Weather Variables Associated with Infection of Tomato Fruit by *Colletotrichum coccodes*

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ABSTRACT

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Field experiments were conducted to determine the relationship of tomato anthracnose to weather variables. Sixteen potted tomato plants were exposed to field conditions within rows of tomato plants for 4 consecutive days at various time periods during the 1993 and 1994 summer growing seasons. Incidence of fruit infection by *Colletotrichum coccodes* was correlated with rain variables (amount and duration of rain) alone and in combination with other meteorological factors. The best fitting regression equation, accounting for 72% of the variation in anthracnose incidence (arcsine-square root transformed), was $Y = 111.77 - 1.16 \text{ HNRO}$, in which HNRO is the numbers of hours during which no rainfall occurs within 4-day intervals that tomato fruit were exposed to field conditions in central Pennsylvania.

Tomato fruit rot, caused primarily by *Colletotrichum coccodes* (Wallr.) S.J. Hughes, is among the foremost constraints that limit marketable yields in Pennsylvania. Although anthracnose control provided by nonchemical techniques used within disease management systems has improved in recent years, the tomato processing industry relies heavily on registered chemical pesticides, primarily chlorothalonil (BRAVO 720 and BRAVO Weather Stik, ISK Biosciences Corp., Mentor, OH) to approach the yield potential in this regional climate. TOM-CAST, a modified version of the FAST system used to schedule fungicide applications for the control of early blight (13), is reported to provide a degree of anthracnose control (10). These two systems are, however, based upon the association of temperature and moisture data to sporophore and spore formation of *Alternaria solani* Sorauer, the causal agent of early blight, rather than knowledge of the response of *C. coccodes* to the environment.

Tomato anthracnose has been under investigation for over four decades. Most of the previous studies on this disease have focused on identifying and describing the means of survival and sources of causal agent inoculum (1,3,7,8,12,17,18). Current trends of research on tomato anthracnose are directed at designing effective and safe

management schemes through an increased understanding of the ecology and epidemiology of this disease. In order to achieve this goal, it is imperative to identify the critical biological and environmental factors that affect infection of tomato fruit by *C. coccodes*.

Temperature and moisture greatly affect fruit infection and lesion development under controlled environment conditions (6,12,16,17). However, the relation of these factors and other environmental variables to tomato anthracnose under field conditions has not been established. The objective of the present study was to describe the quantitative relationship of meteorological variables to incidence of anthracnose in the field. A portion of this study has been reported (21).

MATERIALS AND METHODS

Plant production. Tomato (*Lycopersicon esculentum* Mill.) plants were grown within a greenhouse environment to provide anthracnose-free indicator plants for exposure to the biological and physical environment encountered by plants growing in a field site with a history of tomato anthracnose. Seeds of the processing cultivar Brigade were sown in vermiculite; 3 weeks after emergence, resultant seedlings were transplanted to 21-cm-diameter plastic pots filled with steam-disinfested soil (1:2:2, vol/vol/vol, sand:peat:vermiculite). The potted plants were maintained in a greenhouse (21 to 26°C) and fertilized with a 15% N, 16% P₂O₅, 17% K₂O fertilizer (Peters Fertilizer Products, Fogelsville, PA) solution every 2 weeks. At the age of 8 weeks, the greenhouse-grown plants were subjected to a 4- to 6-week hardening phase. Hardening consisted of placing the

potted plants outdoors under a wooden shelter (6 by 2 by 3 m) located about 500 m from the field in which the actual experiments were conducted. The shelter rested on a graveled area covered with a black woven polypropylene ground cover (994 Ground Cover; E. C. Geiger, Inc., Harleysville, PA) to prevent weed growth and soil materials from coming into contact with the potted plants, yet allow moisture to leach through. The roof framework was covered with transparent, colorless, polyethylene sheeting to minimize the potential for development of foliar diseases by preventing both dew formation and foliage from becoming wet during periods of rainfall. The sides of the framework were left uncovered to allow air circulation to minimize the potential for establishing elevated air temperatures within the shelter.

Field exposure. Field experiments were conducted within rows of tomato plants established on Hagerstown silt loam (fine, mixed, mesic Typic Hapludalf) soils at the Russell E. Larson Agricultural Research Center at Rock Springs, Center Co., PA (40° 42' 53" N, 77° 56' 25" W). The study area had been planted to tomatoes for many consecutive years and the soil was known to be naturally infested with *C. coccodes*. On 17 May 1993 and 23 May 1994, 6-week-old plants (cultivar Sunny) were mechanically transplanted at 1- by 4.5-foot (30- by 137-cm) spacings. Conventional tillage and, in general, standard recommended cultural practices for the production of processing tomatoes were employed; the exception being that fungicide was not applied to the rows of plants in which the potted, anthracnose-free plants were placed.

On each of 16 dates during the 1993 and 1994 growing seasons, 16 disease-free potted tomato plants were placed within rows of the field-grown plants. At each of four sites within the 0.4 ha field plot, 4 of the 16 potted plants were placed 90 cm apart within rows of the non-sprayed plants. The potted test plants bearing 4- to 5-cm-diameter mature green fruit were 12 to 14 weeks old when exposed for 4 consecutive days to the field environment that was naturally infested with *C. coccodes*. At the time of the first exposure in 1993 (27 August), the presence of typical symptoms of anthracnose on ripening tomato fruit throughout the experimental field site indi-

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cated that inoculum was abundant in the field. In 1994, the first group of indicator plants was exposed (2 June) to the field environment prior to the occurrence of visual anthracnose symptoms on the field grown plants. Therefore, infected ripe tomato fruit with sporulating lesions were placed on the soil surface within rows at exposure sites to ensure that inoculum was present early in the growing season and throughout exposure episodes. At the end of each of the 16 exposure periods, all fruit were harvested from each of the 16 potted plants, washed with tap water, and wiped with 95% ethanol to remove any surface inoculum. Thereafter, fruit were placed on wire racks and maintained in the dark at 28°C for about 8 weeks in a growth chamber (Model M-2, Environmental Growth Chambers, Chagrin Falls, OH) set at 80 to 85% relative humidity (RH) to promote colonization and symptom development. Fruit were examined weekly for typical symptoms of anthracnose and signs of *C. coccodes*. These were easily recognized by the presence of slightly depressed or sunken, circular lesions on the fruit, the presence of visible acervuli on lesions, and/or by sclerotia beneath the epidermis. Visual assessment was confirmed by the isolation of *C. coccodes* from randomly identified symptomatic fruit. The average incidence of anthracnose was then calcu-

lated as the ratio of the number of fruit expressing typical symptoms and signs to the total number of fruit harvested from each subset of 16 potted plants.

Weather variables. Environmental data characterizing air temperature, RH, rainfall, dew period, and solar radiation were obtained from a meteorological station (22,23) located approximately 300 m from the exposure site. Air temperature (°C) and RH (%) were measured with a Campbell Scientific Model HMP35C Probe. Rainfall (cm) was measured with a Weather Measure/Weathertronics Model 6010 Tipping Bucket Rain Gage with Model 6410 Precipitation Gage Wind Screen. The presence and duration (h) of dew were estimated with a gold-plated grid on etched glass excited by 5vdc. Total incoming solar radiation values (Wm^{-2}) were obtained with an Eppley Model 8-48 Black/White Pyranometer sensitive over the wavelengths from 280 to 2800 nm. All sensors were interfaced to a 21X Micrologger (Campbell Scientific, Inc., Logan, UT) that recorded data at 10-min intervals. From these data, variables (Table 1) were defined and used in the analysis of tomato anthracnose incidence in the field.

Data analysis. For each exposure episode, four groups of environmental variables were tallied (Table 2). Each of the four groups included nine weather vari-

ables that were associated with amount and/or duration of rainfall, dew, and solar irradiance, for three intervals of temperature when the relative humidity equaled or exceeded 90%. The arcsine-square root transformation, expressed in degrees, was applied to the anthracnose incidence data. Pearson's product-moment correlation coefficient (r) was computed between each group of environmental variables and the transformed disease incidence data. Stepwise regression was used to identify the subset that best predicted the transformed disease incidence from among the nine weather variables. Criteria for selecting the best subset included an overall F statistic significant at $P \leq 0.05$, a t test of estimated parameters significant at $P \leq 0.05$, values of R^2 and Ra^2 , and residual plots. Other statistics used in model selection and validation included VIF (variance inflation factor), Mallows' C_p and prediction error sum of squares (PRESS) statistics (14,15). Given several regression equations with $p - 1$ independent variables (excluding the intercept), the best equation would be one that leads to the smallest value of C_p (approximately equal to the number of independent variables $p - 1$) and the lowest PRESS value. All analyses were performed using the Statistical Analysis System (SAS Institute Inc., Cary, NC).

RESULTS

The exposure of 16 anthracnose-free tomato plants to field conditions was replicated over 16 time intervals between 27 August 1993 and 29 August 1994 (Table 3). Mature green fruit harvested from those indicator plants did not become infected by *C. coccodes* within 8 weeks following the four exposure intervals during which rainfall did not occur. When rainfall did occur within a 4-day exposure period, the inci-

Table 1. Environmental variables used in analyzing incidence of tomato fruit infection by *Colletotrichum coccodes* that occurred in the field during the 1993 and 1994 growing seasons

Term	Description
Ro	Rainfall (cm)
R1	Rainfall (cm) when T ^a was 16 to 28°C and RH ^b was $\geq 90\%$
R2	Rainfall (cm) when T was 20 to 30°C and RH was $\geq 90\%$
R3	Rainfall (cm) when T was 15 to 30°C and RH was $\geq 90\%$
HRo	Hours of rainfall
HR1	Hours of rainfall when T was 16 to 28°C and RH was $\geq 90\%$
HR2	Hours of rainfall when T was 20 to 30°C and RH was $\geq 90\%$
HR3	Hours of rainfall when T was 15 to 30°C and RH was $\geq 90\%$
Do	Hours of dew
D1	Hours of dew when T was 16 to 28°C and RH was $\geq 90\%$
D2	Hours of dew when T was 20 to 30°C and RH was $\geq 90\%$
D3	Hours of dew when T was 15 to 30°C and RH was $\geq 90\%$
HNRo	Hours with no rainfall
HNR1	Hours with no rainfall when T was 16 to 28°C and RH was $\geq 90\%$
HNR2	Hours with no rainfall when T was 20 to 30°C and RH was $\geq 90\%$
HNR3	Hours with no rainfall when T was 15 to 30°C and RH was $\geq 90\%$
radHR	Solar irradiance (Wm^{-2}) during hours of rainfall
radNR	Solar irradiance (Wm^{-2}) during hours of no rainfall
Rrad	Rainfall (cm) during hours of solar radiation ($> 0 \text{ Wm}^{-2}$)
HRrad	Hours of solar radiation ($> 0 \text{ Wm}^{-2}$) during rainfall
HradNR	Hours of solar radiation ($> 0 \text{ Wm}^{-2}$) during periods of no rainfall

^a T = average air temperature.

^b RH = average relative humidity.

Table 2. Grouping of environmental variables defined in Table 1 for the application of stepwise regression to identify the subset of weather variables that best predicts the incidence of tomato fruit infection by *Colletotrichum coccodes*

Group	Variable
1	Ro, HRo, HNRo, Do, radHR, radNR, Rrad, HRrad, HradNR
2	R1, HR1, HNR1, D1, radHR, radNR, Rrad, HRrad, HradNR
3	R2, HR2, HNR2, D2, radHR, radNR, Rrad, HRrad, HradNR
4	R3, HR3, HNR3, D3, radHR, radNR, Rrad, HRrad, HradNR

Table 3. Incidence of fruit infection by *Colletotrichum coccodes* in field-exposed potted tomato plants and the accumulated rainfall during each exposure period

Exposure period	Incidence (%) ^a	Rainfall (cm)
1993		
27 Aug to 31 Aug	0	0
31 Aug to 04 Sep	15	3.17
04 Sep to 08 Sep	0	0
1994		
02 Jun to 06 Jun	0	0
14 Jun to 18 Jun	0	0.30
18 Jun to 22 Jun	0	1.14
23 Jun to 27 Jun	2	0.53
27 Jun to 01 Jul	1	1.06
04 Jul to 08 Jul	9	0.76
09 Jul to 13 Jul	0	0
14 Jul to 18 Jul	1	1.45
20 Jul to 24 Jul	15	3.48
24 Jul to 28 Jul	5	1.52
01 Aug to 05 Aug	5	5.23
20 Aug to 24 Aug	13	2.46
25 Aug to 29 Aug	14	2.44

^a Incidence is based upon all fruit harvested from 16 plants per exposure period.

dence of anthracnose fruit infection ranged from 0 to 15%. Although there were two 4-day exposure periods between 14 and 22 June 1994 when rainfall was recorded but fruit infection did not occur, those accumulated rainfalls of only 0.30 and 1.14 cm occurred immediately prior to harvesting and surface sterilizing the fruit.

The arcsine-square root transformation of disease incidence was highly to moderately correlated to most of the rainfall variables alone, or in combination with the other weather variables, considered in this experiment (Table 4). Among the 21 variables appraised, the only nonsignificant correlation coefficients ($P > 0.05$) involved: a) the number of hours within a 4-day exposure that no rainfall was recorded but the RH was $\geq 90\%$ and the average air temperatures were between 16 and 28°C (HNR1), between 20 and 30°C (HNR2), and between 15 and 30°C (HNR3); and, b) solar irradiance during intervals of time when rainfall was recorded (radHR) and during intervals when no rainfall occurred (radNR).

Table 4. Pearson's product-moment correlation coefficient (r) of arcsine-square root of anthracnose incidence with environmental variables defined in Table 1

Variable	r	$P(>F)$
Ro	0.721	0.002
R1	0.664	0.005
R2	0.603	0.013
R3	0.678	0.004
HRo	0.815	0.000
HR1	0.807	0.000
HR2	0.710	0.002
HR3	0.811	0.000
Do	0.665	0.005
D1	0.730	0.001
D2	0.684	0.004
D3	0.707	0.002
HNRo	-0.850	0.000
HNR1	0.458	0.074
HNR2	0.168	0.533
HNR3	0.425	0.101
radHR	0.395	0.130
radNR	-0.438	0.090
Rrad	0.526	0.036
HRrad	0.600	0.014
HradNR	-0.739	0.001

The coefficients and associated statistics for the best regression equations for predicting the arcsine-square root of the proportion of fruit infected by *C. coccodes* for each of the four groups of nine variables considered in this experiment are shown in Table 5. The selected model within each of the four groups of environmental variables contained two or three parameters (including the intercept) and explained 65 to 72% of the variability in anthracnose incidence (arcsine-square root transformed). The VIF values associated with the independent variables in each of the four models were equal, or very close, to 1. In contrast to group 2, models for groups 1, 3, and 4 had C_p values lower than the number of parameters they contained. The value of the PRESS statistic was lowest for group 1 and highest for group 2.

Based upon the previously defined criteria, the model chosen for estimating fruit infection by *C. coccodes* from the environmental variables in group 1 (Table 2) is therefore identified as the best among the four regression models presented in Table 5. This model, accounting for 72% of the variation in anthracnose incidence (arcsine-square root transformed), predicts disease incidence from the numbers of hours during which no rainfall occurs within 4-day intervals in which tomato fruit are exposed to field conditions in central Pennsylvania.

DISCUSSION

Research and extension personnel, crop consultants, and/or growers may be confronted with a number of difficulties when attempting to predict the likelihood that current and/or past conditions favor the onset of infection of tomato fruit by *C. coccodes*. The onset and duration of the infection period is influenced by, but not limited to, age uniformity of plants, local weather conditions, and constancy of initial inoculum levels. In this study attempts were made to produce anthracnose-free plants of uniform age using identical growing conditions from one array to the other. To minimize physiological differences between plants grown in the greenhouse and those in the field, greenhouse-grown plants were subjected to a 4- to 6-

week hardening phase before being exposed to actual field conditions. The greenhouse environment and hardening phase technique were utilized to prevent the potted indicator plants from becoming infected by *C. coccodes* prior to their placement among the population of tomato plants in the 0.4 ha research plot.

When the investigation was initiated in 1993, the first set of 16 indicator plants was not exposed to the field environment until 27 August. At that time, ripening fruit on the field-grown plants displayed typical symptoms of tomato anthracnose. However, when the initial set of 16 indicator plants was placed among the field grown plants in 1994, the young transplants had been in the field for only 10 days and had not yet set fruit nor displayed foliar or stem symptoms of anthracnose. Therefore, during each exposure period in 1994, the presence of uniform inoculum of sufficient volume to inoculate the indicator plants was ensured by placing infected fruit with sporulating lesions on the soil surface at the outer edge of the canopy drip line. These fruit were initially inoculated and maintained under the same environmental conditions prior to each of the 13 exposures in 1994.

Results of this field investigation support the hypothesis that anthracnose epidemics of tomato fruit are greatly influenced by environmental factors. In previous controlled environment studies of fruit inoculated with *C. coccodes*, appressorial formation occurred readily at 16 to 28°C, and fruit infection occurred readily at 20 to 30°C (20). Knowledge of these temperature ranges in conjunction with other epidemiological information from the literature on *C. coccodes* (5,6,9,19) provided the basis for screening the various environmental variables monitored in the field.

Stepwise model-building techniques have been employed extensively by plant pathologists to quantitatively describe the relationship of weather variables to disease intensity and severity. Whereas accurate regression models were successfully derived in several studies (4,11,24), high multicollinearity among predictor variables

Table 5. Regression coefficients and associated statistics for the models predicting the arcsine-square root of the proportion of fruit infected by *Colletotrichum coccodes* for each group of the nine environmental variables defined in Table 2

Group	Variable	Coefficient	VIF	$P(>F)$	R^2	Ra^2	C_p	PRESS
1	Intercept	111.77	1.0	< 0.001	0.72	0.70	-4.43	469
	HNRo	-1.16						
2	Intercept	2.24	1.0	< 0.001	0.65	0.63	3.75	584
	HR1	1.40						
3	Intercept	62.29	1.3	< 0.001	0.70	0.65	0.16	566
	HradNR	-1.06						
	D2	0.65						
4	Intercept	1.96	1.0	< 0.001	0.66	0.63	0.05	566
	HR3	1.37						

hindered the application of this process to data derived from other investigations. This is exemplified by the study of Bowers et al. (2), who examined the association of rain variables to Phytophthora blight of pepper caused by *Phytophthora capsici*. In spite of being highly correlated, direct and indirect effects of rain variables on the incidence of Phytophthora blight were assessed by the method of path coefficient analysis.

In the present investigation, four regression models were developed. The value of the VIF for each model was very close to 1 (Table 5), indicating negligible multicollinearity among predictor variables and stability of regression coefficients (14). Of the 21 environmental variables analyzed, those that best predicted the arcsine-square root transformation of the incidence of fruit infection for each of the four groups of environmental variables were those characterizing a) the number of hours without rain (HNRO), b) hours of rainfall when the temperature was between 16 and 28°C and the average RH was $\geq 90\%$ (HR1), c) hours of solar radiation $> 0 \text{ Wm}^{-2}$ during periods of no rain (HradNR) along with the number of hours dew was present when the temperature was between 20 and 30°C and RH $\geq 90\%$ (D2), and d) the number of hours of rainfall when the temperature was between 15 and 30°C and the average RH was $\geq 90\%$ (HR3).

By the criteria of R^2 , Mellow's C_p , and the PRESS statistics, the equation for group 1 (Table 5) would be the best model for predicting fruit infection. For this regression model, the arcsine-square root transform of anthracnose incidence (expressed in degrees) is estimated simply through the analysis of duration of rainfall episodes monitored within 4-day intervals. The independent variable is the number of hours that no rain (HNRO) occurred within the 4-day period. This model implies that the greatest incidence of infection may be expected following a 4-day period which included few hourly intervals of 'No Rain,' and that disease incidence decreases by approximately 1.16 degree units for each hour rainfall did not occur within the 4-day interval. This model was derived from disease incidence data of 0 to 15% and intervals of 74 to 95 h in which no rainfall occurred within the 91 to 98 h that the indicator plants were exposed to field conditions.

Rainfall does play a significant role in distributing conidial inoculum by splash dispersal. Although the intensities of individual rainfall episodes were not recorded, it may be assumed that for a given amount of rainfall, the intensity would increase as the number of hours of 'No Rain' per 4-day interval increased. Rainfalls of high intensity would enhance the likelihood of splash dispersal contributing to fruit infection

more so than would an equal amount of total rainfall occurring over longer time periods.

Although the recommended model for environmental variables in group 2 is driven by hours of rainfall when the average temperature was between 16 and 28°C (HR1), the equation had poor predictive ability as revealed by its high PRESS value. In the absence of the rainfall variable, a model based on the dew variable alone would commonly be inconsistent with the epidemiology of tomato anthracnose unless, however, it is assumed that conidial inoculum of *C. coccodes* is present on plant surfaces as a result of dispersal by air. Both dew and rainfall provide free moisture needed for conidial germination, appressorial formation, and subsequent fruit infection by *C. coccodes*. In light of the epidemiological importance of rainfall and dew, the present investigation suggests that the regression model derived from the environmental variables defined for either group 1, 3, or 4 may be considered for estimating the incidence of fruit infection in the field.

Previous studies have indicated an association of rainfall with the subsequent outbreak of tomato anthracnose. Their results are supported by the high correlations found between rainfall variables and anthracnose incidence in the present investigation. However, in most of the previous studies, other environmental variables such as temperature and relative humidity were not taken into consideration when relating rainfall to tomato anthracnose. This study emphasized the importance of these factors in accounting for variability in fruit infection in the field.

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