significantly increased by use of fenamiphos with K 326 but not by any of the cultivar rotation strategies.

Key words: fenamiphos, *Globodera tabacum solanacearum*, nematode management, *Nicotiana tabacum*, resistance, tobacco, tobacco cyst nematode.

Many Virginia flue-cured tobacco (*Nicotiana tabacum* L.) producers spend as much as $250/ha to control tobacco cyst nematodes, *Globodera tabacum* ssp. *solanacearum* (Miller and Gray) Stone (TCN). Although rotating tobacco with nonhost crops can significantly reduce TCN population densities (7), the low economic value of rotation crops, relative to flue-cured tobacco, has discouraged the use of longer rotation intervals for TCN control. Although TCN-resistant cultivars of flue-cured tobacco are available, these cultivars are not immune and are intolerant of nematode parasitism (1,6). As a result, flue-cured tobacco producers in Virginia routinely apply nonfumigant nematicides for TCN control.

Previous work in Virginia indicated that planting TCN-resistant flue-cured tobacco cultivar NC 567 in severely infested fields effectively reduced TCN population densities at the end of one growing season and at the beginning of the following growing season (5). Economic returns were increased by planting NC 567 and applying fenamiphos for 2 consecutive years, followed by use of a susceptible flue-cured tobacco cultivar with excellent agronomic characteristics (K 326). However, the experimental design of the study did not allow identification of the optimal resistant–susceptible cultivar rotation interval. In addition, a single TCN-resistant cultivar was used throughout the study. The objectives of the work reported here were to 1) evaluate rotation of TCN-resistant and susceptible cultivars on 1-year versus 2-year intervals and 2) to compare the flue-cured tobacco cultivar Speight G-80 (Sp G-80) with NC 567 as the resistant cultivar in rotations of TCN-resistant and susceptible cultivars.

MATERIALS AND METHODS

A rotation interval experiment and a resistant cultivar experiment were conducted in a TCN-infested commercial flue-cured tobacco field in 1987, 1988, and 1989. The soil was an Appling sandy loam (Typic Hapludult, clayey, siliceous, thermic; ca. 60% sand, 20% silt, 20% clay; 1% organic matter) with a 0–7% slope. A randomized complete block design with six

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[2] Assistant Professor of Plant Pathology, Southern Piedmont Agricultural Experiment Station, Virginia Polytechnic Institute and State University, P.O. Box 448, Blackstone, VA 23824.

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TABLE 1. Experimental treatments involving alternate use of fenamiphos and flue-cured tobacco cultivars resistant (NC 567, Sp G-80) and susceptible (K 326) to *Globodera tabacum* ssp. *solancearum*.

Treatment†	1987 Cv.	1987 Nematicide	1988 Cv.	1988 Nematicide	1989 Cv.	1989 Nematicide
			Rotation interval experiment			
K−K−K−	K 326	No	K 326	No	K 326	No
K+K+K+	K 326	Yes	K 326	Yes	K 326	Yes
K−N+K−	K 326	No	NC 567	Yes	K 326	No
N−N−N−	NC 567	No	NC 567	No	NC 567	No
N+N+N+	NC 567	Yes	NC 567	Yes	NC 567	Yes
N+N+K−	NC 567	Yes	NC 567	Yes	K 326	No
			Resistant cultivar experiment (NC 567 versus Sp G-80)			
K+K+K+	K 326	Yes	K 326	Yes	K 326	Yes
N+K+N+	NC 567	Yes	K 326	Yes	NC 567	Yes
N+N+K+	NC 567	Yes	NC 567	Yes	K 326	Yes
S+K+S+	Sp G-80	Yes	K 326	Yes	Sp G-80	Yes
S+S+K+	Sp G-80	Yes	Sp G-80	Yes	K 326	Yes
S+S+S−	Sp G-80	Yes	Sp G-80	Yes	Sp G-80	No

† K = K 326; N = NC 567; S = Sp G-80; + = with fenamiphos; − = without fenamiphos.

treatments and four replications was used for each experiment. Each treatment consisted of a TCN control strategy involving use of resistant and (or) susceptible cultivars with or without fenamiphos, over a 3-year period (Table 1). Continuous use of a TCN-susceptible cultivar (K 326), with or without fenamiphos, was compared with use of a resistant cultivar (NC 567 or Sp G-80) at 1-year or 2-year intervals. The nematicide fenamiphos (6.7 kg a.i./ha) was applied preplant each year using a tractor-mounted hydraulic sprayer calibrated to deliver 297–309 liters/ha of total solution when traveling at 4.8 km/hour and with a pressure of 172–220 kPa. Plots were disked immediately after nematicide application. Plots consisted of four rows 1.2 m apart and 34.4 m long in 1987 and 1988. Selected plots were reduced to three rows 1.2 m apart and 34.4 m long in 1989 to satisfy new requirements for wider "sled rows" in the experiment. Data were taken from the center two rows in four-row plots and from the center row of three-row plots. Nematode egg densities were monitored each year by removing 24 soil cores (2 cm d × 16 cm long) from each plot. Soil samples were taken just before nematicide application, at 6–10 weeks after transplanting, and after final harvest. Tobacco cyst nematode eggs were extracted from soil samples by elutriation in 1987 and by centrifugation with sugar-flotation in 1988 and 1989 (3,9). As individual leaves ripened, they were harvested and cured. Individual harvests were weighed and graded by USDA marketing service inspectors after the final harvest had been cured. Grade indices that group federal flue-cured tobacco grades according to equivalent economic value were used to describe treatment effects on flue-cured tobacco quality (2,10). Average market prices ($2.16–$4.19/kg) were obtained from USDA market news reports for the third week in October. Gross economic returns were calculated for each plot by summing the product of priming weight and average market value for the appropriate grade in each priming. Nematicide costs were estimated by surveying local agrichemical dealers. Net economic returns to nematode management were estimated by subtracting nematicide costs from gross economic returns. Experimental results were evaluated by analysis of variance (8). Nematode counts were transformed using base 10 logarithms prior to statistical analysis. Means for individual strategies were compared with the Waller-Duncan k-ratio test (8).

TABLE 2. Numbers of *Globodera tabacum* ssp. *solanacearum* eggs in soil in 1987–89 as affected by application of fenamiphos and (or) planting a resistant tobacco cultivar for 1 or 2 years.

	Eggs/500 cm³ soil								
	1987			1988			1989		
Treatment†	25 May	6 July	12 Oct.	17 May	5 Aug.	12 Oct.	25 May	6 July	12 Oct.
K−K−K−	12,950 ab	3,500 bc	11,350 a	2,344 a	2,086 a	5,469 a	3,045 a	18,990 a	4,645 a
K+K+K+	35,150 a	6,450 ab	6,500 a	9,898 a	2,344 a	8,594 a	2,095 a	6,895 ab	2,270 a
K−N+K−	32,350 a	7,050 ab	11,250 a	7,555 a	1,820 a	3,906 ab	1,110 a	4,110 b	3,360 a
N−N−N−	6,750 b	2,050 c	1,450 b	2,609 a	515 a	3,125 ab	845 a	1,425 b	1,040 b
N+N+N+	35,350 a	15,500 a	5,850 ab	3,609 a	2,867 a	4,688 ab	975 a	1,495 b	395 b
N+N+K−	23,950 a	9,600 ab	2,520 b	1,820 a	1,828 a	3,125 b	975 a	2,460 b	2,740 a

Nematode counts were transformed, $\log_{10}(x + 1)$, prior to statistical analysis. Results presented are nontransformed means of four replications. Means within a column followed by the same letter(s) are not significantly different according to the Waller-Duncan test, k-ratio = 100, $P = 0.05$.
† See Table 1 for detailed descriptions of treatments.

RESULTS

Initial 1987 TCN egg densities were significantly lower in some plots where NC 567 was to be planted than those where K 326 was used (Table 2). Midseason TCN egg densities were also higher in 1987 in some fenamiphos-treated plots with the resistant cultivar NC 567 than in untreated plots with the susceptible cultivar K 326. Final 1987 TCN egg densities, however, were significantly reduced by planting NC 567 rather than K 326 (Table 2). Differences in TCN egg densities among K 326, NC 567, and Sp G-80 were not significant ($P \leq 0.05$) in 1987 (Table 3). Grade indices were higher in 1987 when K 326 was grown in soil treated with fenamiphos than when NC 567 was planted in untreated soil (Table 4). Average prices were also lower in 1987 when NC 567 was used and fenamiphos was not (Table 4). However, yields and net economic returns among K 326, NC 567, and Sp G-80 were not different ($P \leq 0.05$) in the resistant cultivar test, since fenamiphos had been applied (Table 5).

Significant differences in initial and midseason TCN egg densities were not detected in 1988 (Tables 2, 3). Planting NC 567 in 1988 reduced TCN egg densities at harvest (Table 2), but, as in 1987, differences in TCN egg densities at harvest among K 326, NC 567, and Sp G-80 were not significant (Table 3). Agronomic traits showed few differences in the 1988 rotation interval study (Table 4). Net economic returns, however, were significantly higher

TABLE 3. Numbers of *Globodera tabacum* ssp. *solanacearum* eggs in soil in 1987–89 after rotating resistant tobacco cultivars NC 567 or Sp G-80 with a susceptible cultivar, K 326.

	Eggs/500 cm³ soil								
	1987			1988			1989		
Treatment†	25 May	6 July	12 Oct.	17 May	5 Aug.	12 Oct.	25 May	6 July	12 Oct.
K+K+K+	13,400 a	2,475 a	6,400 a	2,867 a	516 a	9,375 a	1,000 ab	3,890 a	2,110 a
N+K+N+	12,950 a	3,700 a	5,000 a	3,906 a	523 a	7,812 a	445 ab	2,260 ab	180 b
N+N+K+	12,025 a	4,300 a	2,175 a	2,344 a	1,820 a	7,812 a	675 ab	2,380 ab	745 ab
S+K+S+	9,150 a	4,950 a	2,050 a	3,641 a	1,297 a	9,375 a	1,470 a	3,310 a	290 ab
S+S+K+	7,800 a	4,650 a	1,800 a	2,344 a	773 a	4,687 a	410 b	1,180 b	155 ab
S+S+S−	6,500 a	2,600 a	1,300 a	3,383 a	2,336 a	2,344 a	950 ab	1,975 ab	240 ab

Nematode counts were transformed, $\log_{10}(x + 1)$, prior to statistical analysis. Results presented are nontransformed means of four replications. Means within a column followed by the same letter(s) are not significantly different according to the Waller-Duncan test, k-ratio = 100, $P = 0.05$.
† See Table 1 for detailed descriptions of treatments.

TABLE 4. Agronomic performance of flue-cured tobacco resistant (NC 567) and susceptible (K 326) to *Globodera tabacum* ssp. *solancearum* with and without fenamiphos over a 3-year period.

Treatment†	Cultivar harvested	Fenami-phos	Yield (kg/ha)	Grade index‡	Avg. price ($/kg)	Net return ($/ha)
			1987			
K−K−K− K−N+K−	K 326	No	2,589 a	41.5 ab	3.49 a	9,055 a
K+K+K+	K 326	Yes	2,961 a	48.2 a	3.52 a	10,229 a
N−N−N−	NC 567	No	2,442 a	35.2 b	3.35 b	8,199 a
N+N+N+ N+N+K−	NC 567	Yes	2,815 a	40.4 ab	3.47 a	9,560 a
			1988			
K−K−K−	K 326	No	2,465 a	62.2 a	3.57 a	8,836 a
K+K+K+	K 326	Yes	3,274 a	58.5 a	3.52 a	11,355 a
K−N+K−	NC 567	Yes	2,922 a	55.5 a	3.52 a	10,059 a
N−N−N−	NC 567	No	2,655 a	58.2 a	3.44 a	9,145 a
N+N+N+	NC 567	Yes	2,971 a	57.0 a	3.44 a	10,046 a
N+N+K−	NC 567	Yes	2,609 a	54.0 a	3.35 a	8,687 a
			1989			
K−K−K−	K 326	No	2,065 b	51.0 a	3.63 a	7,497 b
K+K+K+	K 326	Yes	2,875 a	54.8 a	3.63 a	10,242 ab
K−N+K−	K 326	No	2,272 ab	54.8 a	3.62 a	8,211 ab
N−N−N−	NC 567	No	2,781 ab	49.2 a	3.65 a	10,148 ab
N+N+N+	NC 567	Yes	2,848 ab	50.8 a	3.65 a	10,158 ab
N+N+K−	K 326	No	2,950 a	48.8 a	3.60 a	10,644 a
			Averages for 1987–89			
K−K−K−			2,457 b	51.6 a	3.57 a	8,761 b
K+K+K+			3,036 a	53.8 a	3.56 ab	10,608 a
K−N+K−			2,510 b	50.6 a	3.54 ab	8,810 b
N−N−N−			2,626 ab	47.6 a	3.48 ab	9,164 ab
N+N+N+			2,947 a	49.8 a	3.53 ab	10,177 ab
N+N+K−			2,722 ab	47.2 a	3.47 b	9,374 ab

Data presented are means of four replications. Means within columns (and within year) followed by the same letter(s) are not significantly different according to the Waller-Duncan test, k-ratio = 100, $P = 0.05$.
† See Table 1 for detailed descriptions of treatments.
‡ Scale of 0 (poor) to 100 (best) in 1987–88; scale of 1 to 100 in 1989.

in fenamiphos-treated plots when K 326 was grown in 1988 after use of NC 567 in 1987, relative to continuous use of NC 567 in both years (Table 5). Average prices in 1988 were significantly lower in fenamiphos-treated plots planted continuously with resistant cultivars (NC 567 and Sp G-80) relative to K 326 (Table 5).

The TCN egg densities before planting tended to be lower in 1989 when NC 567 or Sp G-80 had been planted in 1987 and (or) 1988 (Tables 2, 3). In 1989, the only significant difference among initial TCN egg densities was between fenamiphos-treated plots planted continuously with Sp G-80 and those planted with Sp G-80 in 1987 and K 326 in 1988 (Table 3). Mid-season TCN egg densities were significantly lower in 1989 when NC 567 had been planted in 1987 and (or) 1988 or when Sp G-80 had been planted in both 1987 and 1988 (Tables 2, 3). Egg densities after final harvest in 1989 were also lower in plots where NC 567 had been planted. Use of fenamiphos increased yield of K 326 in 1989 (Table 4). Yield and net economic returns from use of K 326 without fenamiphos also increased in 1989 where K 326 was grown after use of NC 567 in 1987 and 1988. Differences in yield or net economic returns among cultivar rotation treatments in fenamiphos-treated plots in 1989 were not significant. Grade indices and average prices were similar among all treat-

TABLE 5. Agronomic performance of flue-cured tobacco resistant (NC 567 or Sp G-80) or susceptible (K 326) to *Globodera tabacum* ssp. *solanacearum* with and without fenamiphos over a 3-year period.

Treatment†	Cultivar harvested	Fenamiphos	Yield (kg/ha)	Grade index‡	Avg. price ($/kg)	Net return ($/ha)
			1987			
K+K+K+	K 326	Yes	2,734 a	45.2 a	3.53 a	9,439 a
N+K+N+ N+N+N+	NC 567	Yes	2,549 a	40.4 a	3.49 a	8,679 a
S+K+S+ S+S+K+ S+S+S−	Sp G-80	Yes	2,726 a	38.3 a	3.42 a	9,125 a
			1988			
K+K+K+	K 326	Yes	3,220 a	73.8 a	3.67 a	11,588 ab
N+K+N+	K 326	Yes	3,606 a	63.2 a	3.59 ab	12,734 a
N+N+N+	NC 567	Yes	2,748 a	62.2 a	3.48 bc	9,375 b
S+K+S+	K 326	Yes	2,910 a	64.8 a	3.57 abc	10,225 ab
S+S+K+ S+S+S−	Sp G-80	Yes	2,891 a	59.2 a	3.44 c	9,759 ab
			1989			
K+K+K+	K 326	Yes	3,118 a	48.8 a	3.63 a	11,038 a
N+K+N+	NC 567	Yes	3,749 a	47.0 a	3.66 a	13,457 a
N+N+N+	K 326	Yes	3,879 a	49.2 a	3.64 a	13,857 a
S+K+S+	Sp G-80	Yes	3,321 a	46.0 a	3.68 a	11,936 a
S+S+K+	K 326	Yes	3,445 a	45.8 a	3.65 a	12,350 a
S+S+S−	Sp G-80	No	3,283 a	45.8 a	3.64 a	11,940 a
			Averages for 1987–89			
K+K+K+			3,024 a	55.9 a	3.61 a	10,688 a
N+K+N+			3,298 a	50.2 ab	3.59 a	11,634 a
N+N+N+			3,062 a	50.6 ab	3.55 ab	10,626 a
S+K+S+			2,998 a	49.4 ab	3.53 ab	10,456 a
S+S+K+			3,066 a	48.1 b	3.52 ab	10,606 a
S+S+S−			2,909 a	47.8 b	3.49 b	10,053 a

Data presented are means of four replications. Means within columns (and within year) followed by the same letter(s) are not significantly different according to the Waller-Duncan test, k-ratio = 100, $P = 0.05$.

† See Table 1 for detailed descriptions of treatments.

‡ Scale of 0 (poor) to 100 (best) in 1987–88; scale of 1 to 100 in 1989.

ments in both experiments in 1989 (Tables 4, 5).

Average yield and net economic returns for the 3 years of the study were increased significantly by use of fenamiphos, but not by any of the resistant–susceptible cultivar rotation strategies (Tables 4, 5). Rotating K 326 with NC 567 did not significantly alter the 3-year averages for flue-cured tobacco grade index, but use of K 326 in 1989 after planting Sp G-80 in 1987 and 1988 significantly reduced the 3-year average grade indices relative to continuous use of K 326 (Tables 4, 5). Average prices for the 3-year study period were also higher in fenamiphos-treated plots when K 326 was planted continuously or rotated with NC 567 than when K 326 was planted once every 2 years or Sp G-80 was planted every year (Table 5).

DISCUSSION

The results of this study agreed with previous work demonstrating a significant reduction in TCN egg densities at the end of the growing season when NC 567 was grown (4,5). Similar effects on TCN egg densities were observed from planting Sp G-80, but were not as clear as the reductions in TCN egg densities associated with use of NC 567 (Table 3). Yields and net economic returns were generally similar from cultivar rotation strategies involving Sp G-80 versus NC 567 (Table 5). Flue-cured tobacco producers should, therefore, be able to use either of the TCN-resistant cultivars tested in a resistant cultivar rotation strategy.

Although a trend toward lower initial TCN egg densities in the year following use of a resistant cultivar was apparent in the results of this study, statistically significant associations between preplant TCN densities and the resistance or susceptibility of the cultivar grown in the previous year were not obtained (Tables 2, 3). The general agreement with previous work (5), however, suggests that the lack of statistical significance in these trends may be due to the high variance in the data.

Increases in yield of K 326 without fenamiphos when a TCN-resistant cultivar had been planted in the previous year (only) were consistent but not statistically significant (Tables 4, 5). Midseason TCN populations were lower for K 326 without fenamiphos in 1989 when NC 567, rather than K 326, had been planted in 1988 (Table 2), but other similar comparisons did not indicate statistically significant differences. Increased yield and net economic returns from K 326 without fenamiphos were also found when NC 567 had been planted in the two previous growing seasons (Table 4), agreeing with previous work (5). Similar trends in fenamiphos-treated plots were not statistically significant (Table 5). The relatively high final harvest TCN egg densities observed for K 326 in 1989 after use of NC 567 in 1987 and 1988 suggest that the benefits of previous use of resistance may not persist beyond the first year that a susceptible cultivar is grown (Table 2).

The results of this study suggest that application of fenamiphos remains necessary for maximization of economic returns to flue-cured tobacco production. Although the TCN-resistant cultivars effectively reduced population densities of the nematode, resulting in significant yield increases for K 326 the following year, the inferior agronomic performance of the resistant cultivars, relative to K 326, prevented statistically significant increases in net economic returns over the long term. Average net economic returns over the 3-year period of this study were $431/ha greater when K 326, rather than NC 567, was used with fenamiphos every year (Table 4). Continuous use of K 326 with fenamiphos resulted in average net economic returns $1,234/ha greater than planting NC 567 in 1987 and 1988, followed by use of K 326 in 1989 (Table 4). An apparent decline in TCN egg densities in all plots from 1987 to 1988 and 1989 may be responsible for the lack of long-term agronomic response to the use of TCN-resistance (Tables 2–5). The reasons for these trends are unknown. Decreasing overall TCN densities, however, may have resulted in overestimation of yields and gross economic returns from continuous use of a susceptible cultivar, with or without fenamiphos. Such results would lead to underestimation of the economic benefits of using TCN-resistant cultivars.

Planting NC 567 in 1987 and 1988 successfully reduced TCN egg densities to a level at which a susceptible flue-cured tobacco cultivar could be grown without fenamiphos and still produce yields and net economic returns equivalent to those resulting from application of fenamiphos (Table 4). Similar results were obtained in 1986, when K 326 was grown without fenamiphos in plots with initial TCN populations below 2,000 eggs/500 cm^3 soil (5). Using a TCN-resistant cultivar for 2 consecutive years reduced 1989 initial TCN densities to below 1,000 eggs/500 cm^3 soil (Tables 2, 3). Continued research is needed to develop a method to minimize the indirect costs of TCN resistance in flue-cured tobacco and to identify an economic threshold for TCN on flue-cured tobacco.

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