A Model for Detecting Infection Periods of *Coccomyces hiemalis* on Sour Cherry

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ABSTRACT

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A regression model relating hours of continuous moist chamber exposure and temperature to infection of sour cherry by conidia of *Coccomyces heimalis*, cherry leaf spot fungus, was developed from published data. The model is $EFI = [-11.0 + 0.2858W + 1.4639T - 0.0019W^2 - 0.0389T^2 - 0.003WT]^2$, in which T = temperature (C), W = hours of leaf wetness, and EFI = environmental favorability index from 0 to 100. An EFI of 14 was selected to delineate the minimum conditions for infection under field conditions. EFI was ≥14 in 62 of 65 validations for which infection was detected by observing marked shoots of orchard trees every 4–7 days, and <14 in 15 of 18 validations for which no infection occurred. In 34 of 35 cases in which infection was detected by exposing potted trees during putative infection-favoring weather, EFI was ≥14; and in 20 of 39 cases in which no infection occurred, the EFI was <24. The infection model is useful between 8 and 28 C, and for leaf wetness periods up to 70 hr. Daily EFI values were linearly related to rates of disease increase in Michigan in 1978 and 1979.

Additional key words: epidemiology, *Prunus cerasus*.

Cherry leaf spot, which is caused by *Coccomyces hiemalis* Higgins, is a major disease of sour cherry (*Prunus cerasus* L. 'Montmorency') throughout Michigan cherry-growing regions. Ascospores from apothecia in leaves that have overwintered on the orchard floor initiate primary infections in the spring. Conidia from acervuli on infected leaves initiate secondary infection, a process that is repeated several times throughout the growing season.

Infection by ascospores and conidia is governed by the duration of wetting from rain and by temperature. A predictive system, similar to that of Mills (7) for predicting infection by the apple scab fungus, might be useful in developing disease management strategies for leaf spot control. The objectives of this study were to develop and validate a model for identifying environmental periods favorable for infection by the leaf spot fungus and to relate the frequency and favorability of these periods to disease progress.

MATERIALS AND METHODS

A multiple regression equation relating infection of leaves to hours of moist chamber wetting and temperature was generated from numerical values published in Fig. 22 of Keitt et al (5). These workers inoculated sour cherry trees with conidial suspensions of *C. hiemalis* and incubated them continuously in a moist chamber for 4–70 hr and at temperatures ranging from 8 to 28 C. These data, which were furnished to us by J. D. Moore, University of Wisconsin, Madison, and the corresponding values predicted by the regression equation were computer-plotted with a three-dimensional plotting program (12). Although Keitt et al (5) expressed infection as the average number of lesions per maximally infected square inch per leaf, we converted the published values to a relative percentage of the maximum disease intensity observed for their combined data. This relative scale of 0 to 100 was called an environmental favorability index (EFI). Various regression models were applied to the moist chamber data to find one that would explain the greatest percentage of variability.

Disease data for validation of the model were obtained by monitoring leaf spot infection and disease progress in three Montmorency cherry orchards and one nursery planting. Orchards JO4 and KL1, which are located near East Lansing, MI, consisted of 9- and 21-yr-old trees, respectively, in 1978. Orchard SH5A consisted of 7-yr-old trees in a mixed-cultivar planting and SH5B consisted of a 5-yr-old planting of open-pollinated Montmorency seedlings. Both plantings were located at the South Haven Experiment Sation, South Haven, MI. Orchard KL1 was used in 1978, SH5B in 1979, and JO4 and SH5A in 1978 and 1979. Five spur and five terminal shoots on each of four unsprayed trees in each planting were selected for assessing disease development during the growing season. The number of lesions on all leaves, the number of leaves, and the number of leaf nodes on these spurs and shoots were counted every 4–7 days. Occurrence of infection was determined by the appearance of new lesions on leaves of the same terminal shoot. The mean number of lesions per leaf on 40 shoots for SH5A, SH5B, and KL1 and 20 shoots for JO4 was calculated for each observation date, then expressed as a percentage of the maximum average number of lesions per leaf observed at each orchard.

To establish which wetting periods were suitable for infection, potted Montmorency cherry trees on *Prunus mahaleb* rootstock were exposed during each rainy period. In 1978, two groups of four trees were placed in orchard KL1 and four groups of three trees were placed in orchard JO4. In 1979, single groups of 12 and nine trees were exposed in planting JO4 and SH5B, respectively. After each rain, the exposed trees were removed from the orchards and placed in a cold frame. After a 2-wk incubation period, the trees were examined for lesions and classified as infected or uninfected. Trees grown in the cold frame throughout the season served as controls.

Relative humidity, air temperature, leaf wetness, and rainfall data for use in testing the model and for assessing the favorability of the environment for infection were collected at each location. Relative humidity and air temperature were measured with a 7-day recording hygrothermograph (Bendix Co., Inc., Baltimore, MD 21204) placed in a standard weather shelter 2 m above the ground. Calibration of the hygrothermograph was checked biweekly with a sling psychrometer. A 7-day recording leaf wetness meter (M. deWit, Hengelo, The Netherlands) was placed 1 m above the ground in the drip line of a tree to measure the duration of leaf wetness. Rainfall was measured daily with a dip-stick rain gauge

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and the data were used to verify that periods of leaf wetness recorded by the wetness meter were initiated by rain.

We assumed rather arbitrarily that intermittent wetting with individual dry periods <8 hr would allow infection to proceed. Therefore, rain-initiated leaf wetness periods were not terminated until the lapse of an 8-hr dry period. Initiation and termination times of wetting were rounded to the nearest hour. Average air temperatures were the arithmetic means of hourly observations during the wet period.

To establish if ascospores and conidia of the leaf spot fungus were disseminated in each wetting period, three battery powered Rotorod spore samplers (Ted Brown Associates, Los Altos Hills, CA 94022), activated by a moisture sensor (9), were located 0.5 m above the ground and within 2 m of a group of exposed plants. Each sampler was protected by a rain shield placed 4 cm above the collection head. Type U collection heads with 64 mm long 'I' rods coated with silicone compound G-697 (General Electric, Waterford, NY 12188) were used in orchard KL1 and retractable collection heads with 32 mm long rods coated with G-697 were used in orchards JO4 and SH5B. After each rainy period the plastic rods were collected and mounted in cotton blue-lactophenol for examination with a light microscope at ×400.

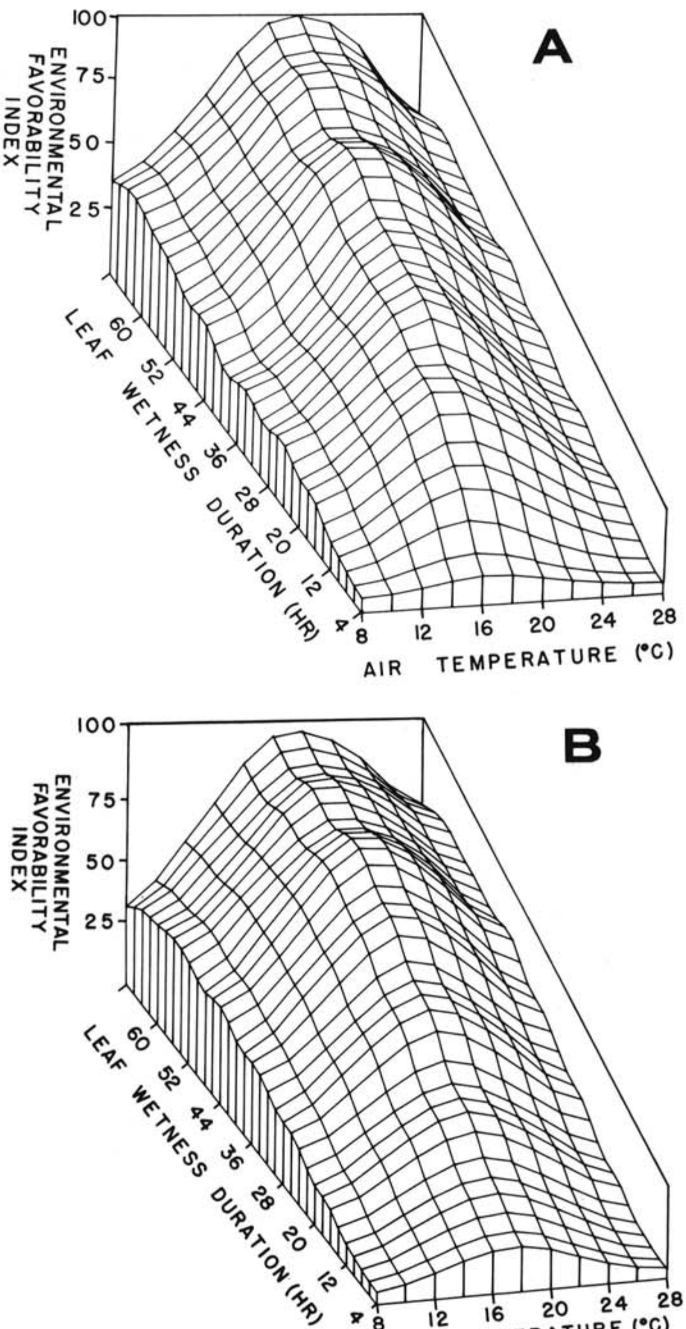

Fig. 1. Relationship of temperature and wetting to infection by *Coccomyces hiemalis* of Montmorency sour cherry leaves. **A,** From empirical data by G. W. Keitt et al 1937. Wisconsin Agric. Exp. Stn. Res. Bull. 132 and **B,** predicted from regression equation. Levels of leaf infection are plotted on a relative scale.

RESULTS

Infection model development. A regression model was developed for relating temperature and length of moist chamber exposure to infection. A suitable second-order model was of the form:

$$EFI = b_0 + b_1 W + b_2 T + b_{11} W^2 + b_{22} T^2 + b_{12} WT + \epsilon$$

in which W = hours of continuous moisture and T = temperature Celsius. The b values are least-squares estimates of the partial regression coefficients and ϵ is a normally distributed random variable with mean zero and variance σ^2. This model accounted for 93% of the observed variation in infection and all estimated coefficients were statistically significant (P=0.01). The actual equation is:

$$EFI = (-11.0 + 0.2858W + 1.4639T - 0.0019W^2 - 0.0389T^2 - 0.0030WT)^2$$

The relationship of temperature and wetting to infection is shown in a computer-generated surface representing the original 54 data points (Fig. 1A). A comparative surface generated from predicted points (Fig. 1B) indicates a good fit of the model for temperatures ranging from 8 to 28 C and wetting durations up to 68 hr. Examination of residuals (2) (ie, the difference between the original data points and those predicted by the regression model) supports the assumption that errors are independent and normally distributed with a mean of zero and a constant variance (Fig. 2). The model tends to overpredict with EFI values less than 20 and underpredict with EFI values greater than 70.

Infection model validation. The following assumptions were made for predicting infection by *C. hiemalis* with the model in the field: temperature was the average air temperature during a wetness period, wetness was the hours of wetting recorded by the deWit recorder, and conditions were not favorable for infection unless EFI ⩾14. An EFI of 14 fits Keitt's (4) conclusion that 5 hr of wetting at 20 C were the minimum conditions for infection.

Putative infection periods were verified by monitoring weather parameters, trapping spores, and observing subsequent disease development in three orchards in 1978 and two orchards in 1979.

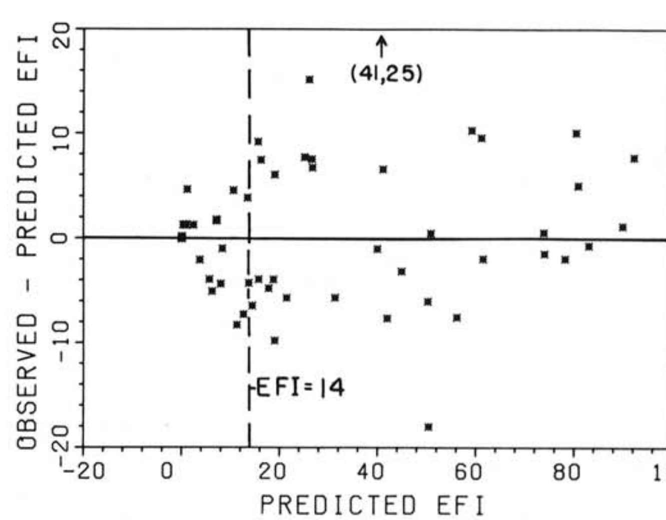

Fig. 2. Plot of residuals against predicted environmental favorability index (EFI) indicating that the errors are independent, have zero mean, and a constant variance. Dotted line indicates EFI value considered to delineate minimum environmental conditions for infection of Montmorency sour cherry by *Coccomyces hiemalis.*

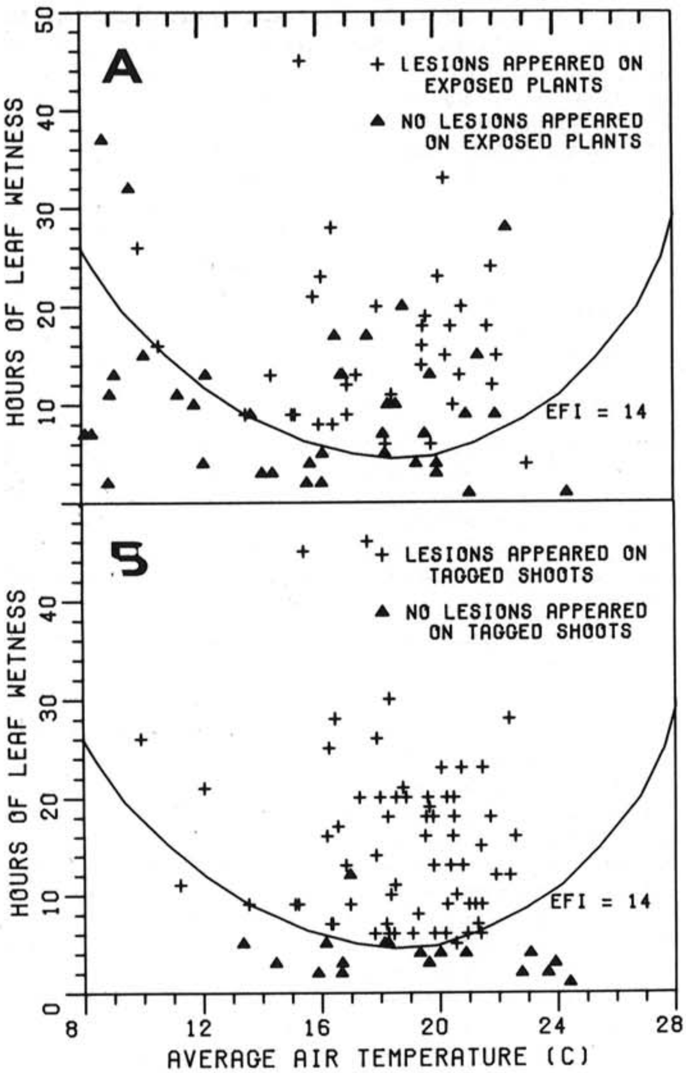

Fig. 3. Wetting periods followed and not followed by infection of Montmorency sour cherry leaves by *Coccomyces hiemalis* **A,** on potted Montmorency cherry trees exposed per wetting period and **B,** on shoots of orchard trees observed every few days for leaf spot development in relation to an infection curve generated from an infection model. Data are for orchards KL1, JO4, and SH5B in 1978 and JO4 and SH5B in 1979.

After each rain, temperature and wetness duration values from the recording charts were used in the infection model to calculate EFI values. In 95% of 65 cases where infection was detected by the appearance of new lesions on leaves of terminal shoots observed every 4–7 days, the EFI was greater than 14; and in 83% of 18 cases in which no infection occurred, the EFI was less than 14 (Fig. 3B). In 97% of 35 cases in which infection was detected by exposing potted cherry trees during each wetting period, the EFI was greater than 14; and in 51% of 39 cases in which no infection occurred, the EFI was less than 14 (Fig. 3A). Examination of the other 49% (19 cases) in which infection was predicted but the exposed plants were not infected, revealed that in 14 cases no spores were trapped and in five cases no spore trapping data were taken. However, in five of the 14 and in three of the five cases, new lesions were observed on leaves of terminal shoots in the orchard. Overall, the model predicted correctly in 93% of the cases that involved marked terminal shoots and in 75% of the cases that involved exposing potted trees.

Relation of environmental favorability index to infection rate. The percentage data for JO4 in 1978 and SH5A in 1979 were plotted against EFI values calculated with the infection model (Fig. 4). It was observed that intervals with several high EFI values (20–27 July 1978 for JO4) were followed by increases in disease (28 July to 10 August for JO4) and intervals with low EFI values (5–27 July 1979 for SH5A) were followed by periods of little or no disease increase (13 July to 4 August for SH5A). Similar patterns were observed in data for orchards SH5A and KL1 in 1978 and JO4 and SH5B in 1979.

The hypothesis that the EFI, which reflects the combined effects of temperature and wetness on infection, is related to the rate of disease increase was tested by regression analysis. Proportional rates of change in lesions per leaf and average daily EFI values were calculated for time intervals within which defoliation did not hamper disease assessment (Table 1). Since incubation periods have been reported to range from 5 to 11 days (5), EFI values were summed for the interval 8 days prior to the disease change interval. A linear regression model of the form:

$$Y = b_0 + b_1 X$$

in which Y is rate of change in disease per day, X is the average daily EFI, and the b values are the estimated regression coefficients was fitted to the data from each orchard excepting those for SH5A-1979 and SH5B-1979 which were combined (Table 2). Before pooling the five data sets for regression analysis, tests for homogeneity of regression coefficients (1,10) were performed. The resultant F-statistics were not significant (P=0.05), indicating that

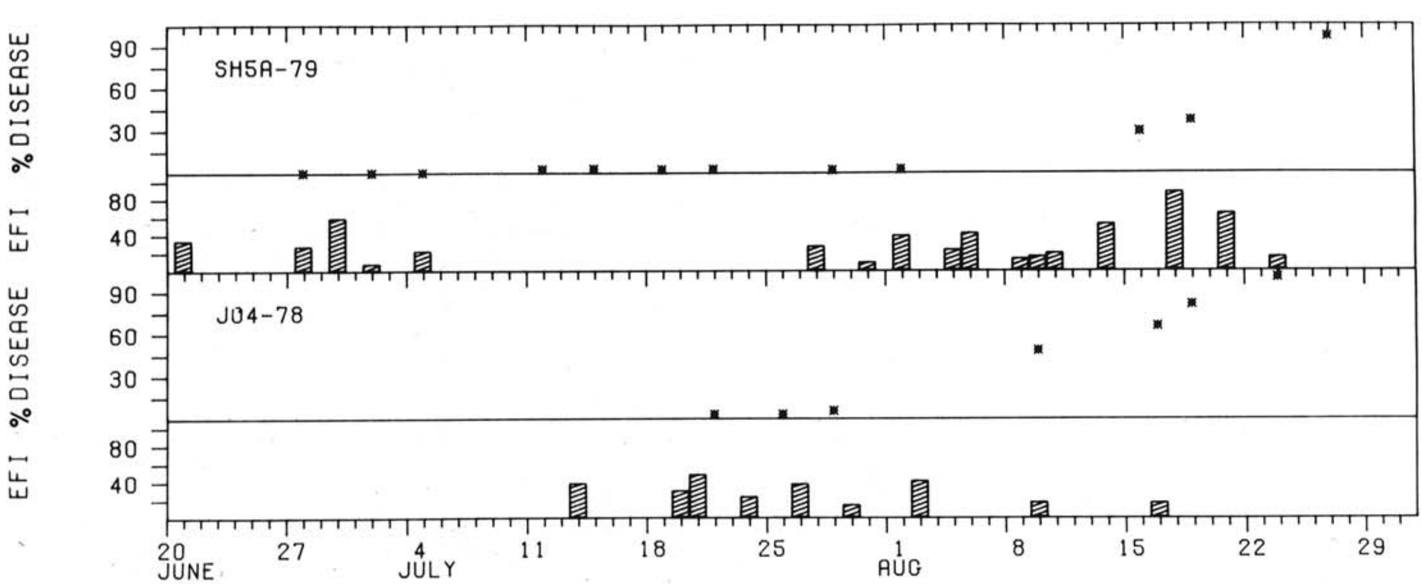

Fig. 4. The relation of the progress of cherry leaf spot epidemics in two orchards to the frequency and favorability of wetting periods as expressed by daily environmental favorability index (EFI) values.

the hypothesis that all five regression coefficients are homogeneous cannot be rejected. The combined model (Fig. 5) shows that frequency and favorability of wetting periods, as measured by average daily EFI values, are directly related to infection rates.

DISCUSSION

A multiple regression model was developed for identifying rainy periods favorable for infection by the cherry leaf spot fungus. The term "environmental favorability," rather than "relative disease severity," was used in this model because the EFI does not account for variations in inoculum levels or host susceptibility. Therefore, EFI may indicate that considerable infection is expected at times when little or no infection is seen because of limited inoculum.

TABLE 1. Proportional rates of change in cherry leaf spot severity and average daily environmental favorability index calculated with an infection model from temperature and leaf wetness data taken in six sour cherry orchards in Michigan

Day of year		Lesions per leaf (mean number)		Rate of disease increase[a]	Average daily environmental favorability index[b]
t_1	t_2	$D(t_1)$	$D(t_2)$		
Orchard JO4-1978					
206	209	0.24	0.43	0.187	9.53
209	221	0.43	3.67	0.179	9.80
221	228	3.67	4.99	0.044	5.69
228	230	4.99	6.17	0.106	7.90
230	235	6.17	7.61	0.042	3.10
Orchard SH5A-1978					
179	192	0.04	0.97	0.239	10.08
206	213	0.79	5.82	0.285	9.96
213	220	5.82	6.54	0.017	4.66
220	227	6.54	15.45	0.123	10.14
227	234	15.45	19.18	0.030	2.99
234	242	19.18	45.59	0.109	4.99
Orchard KL1-1978					
181	188	0.19	0.77	0.197	8.99
188	195	0.77	1.32	0.077	5.10
213	216	0.98	2.31	0.287	14.23
216	220	2.31	3.13	0.076	4.05
223	228	2.43	6.28	0.190	8.62
228	234	6.28	7.27	0.025	2.72
Orchard JO4-1979					
188	203	0.07	3.51	0.269	9.98
203	215	3.51	4.13	0.014	1.70
215	228	4.13	38.86	0.172	9.83
Orchard SH5A-1979					
178	185	0.04	0.05	0.028	4.69
185	195	0.05	1.57	0.355	11.20
213	227	1.39	15.22	0.171	9.68
230	238	19.35	50.29	0.136	6.39
Orchard SH5B-1979					
185	195	0.03	1.48	0.393	11.20
213	227	1.48	7.26	0.113	9.68
230	238	8.38	22.04	0.121	6.39

[a] Defined as the $\log_e D(t_2) - \log_e D(t_1)$ divided by $t_2 - t_1$.
[b] Defined as the sum of the EFI values from $t_1 - 8$ to $t_2 - 8$ divided by $t_2 - t_1$.

The model was developed from conidial infection data and validated primarily for secondary infection periods having air temperatures between 15 and 23 C. Additional data are needed to determine the effectiveness of the model in detecting primary infection periods. Most wet periods that appeared favorable for infection but failed to give detectable infection occurred in May and early June when infection was caused by primary inoculum. Keitt et al (5) observed little or no disease development following ascospore discharges from some continuous wet periods under conditions that appeared to be favorable for infection. Ascospore discharge was heaviest at the end of these wet periods, when leaves containing apothecia were drying (5). Thus, split wet periods may be more favorable than continuous wet periods for severe primary infection.

The method we used to connect split wetting periods was taken from an apple scab infection prediction system (4). Extending wetting periods when relative humidity is above 90% has been used to determine the length of leaf wetness duration for apple scab (3,8) and may increase the model's ability to predict cherry leaf spot disease severity. Additional work is needed to determine the best criteria for connecting wetting periods that are not contiguous.

The model allows for consideration of new disease management strategies based on the use of fungicides having postinfection eradicant activity against the leaf spot fungus (6,11). Work is

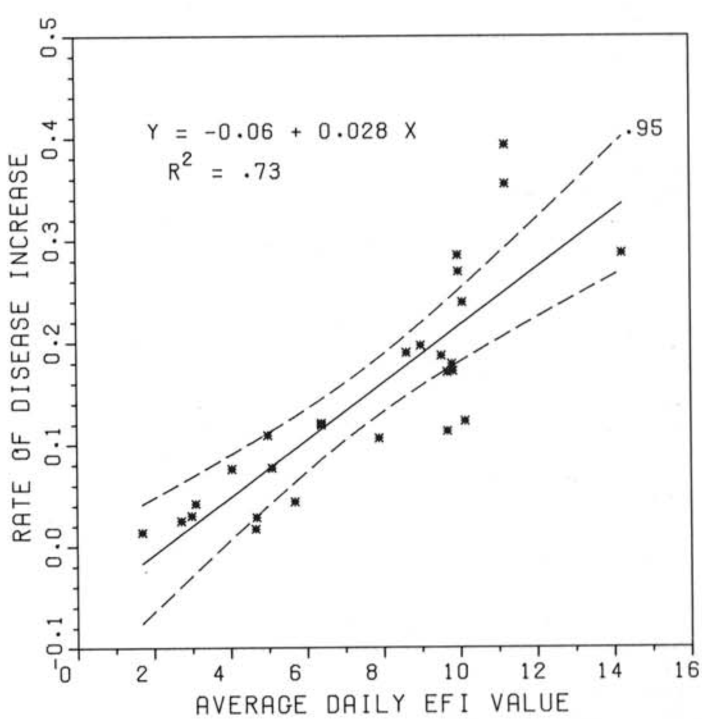

Fig. 5. Fitted regression line and 95% confidence limits for data from Table 1 relating proportional rate of change in mean number of cherry leaf spot lesions per leaf to average daily environmental favorability index 8 days prior to the interval of disease increase.

TABLE 2. Regression statistics for testing the linear relationship between average daily environmental favorability index and proportional rate of change in cherry leaf spot disease severity for six orchards in Michigan

Orchard-year	Intercept[a]	Slope[a]	Standard error of slope	F-statistic[a]	Coefficient of determination
JO4-1978	−0.055 NS	0.0231	0.0053	19	0.86
SH5A-1978	−0.063	0.0276	0.0093	9	0.69
KL1-1978	−0.026 NS	0.0231	0.0018	158	0.98
JO4-1979	−0.031 NS	0.0254 NS	0.0098	7 NS	0.87
SH5-1979[b]	−0.186 NS	0.0439	0.0125	12	0.71
Combined[c]	−0.065	0.0281	0.0034	68	0.73

[a] All values except those followed by NS were significant, $P = 0.05$.
[b] Data from orchards SH5A-1979 and SH5B-1979 were combined.
[c] Data from all orchards were combined.

currently underway to test the effectiveness of fungicide applications applied after leaf spot infection is detected with the model. The relationship between average daily EFI and proportional rate of change in disease severity may be used to determine if a fungicide application is necessary when more is known about the economic threshold of cherry leaf spot.

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