Development of a Pathogen Growth Response Model for the Virginia Peanut Leaf Spot Advisory Program

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The use of trade names implies neither endorsement of the products by Virginia Polytechnic Institute and State University nor criticism of similar ones not mentioned.
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We wish to thank Barron Britt, Steve Byrum, and Clarence Burkholder for technical asssistance.
The financial support of the Virginia Peanut Growers' Association, and professional support of the USDA-ARS Peanut Research Unit in Virginia are gratefully acknowledged.
Accepted for publication 16 September 1992.

ABSTRACT

Cu, R. M., and Phipps, P. M. 1993. Development of a pathogen growth response model for the Virginia peanut leaf spot advisory program. Phytopathology 83:195-201.

A new advisory program (ADV) to improve the efficiency of fungicide applications for control of early leaf spot of peanut was developed on the basis of growth responses of *Cercospora arachidicola* to specific environmental conditions. The new program, 89-ADV, assigned time-duration values to conditions conducive to infection (TDV_i). Cumulative TDV_i levels were used to determine the critical times for fungicide applications. Various spray thresholds (TDV_i = 48, 72, and 96) of the 89-ADV program, along with a 14-day spray schedule and the original advisory program that was released in 1981 (81-ADV), were tested on Florigiant peanut during 1987–1989. Area under the disease progress curve (AUDPC) and leaf spot incidence at harvest were significantly lower in plots sprayed with chlorothalonil (1.26 kg/ha) according to the 89-ADV program than in plots sprayed according to the 81-ADV program. The plots of the 89-ADV program had a TDV_i = 48 threshold. Higher advisory thresholds (TDV_i = 72 and 96) in the 89-ADV program resulted in similar or better disease control than the 81-ADV program at fewer sprays per season. In 1988 and 1989, crop yield and value were significantly improved using the 89-ADV program with a TDV_i of 48 in comparison with the 81-ADV program. No significant differences in yield or value were apparent in comparisons of the 89-ADV program and a 14-day spray schedule. Evaluations of spray programs under simulated disease environments constructed from historical weather data from 1983 to 1986 also demonstrated the superior disease control efficiency of the 89-ADV program with a TDV_i of 48 to that of the 81-ADV program. In both field and simulated tests, the number of sprays per season with the 89-ADV program at TDV_i = 48 and the 81-ADV program were similar. Based on these results, the 89-ADV program with a spray threshold of TDV_i = 48 was adopted as the on-line advisory program in Virginia for growers at the start of the 1989 growing season.

Early and late leaf spot caused by *Cercospora arachidicola* Hori and *Cercosporidium personatum* (Berk. Curt.) Deighton, respectively, are the most devastating foliar diseases of peanut (*Arachis hypogaea* L.) worldwide. Without foliar applications of fungicide, losses to these diseases have been reported to be as high as 50% of potential yield (32). Early leaf spot is the predominant foliar disease in the Virginia-North Carolina peanut production area. Programs to manage early leaf spot include the use of cultivars with partial resistance (8), disease-suppressive crop management practices (15,32), applications of fungicides (8,32), and computerized decision-support systems for fungicide application (21,27).

Agronomic practices, such as moldboard plowing to bury crop residues and crop rotation, may reduce levels of initial inoculum in soil (32), but these approaches have limited value with a polycyclic disease on a long-season crop. Survival structures of the pathogen, coupled with characteristics for long-distance dispersal of inoculum, render crop rotation a less viable option to control the disease. Sources of germplasm with promising resistance to early and late leaf spot have been identified, but plant breeders have had limited success in providing commercially acceptable, resistant cultivars that might reduce the need for fungicides (1,9,13,14,19).

The use of fungicide remains the single most effective method of leaf spot control. The extensive use of fungicide, however, has not been without problems. *C. arachidicola* and *C. personatum* have reportedly developed resistance to benomyl, a benzimidazole carbamate fungicide (5,16), and the repeated use of chlorothalonil can increase the severity of Sclerotinia blight of peanut (28). The risk of pathogen resistance to fungicides, the effects of fungicides on nontarget organisms, and the cost of fungicides can be minimized by reducing the frequency of fungicide applications. The original version of the Virginia peanut leaf spot advisory (81-ADV) was the first expert system to be adopted by growers for control of leaf spot on a commercial scale (27). This advisory program identified periods conducive to disease development and thus allowed for reduced fungicide input in peanut production at minimal risk of loss of yield or crop value.

The 81-ADV program for fungicide application employed the disease-forecasting technique of Jensen and Boyle (10,11). Their forecasting technique was founded on the correlation of leaf spot incidence in the field with an infection index. Subsequently, this correlation was used by Parvin, Smith, and Crosby (21) to develop the first daily, worded, computerized advisory. The 81-ADV program was first delivered to peanut growers in southeast Virginia in 1981. As early as 1983, the program was shown to successfully reduce the number of fungicide applications from an average of 6.75 on a 14-day spray schedule to about three per season (27). However, in some years, fungicide application according to the 81-ADV program allowed late-season development of disease to levels that caused grower concern. Although yields were generally similar to those of a 14-day spray program, improving the 81-ADV program was suggested (12).

Existing research concerning the biology of *C. arachidicola* and the epidemiology of early leaf spot in peanuts has offered fundamental data for improving the 81-ADV program. Alderman et al (4) reported that initial inoculum of *C. arachidicola* appears during conditions characterized by RH >90% and temperature <17 C for about 10 h per day on a 3-day running average (4). Spore density increased during periods of increased temperature with duration of RH >90%. A 48-h period with RH ≥95% and 16–25 C temperatures resulted in a high percentage of spore germination on leaves (3). Spore germination was low at temperatures of 28–32 C. The rates of germ tube elongation were similar for both temperature ranges. Oso (20) and Miller (18) had previously defined the temperature range favorable for spore germination as 15–33 C with RH ≥95%. They reported that temperatures near 37 C were lethal to germinating spores. Alderman and Beute (3) reported the termination of germ tube elongation after 8 h of dry (30–40% RH) conditions when germinating spores were exposed to a cyclic dry-wet regime. Jewell (12) confirmed the correlation between the weather-dependent infection index of Jensen and Boyle (11) and early leaf spot incidence but found a stronger correlation of disease incidence with cumulative hours of RH ≥95% (12).

The objectives of this research were: 1) to develop an advisory program that reflects specific growth responses of the pathogen to weather conditions in the Virginia peanut production area, 2) to evaluate and compare advisory programs with the 14-day spray program in replicated field trials, and 3) to compare the advisory programs under simulated environments reconstructed from historical weather data.

MATERIALS AND METHODS

A new advisory program (89-ADV) was developed after review of research on specific growth responses of *C. arachidicola* to meteorological conditions (2–4,12,18,20,31). The computerized 89-ADV program included modules that were designed to provide information on sporulation, germination, lethal conditions, infection, and disease pressure. Conditions conducive to spore germination and germ tube elongation, as well as conditions lethal to germinating spores, were assigned weighted values for each hour of occurrence. The weighted values, called time-duration values (TDV), were accumulated and used to determine the critical times for fungicide applications.

Conditions for sporulation, germination, and infection. The first module of the 89-ADV program used TDVs to predict the occurrence of environmental conditions conducive to sporulation (TDV_s). Temperatures of 16–32 C with RH >90% were considered conducive to sporulation (3). A cumulative TDV_s of 10 was adopted as the threshold for initiating sporulation (Table 1). After the first occurrence of these conditions, spores of the pathogen were presumed to be present for the remainder of the cropping season.

Additional modules accumulated TDVs for germination (TDV_g), infection (TDV_i), and lethal conditions (TDV_{lc}). Each hour of conditions with RH ≥95% and temperatures ≥16≤25 C, >25≤28 C, and >28≤32 C were assigned TDV_g values of 3, 2, and 1, respectively (Table 1). These temperatures had been previously defined to favor high, moderate, and low percentages of germination after 48 h of RH ≥95% (3). TDV_i accounted for the total hours of conditions conducive to infection with RH ≥95% and temperatures 16–32 C. The TDV_i was used to determine the timing of fungicide applications after sporulation. TDV_{lc} reflected the cumulative hours of conditions that could be lethal to germinating spores, which were considered to be temperatures ≥37 C for 5 h consecutively or RH ≤40% for 8 h consecutively. In the absence of lethal conditions, germination of spores was assumed to occur after a cumulative TDV_i of 48. Germ tube elongation, stomatal tropism, and initial penetration were assumed to occur after reaching the cumulative TDV_i of 72. Infection was assumed to occur after a cumulative TDV_i of 96. A postinfection phase, when initial symptoms might be visible, was assumed at a cumulative TDV_i of 120.

Thresholds for spray advisory. Cumulative TDV_i levels of 48, 72, and 96 were tested as thresholds for fungicide application. Each threshold was tested in the field by applying fungicide as close as possible to the advisory threshold and then evaluating the efficiency of disease control. At a specified advisory threshold, the program also indicated the level of disease pressure based on the weighted values of TDV_g (Table 2). This information could be useful for judging the type of spray response necessary for achieving an acceptable level of disease control. At the TDV_i = 48 spray threshold, disease pressure levels of low, moderate, and high were assigned to cumulative TDV_g levels ≥48, 96, and 144, respectively. Estimates of disease pressure for use with other TDV_i thresholds were developed in a similar manner.

Agro-environmental monitoring system. An agro-environmental monitoring system (AEMS), a network of computers and electronic meteorological sensors in remote locations, was used to collect temperature and RH data for this research (27,29). Daily operation and maintenance of the system was funded by the Virginia Cooperative Extension Service, the Virginia Agricultural Experiment Station, USDA-ARS, and the Virginia Peanut Growers' Association. AEMS data-gathering units were at three locations in the peanut production area; these units were named for the communities located nearest the station (Capron, Holland, and Waverly). It was estimated that about 85% of the total peanut acreage in Virginia falls within a 24-km (15-mi) radius of these stations (26). Meteorological parameters were recorded every 10 min, 24 h per day, and transmitted daily to the AEMS central computer at the Tidewater Agricultural Experiment Station where data were processed. Daily advisories for localities surrounding the three stations were updated and reviewed each day at 4 p.m.

Logic of the advisory program. The 89-ADV utilized ambient temperature and RH data provided by AEMS. At the start of each growing season, data sets were checked for conditions conducive to sporulation. The program continued to loop for data until an accumulated TDV_s of 10 was achieved. Thereafter, spores were presumed to be present during the remainder of the growing season.

TABLE 1. Time-duration values assigned to each hour of specific meteorological conditions for sporulation, germination, infection, and lethal conditions

Meteorological parameters	Time-duration value (TDV)[a]			
	TDV_s	TDV_g	TDV_i	TDV_{lc}
RH > 90%				
Temperature > 16 ≤ 32 C	1	0	0	0
RH ≥ 95%				
Temperature > 28 ≤ 32 C	1	1	1	0
Temperature > 25 ≤ 28 C	1	2	1	0
Temperature ≥ 16 ≤ 25 C	1	3	1	0
RH < 40%	0	0	0	1
Temperature ≥ 37 C	0	0	0	1
TDV threshold[b]	10	48	96	5–8[c]

[a]TDV is the time-duration value assigned to each hour of specific conditions (TDV_s = sporulation, TDV_g = germination, TDV_i = infection, and TDV_{lc} = lethal conditions).

[b]Threshold values reflect the estimated cumulative TDV for completion of a specific event.

[c]Lethal conditions occurred after five consecutive hours of ambient temperature ≥ 37 C or eight consecutive hours of RH < 40%.

TABLE 2. Parameters for estimating disease pressure at various thresholds of the 89-ADV program

Spray threshold	Disease pressure index[a]		
	1	2	3
TDV_i = 48	≥ 48[b]	≥ 96	≥ 144
TDV_i = 72	≥ 72	≥ 144	≥ 216
TDV_i = 96	≥ 96	≥ 192	≥ 288

[a]Indices (1 = low, 2 = moderate, and 3 = high) provide an estimate of disease pressure levels at a specific TDV_i threshold.

[b]The cumulative TDV_g at each advisory threshold was used as an indicator for the type of spray response. Increasing values in the disease pressure index indicate decreasing tolerance for delays in fungicide application.

After the initial occurrence of conditions conducive to sporulation, the second module of the program began to check for conditions conducive to germination and infection. Both TDV_g and TDV_i data were accumulated each day and evaluated. The program looped for more data until a specified advisory threshold for fungicide application was reached. The program also checked data for conditions defined as lethal to germinating spores. TDV_g and TDV_i were reset to zero whenever lethal conditions occurred. At a specified threshold for fungicide application, an estimate of disease pressure was provided on the basis of TDV_g (Table 2). TDV_g and TDV_i were reset to zero at the time of fungicide application and remained at zero for a 10-day period after fungicide application. This period corresponded to the foliar half-life of the fungicide chlorothalonil, the most commonly used fungicide for control of early leaf spot and other foliar diseases. Conditions during the residual period were assumed to be unfavorable for spore germination and infection. The program began collecting TDV_g and TDV_i data at the end of the 10-day residual period.

Data processing and reporting. In 1987 and 1988, an IBM personal computer equipped with a modem was used to retrieve data from AEMS and process the advisory. In 1989, the 89-ADV program was installed on the AEMS central computer and replaced the 81-ADV program as the on-line peanut leaf spot advisory for growers in southeast Virginia (26). A spray threshold of $TDV_i = 48$ was selected for the 89-ADV program by commercial growers. The program developed daily advisories for the Suffolk, Capron, and Waverly stations in an unattended mode from 1 June to 30 September. After reporting conditions favorable for sporulation at $TDV_s = 10$, the 89-ADV program reported the cumulative TDV_i each day with a "no spray needed" message until reports reached a level of $TDV_i = 40$. At this time, the message was changed to "spray needed soon." An advisory message to make the first fungicide application was reported at $TDV_i = 48$. This message, along with the date of its occurrence, was repeated for a period of 10 days. Thereafter, the calendar $date_{x-(n+10)}$ was reported by the advisory program as the "last effective spray date" for leaf spot control. Daily TDV_i records were used to determine this date by counting back from the current date (day_x) for the number ($_n$) of days required to reach the cumulative TDV_i threshold. Added to this date, were 10 days to cover the protection period of the previous spray application. The decision to spray fungicide was based on whether the last fungicide application was made prior to the reported "last effective spray date." Peanuts sprayed before that date were considered vulnerable to infection and application of a fungicide was recommended. If a fungicide spray had been applied since the last effective spray date specified in the advisory, then no treatment was needed.

Field evaluation. Florigiant peanut was planted in a Kenansville loamy sand with a history of corn-peanut rotations at the Tidewater Agricultural Experiment Station. Cultural practices recommended by the Virginia Cooperative Extension Service were followed in crop management (33). Plots, consisting of four 12.1-m rows, spaced 0.9-m apart, were arranged in a randomized complete block design with four replications. Chlorothalonil (Bravo 720, Fermenta ASC Corporation, Mentor, OH) at 1.26 kg a.i./ha was applied to the two center rows of each plot using a CO_2-pressurized sprayer equipped with three D_213 (disk-core combination) nozzles per row. The fungicide was sprayed at 345 kPa and a ground speed of 4.38 km/h, delivering 140 L/ha. Fungicide application was made at TDV_i thresholds of 48, 72, and 96 of the 89-ADV program. Reference standards included an untreated check, fungicide applications according to the 81-ADV program, and fungicide applications on a 14-day spray schedule. Sprays on a 14-day schedule started about 40–45 days after planting and ended about 21 days before harvest.

Leaf spot incidence and defoliation were assessed by visual estimates of the percentage of leaflets with one or more spots at 30-day intervals (27) and by a tagged-plant method at 2-wk intervals. Leaf spot incidence according to the tagged-plant method was determined by counts of infected leaflets (leaflets with one or more spots) and the number of defoliated leaflets on main stems of plants that had been systematically selected and tagged in the early part of the growing season. The sum of infected and defoliated leaflets divided by the total number of nodes times four was used to estimate disease severity. To assess leaf spot control by the various spray programs, area under the disease progress curve (AUDPC) was computed for each spray program by the equation reported by Shaner and Finney (30). Yield at 7% moisture (w/w) was determined by harvesting and weighing peanuts from the two treated rows of each plot. Value was determined by grading a composite sample from all four replicates of each treatment in accordance with federal-state inspection service methods.

Simulated evaluation of advisory programs. Logistic ($\ln(Y/1-Y)$), monomolecular ($\ln(1/1-Y)$), Gompertz ($\ln[1/\ln(1/Y)]$), and a linear model (untransformed Y) were used as growth models to fit the progress of peanut early leaf spot in 1987–1989. Line fitting of various growth models was done by least squares estimates using SAS regression procedures (SAS Institute, Inc. Cary,

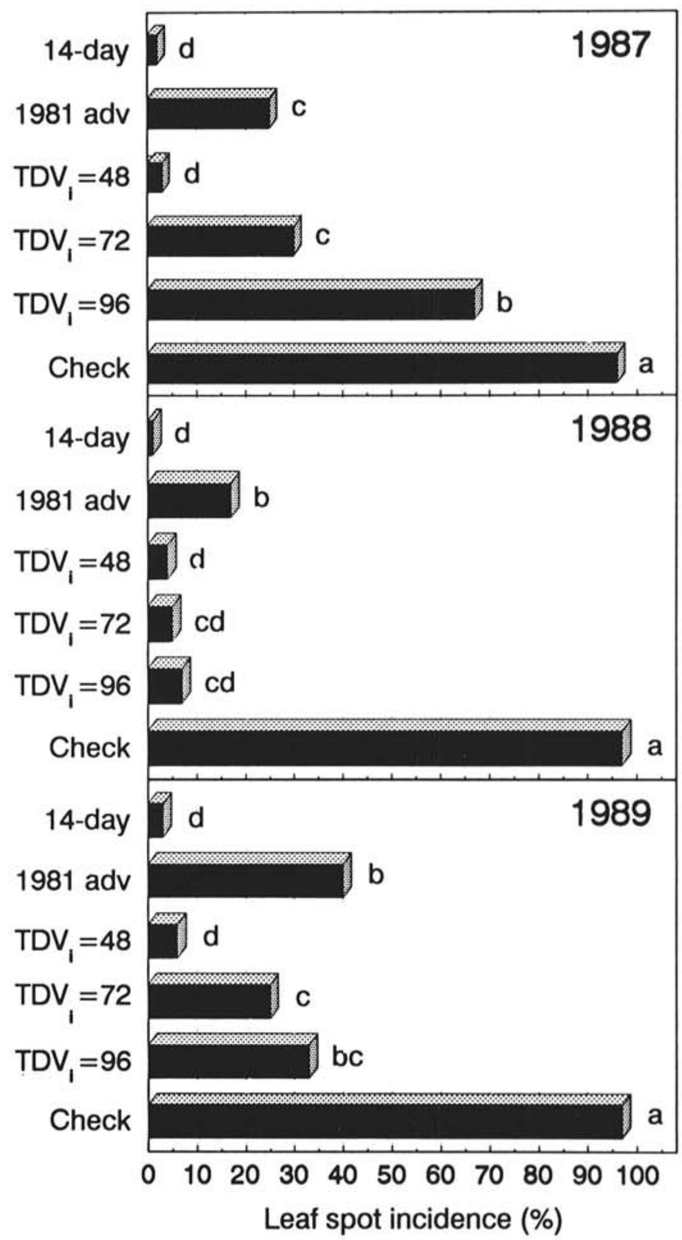

Fig. 1. End-of-season visual estimates of early leaf spot incidence in Florigiant peanut sprayed with chlorothalonil (1.26 kg/ha) according to various spray programs. Bars with the same letters in a given year are not significantly different at $P = 0.05$ according to Waller-Duncan k-ratio T test procedure. TDV_i = time-duration values for treatment application per 89-ADV program.

NC). Number of days after planting and the cumulative TDV_i were separately tested as regressor or predictor in regression analyses. Leaf spot incidence associated with various spray programs was estimated by:

$$Y = -0.168330 + 0.001699X(C_{eff})$$

where Y, X, and C_{eff} were an estimate of leaf spot incidence ($0 < Y < 1$), the cumulative TDV_i ($99 < X < 688$), and the control efficiency of a spray program based on historical data (22–25), respectively. The control efficiency (C_{eff}) of a spray program was determined as: $C_{eff} = 1 - (Y_1 / Y_2)$, where Y_1 and Y_2 were leaf spot incidence for a spray program and the untreated check, respectively. A program simulator that estimated leaf spot incidence from fields sprayed according to the various spray programs was developed based on the best-fitting linear model. Leaf spot incidence associated with various advisory thresholds of the 89-ADV program was compared with the 81-ADV program, a 14-day spray schedule, and an untreated check. Parameters for evaluation of program performance included the number of spray applications per season and leaf spot incidence at the end of the growing season.

Since 1981, AEMS has recorded meteorological data every 10 min, 24 h per day. Complete records of all data have been maintained in files at the Tidewater Agricultural Experiment Station. To compare the performance of advisory programs during the years before development and field testing, the simulator estimated the progress of early leaf spot of peanut using historical data. The program simulator used historical data from 1983–1986 and listed dates when fungicide sprays were needed based on the cumulative TDV_i thresholds.

RESULTS

Field evaluation. Disease incidence in untreated or check plots approached 100% at the end of each cropping season during

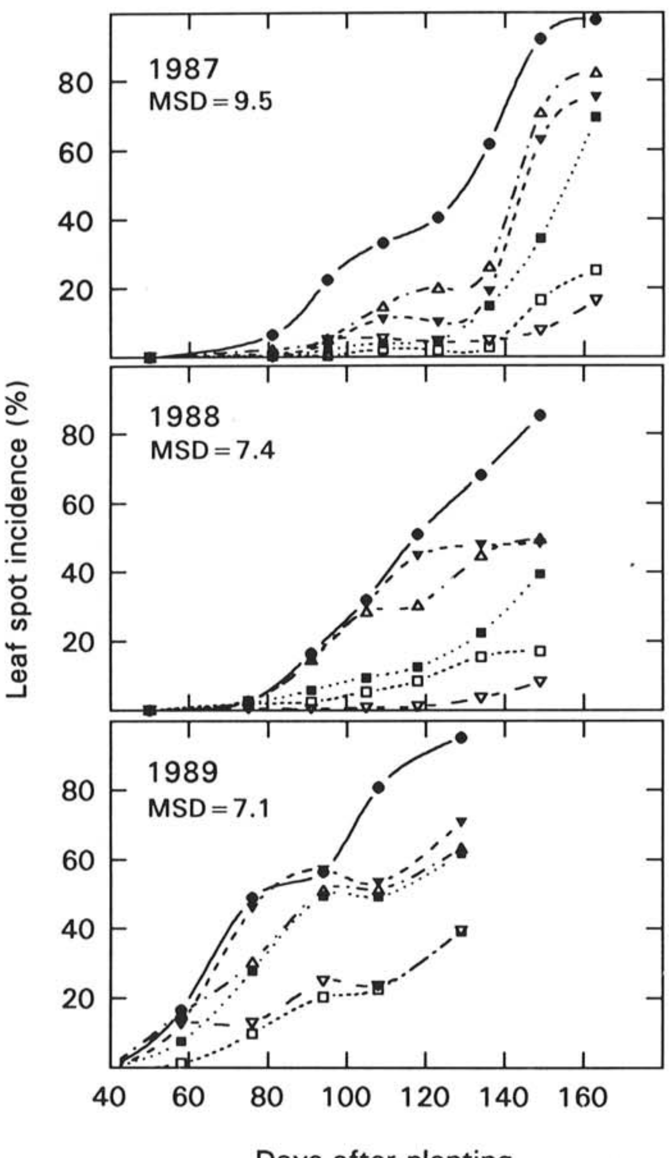

Fig. 2. Disease progress curves for early leaf spot as determined by the tagged plant method in Florigiant peanut when treated with chlorothalonil (1.26 kg/ha). Spray conditions were: 14-day spray schedule (▽), 89-ADV program with spray thresholds of $TDV_i = 48$ (□), 89-ADV program $TDV_i = 72$ (■), 89-ADV program $TDV_i = 96$ (△), 81-ADV program (▼), and untreated check (●). The minimum significant difference (MSD) of 9.5, 7.4, and 7.1 for 1987–1989, respectively, pertains to the final disease rating according to Waller-Duncan k-ratio T test procedure ($P = 0.05$). TDV_i = time-duration values for treatment. ADV = advisory program.

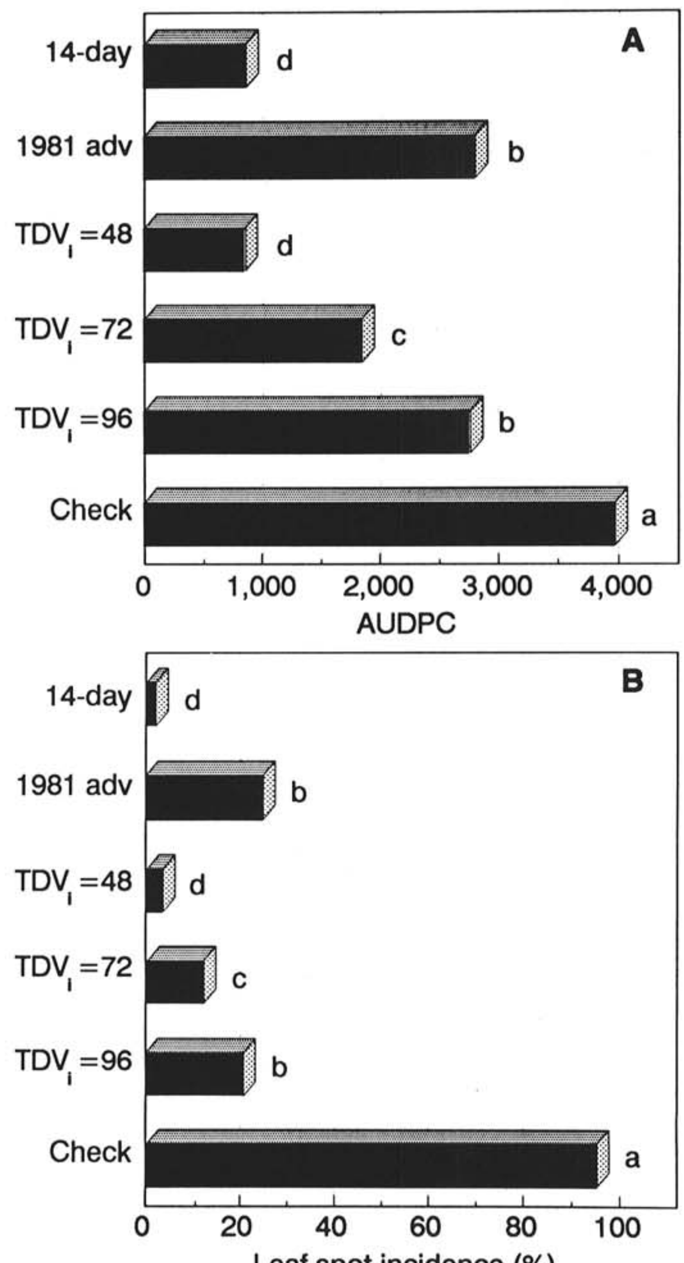

Fig. 3. A, Area under the disease progress curve (AUDPC) and **B,** end-of-season visual estimates of leaf spot incidence with spray programs using chlorothalonil (1.25 kg/ha) over a 3-yr period (1987–1989). Bars with the same letter are not significantly different at $P = 0.05$ according to Waller-Duncan k-ratio T test procedure. TDV_i = time-duration values for treatment. ADV = advisory program.

TABLE 3. Effect of spray programs on yield and value of peanut

Spray program[a]	Yield (kg/ha)[b]			Value ($/ha)[c]		
	1987	1988	1989	1987	1988	1989
14-day	4,861 bc	4,977 a	4,350 a	3,256 a	3,284 ab	3,126 a
81-ADV	5,061 ab	4,096 bc	3,571 b	3,450 a	2,861 bc	2,607 b
89-ADV						
$TDV_i = 48$	5,185 a	5,080 a	4,299 a	3,422 a	3,442 a	3,096 a
$TDV_i = 72$	4,936 a–c	4,581 a–c	4,029 ab	3,356 a	2,987 a–c	2,941 ab
$TDV_i = 96$	4,674 c	4,757 ab	4,417 a	3,038 b	3,274 ab	3,118 a
Check	4,375 d	3,949 c	2,505 c	3,020 b	2,750 c	1,883 c

[a]Chlorothalonil at 1.26 kg/ha was applied to Florigiant peanut in each program evaluation.
[b]Yield based on weight of peanuts at 7% moisture (w/w).
[c]Value was determined by grading a composite sample of peanuts from each treatment in accordance with federal-state inspection service methods. Values followed by the same letter(s) in a column are not significantly different according to Waller-Duncan k-ratio T test procedure ($P = 0.05$).

1987–1989 (Fig. 1). Plots sprayed at the threshold of $TDV_i = 48$ in the 89-ADV program exhibited significantly lower leaf spot incidence than plots sprayed according to the 81-ADV program. Furthermore, disease incidence in plots sprayed at $TDV_i = 48$ was not significantly different from levels in plots where the 14-day spray schedule was used. Disease progress in plots sprayed according to the $TDV_i = 48$ threshold mimicked that in plots sprayed on a 14-day spray schedule, according to disease assessments made by the tagged-plant method (Fig. 2). A test for homogeneity of regression coefficients at $P = 0.05$ indicated that disease progress in plots sprayed at the $TDV_i = 48$ threshold was similar to that in plots treated on a 14-day spray schedule. Fungicide applications at advisory thresholds of $TDV_i = 72$ and 96 suppressed leaf spot incidence to about the same level, or better, than applications according to the 81-ADV program during 1988–1989. Disease assessments made by the tagged-plant method confirmed the results of visual estimates. Over the 3-yr period, fungicide applications according to an advisory threshold of $TDV_i = 48$ and the 14-day spray schedule resulted in significantly lower levels of AUDPC and leaf spot at harvest than other spray programs (Fig. 3). Conditions considered lethal to the germinating spores did not alter the timing of sprays in these trials. Therefore, the effect of lethal conditions on the progress of early leaf spot could not be verified.

Yields with the 89-ADV spray threshold of $TDV_i = 48$ were significantly better than those with the 81-ADV program in two of the three years of testing (Table 3). Similar trends in relationships of value ($/ha) were observed. The number of sprays per cropping season averaged 6.7, 4.3, 3.0, 3.0, and 4.0, for the 14-day spray schedule, the 89-ADV program spray thresholds of $TDV_i = 48$, 72, and 96, and the 81-ADV program, respectively. The 81-ADV program and the 89-ADV program, with a $TDV_i = 48$ threshold, had about the same number of fungicide applications per cropping season.

Simulated evaluation of spray programs. TDV_i was a better regressor than number of days after planting in models tested for providing the best estimate of disease progress curves in 1987–1989 field trials (Table 4). The linear model (untransformed Y) had the highest coefficient of determination ($r^2 = 90.7\%$), the lowest root mean square error, and the smallest margin of standard error for parameter estimates. The linear model ($Y = -0.168330 + 0.001699X(C_{eff})$) was used to estimate leaf spot control with fungicide applications according to various advisory thresholds of the 89-ADV program. C_{eff} values of 91.7, 87.8, 78.4, and 40.8% were obtained for a 14-day spray schedule and the 89-ADV program with spray thresholds of $TDV_i = 48$, 72, and 96, respectively, over the 3-yr testing period.

The simulated assessment of disease, based on 1983–1986 historical weather data, closely resembled 1987–1989 actual field trials. AUDPC and leaf spot incidence at harvest, using the 89-ADV program with a spray threshold of $TDV_i = 48$, were not significantly different from those of a 14-day spray schedule (Fig. 4). Both programs provided significantly better disease control than the 81-ADV program. The 14-day spray schedule had an average of 6.75 fungicide applications per cropping season, while the 81-ADV program, as well as a $TDV_i = 48$ threshold in the 89-ADV program, averaged 3.75 fungicide applications per cropping season (Table 5).

TABLE 4. Linear regression statistics and parameter estimates of models used to fit the 1987–1989 disease progress curves of early leaf spot of peanut

Model and (regressor)[a]	r^2 (%)[b]	Root mean standard error	Parameter estimate[b] α	Parameter estimate[b] β	Standard error α	Standard error β
Logistic						
(TDV_i)	60.5	2.27607	−6.9121*	0.0157*	1.27249	0.00303
(DAP)	44.7	2.69216	−10.163*	0.0883*	2.49115	0.02302
Monomolecular						
(TDV_i)	76.1	0.42573	−0.7599	0.0042*	0.23801	0.00057
(DAP)	52.8	0.59837	−1.5537	0.0229*	0.55369	0.00512
Gompertz						
(TDV_i)	89.6	0.43611	−2.4122*	0.0071*	0.24382	0.00058
(DAP)	64.6	0.80505	−3.8024*	0.0389*	0.74494	0.00688
Linear						
(TDV_i)	90.7	0.09410	−0.1683*	0.0017*	0.05261	0.00012
(DAP)	68.3	0.17343	−0.5071	0.0091*	0.16048	0.00148

[a]The logistic, monomolecular and Gompertz models were linearized by transforming disease incidence ($0<Y<1$) to $\ln(Y/1-Y)$, $\ln(1-Y)$, and $\ln[1/\ln(1/Y)]$, respectively. The untransformed Y is referred to as the linear model. The cumulative time-duration value for infection (TDV_i) and days after planting (DAP) were tested separately as the regressor.
[b]The coefficients of determination (r^2) were adjusted for the degrees of freedom. An asterisk indicates that the t statistic of the parameters α (intercept) and β (slope) were significant ($P = 0.05$).

DISCUSSION

An average of 6.7 applications of chlorothalonil (Bravo 720) on a 14-day spray schedule provided excellent control of early leaf spot at 8.4 kg a.i./ha in actual field trials. Essentially, the same level of control was achieved by the 89-ADV program, at the spray threshold of $TDV_i = 48$, with an average of only 4.3 fungicide applications per cropping season, for a total of 5.4 kg a.i./ha. The 81-ADV program called for about the same number of fungicide applications per cropping season as the 89-ADV program with a threshold of $TDV_i = 48$. But the 81-ADV program allowed significantly greater leaf spot incidence and AUDPC over the 3-yr field testing. Previous studies by Phipps and Powell (27) and Matyac and Bailey (17) also showed that fungicide applications according to the 81-ADV program resulted in significantly higher incidence of early leaf spot than the 14-day spray schedule. The 89-ADV program with thresholds of $TDV_i = 72$ and 96 had fewer applications per cropping season than the 81-ADV program (Table 5), and disease control was often similar to, or better than, the 81-ADV program (Fig. 3).

Matyac and Bailey (17) found the logistic model to be the best-fitting curve to describe the progress of early leaf spot using the infection index described by Jensen and Boyle (11) as a

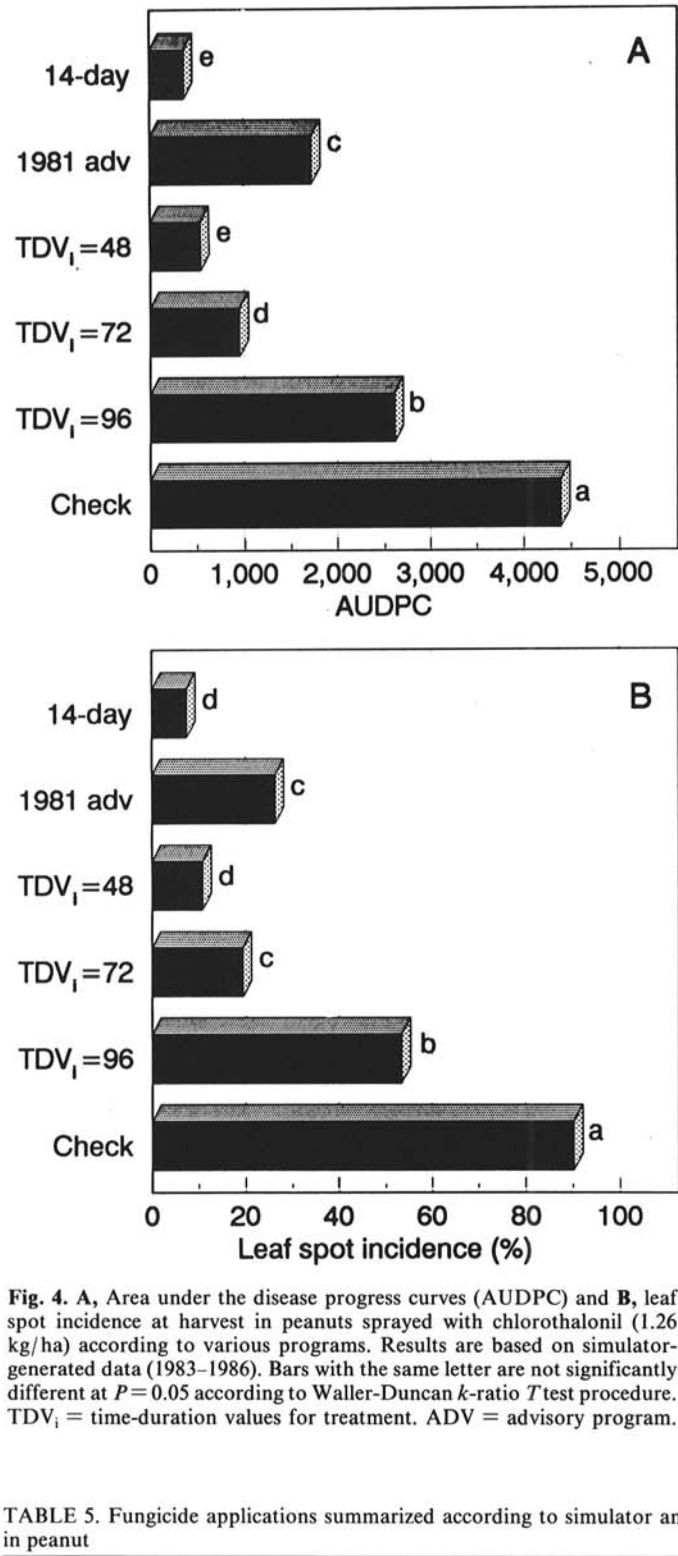

Fig. 4. A, Area under the disease progress curves (AUDPC) and **B,** leaf spot incidence at harvest in peanuts sprayed with chlorothalonil (1.26 kg/ha) according to various programs. Results are based on simulator-generated data (1983–1986). Bars with the same letter are not significantly different at $P = 0.05$ according to Waller-Duncan *k*-ratio *T* test procedure. TDV_i = time-duration values for treatment. ADV = advisory program.

regressor. Johnson and Beute (13) used the Gompertz model, with time in days after planting, as the regressor to be the best-fitting curve. This study, on the other hand, found the linear model (untransformed *Y*) with TDV_i as the regressor to be the best-fitting model for describing the progress of early leaf spot. The use of TDV_i as an epidemiological parameter for predicting disease severity resulted in the highest coefficient of determination (r^2), the lowest root mean square error, and the smallest margin of standard error of parameter estimates, compared to the logistic, monomolecular, and Gompertz models (Table 4).

Results from actual field tests and simulated tests with historical data showed that the 89-ADV threshold of $TDV_i = 48$ for fungicide treatment would suppress disease progress to levels similar to those on a 14-day spray schedule. An advantage of using the 89-ADV program at $TDV_i = 48$ was saving an average of 2.4 fungicide applications per cropping season without any loss of crop yield or value. The 89-ADV program with a spray threshold of $TDV_i = 48$ also provided for better disease control than the 81-ADV program with about the same number of sprays per season. The improved disease control with the 89-ADV program at $TDV_i = 48$ was thought to be achieved by the consideration of meteorological conditions over several days, or even weeks, in determining the need for fungicide application. The 81-ADV program considered only a 5-day window with heaviest emphasis on the preceding 2 days of meteorological conditions for prediction of a disease-favorable condition.

Because of the superior performance of the $TDV_i = 48$ threshold in actual field tests and simulated disease environments, the 89-ADV program was adopted as the on-line peanut leaf spot advisory in 1989. The 89-ADV program currently used by growers in Virginia does not adjust for lethal conditions because the effects on epidemiology of early leaf spot could not be verified. Daily advisories are updated at 4 p.m. ET by the Virginia Cooperative Extension Service and, through a toll-free number, are provided for growers throughout Virginia. The concept of reporting the "last effective spray date" offered the advantage of forewarning growers of the approaching need for fungicide application. This approach removed much of the confusion created by the 81-ADV program that could report a disease-favorable condition for leaf spot one day, and follow with a report of a disease-unfavorable condition a day later.

Threshold values of $TDV_i = 72$ and 96 in the 89-ADV program recommended fewer sprays per season, and disease control was similar to, or sometimes better than, the 81-ADV program. Thresholds greater than $TDV_i = 48$ may be applicable to cultivars with partial resistance to early leaf spot. Fry et al (7) have worked on the idea of incorporating host resistance into the potato late blight forecast. They have ascertained the complementary effect of host resistance and reduced frequency of fungicide application. Matyac and Bailey (17) tested the effect of cultivar selection on the 81-ADV program by adjusting the infection index values by factors of 0.95, 0.90, 0.80, 0.75, and 0.7. The modification was intended for genotypes with partial resistance, so that fewer fungicide applications would be required. In a similar manner, the higher TDV_i thresholds of the 89-ADV program would result

TABLE 5. Fungicide applications summarized according to simulator and field tests of various spray advisory (ADV) programs for leaf spot control in peanut

	Simulator trials[a]					Actual field trials[b]			
Spray program	1983	1984	1985	1986	Mean	1987	1988	1989	Mean
14-day	7	6	7	7	6.75	7	7	6	6.7
81-ADV	3	4	3	5	3.75	5	3	4	4.0
89-ADV:									
$TDV_i = 48$[c]	3	4	4	4	3.75	5	3	5	4.3
$TDV_i = 72$	3	3	4	4	3.50	3	2	4	3.0
$TDV_i = 96$	3	3	3	3	3.00	3	2	4	3.0

[a]Sprays per cropping season based on simulator assessments using historical data. Data from the 14-day spray schedule and the 81-ADV program reflect actual sprays in field trials.
[b]Sprays per cropping season based on actual field trials of each program.
[c]Time duration value of infection (TDV_i).

in a longer spray interval and fewer sprays per season. This approach could be used with cultivars having partial resistance to leaf spot. In the current study, which used the highly susceptible cultivar Florigiant, a threshold of $TDV_i = 48$ was the most appropriate. Cultivars with partial resistance to early leaf spot, like NC 6 and NC 7 as discussed by Phipps and Powell (27), would probably perform well at higher TDV_i thresholds.

Adjusting the spray interval in a calendar program from 10 or 14 to 20 or 28 days to compensate for the rate-reducing effect of partial resistance in cultivars may not be dependable (8). The premise of adjusting the spray interval is based on residual activity of the fungicide and a constant rate of disease progress (34). These assumptions, however, fail to recognize the frequent overwhelming influence that environmental conditions may have on disease progress. The 89-ADV program considers the effect of fluctuating environmental conditions and adjusts the spray interval according to the anticipated effect on disease progress.

The choice of fungicide is another variable that can affect the performance of a disease management program. Various degrees of leaf spot control have been reported with different fungicides sprayed according to various spray programs (27). It seems quite possible that fungicides could be grouped according to mode of action and the timing of application determined by various TDV_i thresholds of the 89-ADV program. The systemic or curative action of some fungicides, such as the ergosterol biosynthesis inhibitors, may allow delays in fungicide application and afford fewer sprays than prophylactic or protectant fungicides such as chlorothalonil and the copper-sulfur compounds. The residual activity of fungicides is another factor to consider. The 10-day residual period after each fungicide application may require adjustment depending on rate of plant growth, environmental factors, and fungicide chemistry. The recent work of Elliott and Spurr (6) described the exponential decay of chlorothalonil residues on peanut leaves. Incorporating their residue decay model into the advisory program may result in a residual half-life for chlorothalonil of 13–17 days and further improve the efficiency of advisory programs.

Choices as to what cultivar to plant and what fungicide to apply are important decisions in leaf spot management. To accommodate these options, the dimensions of the advisory program should be expanded to include the effect of cultivar and fungicide selection. The 89-ADV program provides a mechanism to adjust and compensate for fungicide residual activity on leaves, performance characteristics of fungicides, and the relative resistance of various cultivars to early leaf spot. Large multifactorial experiments that include different cultivars, fungicides, and various advisory thresholds will be needed to generate information for development of expert advisory programs with greater efficiency and a wider margin of dependability.

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