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# Validation of an Anthracnose Forecaster to Schedule Fungicide Spraying for Pepper

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**With the goal of achieving better integrated pest management for hot pepper, a disease-forecasting system was compared to a conventional disease-control method. Experimental field plots were established at Asan, Chungnam, in 2005 to 2006, and hourly temperature and leaf wetness were measured and used as model inputs. One treatment group received applications of a protective fungicide, dithianon, every 7 days, whereas another received a curative fungicide, dimethomorph, when the model-determined infection risk (IR) exceeded a value of 3. In the unsprayed plot, fruits showed 18.9% (2005) and 14.0% (2006) anthracnose infection. Fruits sprayed with dithianon at 7-day intervals had 4.7% (2005) and 15.4% (2006) infection. The receiving model-advised sprays of dimethomorph had 9.4% (2005) and 10.9% (2006) anthracnose infection. Differences in the anthracnose levels between the conventional and model-advised treatments were not statistically significant. The efficacy of 10 (2005) and 8 (2006) applications of calendar-based sprays was same as that of three (2005 and 2006) sprays based on the disease-forecast system. In addition, we found much higher the IRs with the leaf wetness sensor from the field plots comparing without leaf wetness sensor from the weather station at Asan within 10 km away. Since the wetness-periods were critical to forecast anthracnose in the model, the measurement of wetness-period in commercial fields must be refined to improve the anthracnose-forecast model.**

***Keywords*** **:** *Colletotrichum acutatum*, disease-forecast, infection risk, model validation

Pepper anthracnose, caused by *Colletotrichum acutatum* (Simmonds), is an important disease affecting hot pepper (*Capsicum annuum* L.) fruits in Korea (Ahn et al., 2003; Kwon and Lee, 2002; Oh et al., 1988). Conidia are produced in acervuli on infected fruits and dispersed mainly by rain splash. Conidia deposited on fruits germinate and form appressoria prior to penetration into fruits (Freeman et al., 1997). In order to control the disease, fungicides are often applied 10 to 14 times at 7- to 14-day intervals during fruit formation (Bounds et al., 2006). Such a calendar-based management approach may result in excessive fungicide applications when environmental conditions do not favor disease development (Bounds et al., 2007; Dillard et al., 1997).

Disease-forecasting systems based on environmental conditions can alert growers to the need for fungicide application and may be useful for managing anthracnose while reducing the total number of fungicide applications (Ahn et al., 2006; Byrne et al., 1997; Manandhar et al., 1995). An anthracnose infection model has been developed for hot pepper. The model calculates the infection risk (IR) based on the duration of leaf wetness and hourly averaged temperature during the wetness-period. Fungicides are applied when the cumulative IR reaches a predetermined threshold level. However, the approprate IR threshold has not yet been established.

To achieve more environmentally-friendly production of hot pepper at lower costs, hot pepper growers must reduce fungicide sprays. Fungicide applications based on the disease forecasting will help to improve quality, yield, and efficiency. Toward this goal, we evaluated a disease forecasting system for timing fungicide applications to manage anthracnose on hot peppers.

## Materials and Methods

**Plot establishment.** The field study was conducted at the Sun Moon University Research Farm (36°4757.45 N, 127°0408.57 E; 98 m above sea level) in Asan-si, Chungnam, South Korea, from 2005 to 2006. Eight- to ten-week old 'Dabotop' pepper seedlings were transplanted 0.4 m apart in rows spaced 0.6 m apart on 11 June 2005 and 9 May 2006. Each treatment plot consisted of four 3.6 m long rows and contained approximately 24 plants. In 2005, three treatments were applied in a randomized complete block design in the four blocks: (i) unsprayed control, (ii) calendar-based conventional spray with the protective

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fungicide dithianon (Dithi 75WDG at 1.3 Kg a.i./ha, Dongbu, Seoul) at 7-day intervals, and (iii) spray with the curative fungicide dimethomorph (Forum, 25WDG at 1.3 kg a.i./ha, Dongbang Agro, Seoul) based on the disease forecast by the model. In 2006, the conventional spray started from June 29 and a modified model-based spray treatment was added to the model-based spray treatment as in 2005. Because the first model warning may have occurred too late after the start of the rainy season, in the modified schedule, the first three sprays followed the 7-day calendar schedule, with subsequent sprays based on the model recommendations. Pepper plants were subjected to natural infection. Weed, insects, and fertilization requirements were managed according to the standard production practices in Korea.

**Disease-forecasting program and weather data.** An infection model to estimate anthracnose infection on pepper fruits has been developed based on the hourly temperature and wetness-period (W) required for 10% appressorium formation under various temperature (T) regimes. The infection model of $W = -0.659 * T + 25.108$ estimates the wetness-period required for appressorium formation under certain temperature conditions. The infection model was applied to develop an anthracnose forecast program using Microsoft Visual Basic (Version 6.0). The program (Fig. 1) calculates cumulative infection risk (IR) every hour based on hourly temperature and wetness period, and provides advisory information to determine when a curative fungicide is sprayed to control anthracnose on pepper.

The infection risk (IR) was calculated by accumulating the reciprocal of wetness period required for 10% appressorium formation every hour. IR ranged from 0 to 12, corresponding to environmental conditions from unfavorable to highly favorable for anthracnose development. Hourly IRs were summed and accumulated; when a threshold IR of 3 was reached, the fungicide spray was applied.

Hourly measurements of temperature, relative humidity, and leaf-wetness period were carried out using an automated weather station with CR-10 data logger (Campbell Scientific, Inc., Logan, UT) installed in the field prior to transplanting in late April. The hourly weather data were transmitted via a cellular phone modem (Raven100 CDMA Airlink Cellular Modem; Campbell Scientific, Inc., Logan, UT) every hour to a PC server at the Epidemiology Laboratory of Seoul National University. Using the hourly weather data as input, the pepper anthracnose program (Fig. 1) was run on a personal computer and the IR was calculated based on hourly temperature, precipitation, and wetness-period.

**Disease assessment and statistical analysis.** Fifteen pepper plants in the center of the middle two rows of each plot were assessed for fruit infection caused by *C. acutatum*. Percent diseased plants were determined by

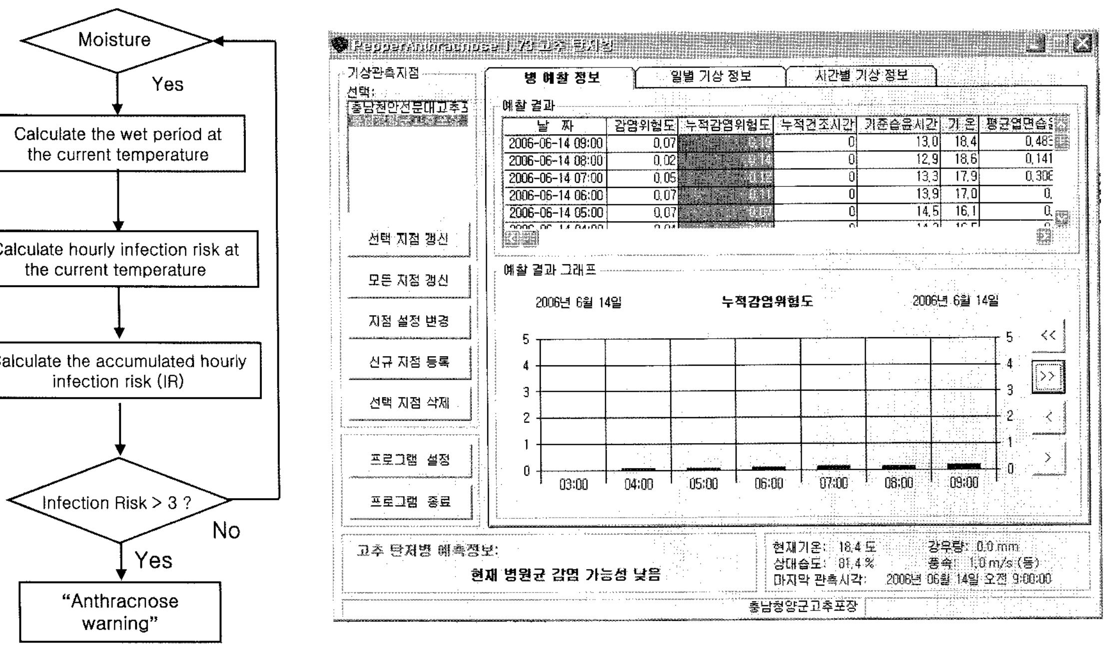


**Fig. 1.** A program to calculate infection risk (IR) based on hourly temperature and the leaf wetness-period. The program ran on an IBM personal computer connected to the Internet server of Seoul National University's Epidemiology Laboratory. The diagram illustrates the logic of the IR calculation. When the cumulative IR exceeded 3, the program warned of the need for fungicide spray.

counting the number of plants with one or more infected fruits. Percent disease fruits were evaluated when fruits were harvested from 15 plants in each plot. Yield and disease assessments were conducted on 18 August and 2 September in 2005 and 4 August and 14 September in 2006.

To compare the effects of treatments, analysis of variance was conducted for the disease assessment and yield data using the S-Link (ver. 2.2, Seoul, Korea) statistical program. Differences among the treatments were examined using Tukey's studentized range test (Ott, 1992).

**Model-based fungicide warnings for major pepper areas.** To expand the model applications to commercial fields, we examined the threshold levels and number of warnings for fungicide spray advisories. We selected 20 major pepper-producing areas with more than 1,000 ha of pepper fields in Korea. Hourly temperature, precipitation, and relative humidity data were obtained from Korea Meteorological Administration (KMA). Because leaf wetness data were not available, it was assumed that plants were wet if hourly precipitation was more than 0.1 mm or relative humidity was greater than 90%. The duration of wetness-period was assumed to be 6 h after the end of a rain event. Fungicide spray advisories were followed if the IR exceeded 2 because IRs exceeding 2 were rare.

## Results

The routine sprays at weekly intervals resulted in 10 applications in 2005 and 8 in 2006 (Fig. 2). In contrast, the forecasting model recommended only three applications of the curative fungicide in both years. There were no significant differences in the percentage of disease fruits among treatments in both years (Table 1). The yield varied between the two years. In 2005, the yield for the routine spray plots at 7-day intervals was statistically higher than yields for the other treatments. However, there were no significant differences in yields in 2006. Overall, the forecaster system reduced fungicide applications by 63-70% without a significant loss in yield.

In each year of the study, anthracnose on fruits was detected in late July or early August when the pepper fruits were changing from green to red. Fungicide sprays significantly reduced anthracnose in both years, except for the percentage of diseased fruits of anthracnose in 2006.

The timing of spraying recommended by the forecaster was quite different in the two years: around Julian days 220-250 in 2005, but days 180-210 in 2006 (Fig. 2). The cumulative IR reached 9 to 12 with greater precipitation

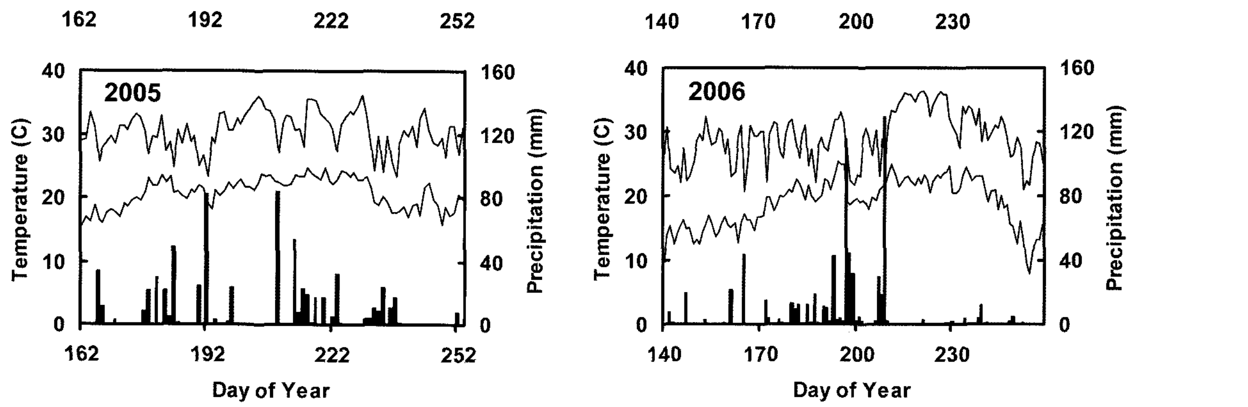


**Fig. 2.** Weather data and fungicide spray schedules according to the model-calculated infection risk (IR) for *Colletotrichum acutatum* in a field in Asan, Chungnam, in 2005 and 2006. IRs were calculated from the measured data, such as hourly temperature, leaf-wetness, humidity and precipitations from the sensors. The upper panels show the infection risk, threshold value, and fungicide sprays for the 7-day interval treatment (conventional), the disease forecaster in 2005 and 2006 (model 1), and the modified forecaster in 2006 in which the first three sprays followed the conventional method and subsequent sprays followed the forecaster warnings (model 2). The lower panels show rainfall (vertical bars) and daily maximum and minimum temperatures.

**Table 1.** Effect of fungicide spray schedules on anthracnose incidence on fruits and plants of red pepper in 2005 and 2006[a]

| | % Diseased fruits[b] | | % Diseased plants[c] | | Yield (kg) | |
|---|---|---|---|---|---|---|
| Treatment schedule | 2005 | 2006 | 2005 | 2006 | 2005 | 2006 |
| Unsprayed control | 24.0 ± 21.2 a | 14.0 ± 3.0 a | 46.7± 18.9 a | 61.6 ± 6.2 a | 0.33 ± 0.16 a | 1.38 ± 0.24 a |
| Seven-day interval | 4.7 ± 2.8 a | 15.4 ± 4.3 a | 16.6± 4.7 a | 43.2 ± 12.7 ab | 1.41 ± 0.22 b | 1.42 ± 0.26 a |
| Disease forecaster | 9.4 ± 4.2 a | 10.9 ± 1.7 a | 26.7± 9.4 a | 34.9 ± 10.5 b | 0.94 ± 0.15 b | 1.52 ± 0.14 a |
| Modified forecaster[d] | – | 11.0 ± 5.0 a | – | 36.8 ± 10.5 b | – | 1.51 ± 0.15 a |
| *F* | 1.38 | 1.43 | 3.01 | 5.65 | 18.22 | 0.43 |
| *P* | 0.377 | 0.282 | 0.193 | 0.019* | 0.021* | 0.737 |

[a]Means in a column followed by the same letter are not significantly different according to Tukey's studentized range test ($P = 0.05$).
[b]% Diseased fruit was evaluated as the percentage of diseased fruit among the total harvested fruit.
[c]% Diseased plant was evaluated as the percentage of diseased plants having fruits with anthracnose among the investigated plants.
[d]Fungicide was first sprayed three times following the conventional method, but then sprayed based on warnings from the disease forecaster.

and lower temperature in 2006 compared to 3 or 4 in 2005. Rain fell throughout August in 2005, leading to IR > 3.

The fungicide advisory recommended 0 to 4 applications in major commercial pepper fields in Korea (Table 2), except at Bonghwa in 2005. The model always resulted in fewer sprayings than the more than 10 applications of the 7-day-interval regime. The recommended spray dates varied by year. In 2006, the forecast model recommended spraying on 19 and 29 July for most locations. In 2005, spraying was recommended on 12 July and 12 August at 10 locations. In

**Table 2.** Warnings and dates of spray recommendations in each growing season according to the forecaster (for infection risk > 2) in major pepper-producing counties in Korea

| Location | | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|
| Chungnam, | Asan[a] | 1 (7/23) | 2 (6/20, 8/19) | 0 | 2 (7/19, 7/28) |
| | Chungyang | 2 (7/23, 8/20) | 4 (6/20, 7/5, 17, 8/19) | 1 (7/12) | 2 (7/19, 7/29) |
| | Kongju | 3 (7/10, 23, 8/19) | 3 (6/21, 7/16, 8/19) | 1 (7/12) | 2 (7/19, 7/29) |
| | Taean[a] | 0 | 2 (6/20, 7/5) | 0 | 1 (7/28) |
| | Yesan | 1 (7/23) | 3 (6/21, 7/16, 8/19) | 0 | 2 (7/19, 7/28) |
| Chungbuk, | Chungju | 3 (7/11, 8/20, 9/13) | 3 (6/21, 7/17, 8/19) | 2 (7/12, 8/12) | 2 (7/19, 30) |
| | Goesan | 3 (6/21, 8/19, 9/13) | 1 (6/21) | 1 (7/12) | 3 (7/11, 7/19, 29) |
| | Jecheon | 0 | 0 | 2 (7/29, 8/12) | 2 (7/13, 7/28) |
| Cheonnam, | Haenam | 3 (7/11, 8/20, 9/13) | 3 (6/21, 7/17, 8/19) | 2 (7/12, 8/12) | 2 (7/19, 7/30) |
| | Naju | 2 (8/19, 9/13) | 3 (6/20, 8/19, 23) | 0 | 1 (7/20) |
| | Yoeugam[a] | 0 | 0 | 0 | 1 (7/20) |
| | Yeouggwang[a] | 2 (7/11, 8/19) | 1 (6/26) | 0 | 0 |
| Cheonbuk, | Imsil | 0 | 2 (6/21, 7/15) | 2 (6/29,8/20) | 3 (7/3,7/19,7/27) |
| | Jeongeup | 0 | 0 | 0 | 1 (7/19) |
| Kyungbuk, | Andong | 3 (7/10, 8/19, 9/13) | 3 (6/20, 7/16, 8/19) | 2 (7/11, 8/12) | 2 (7/16, 7/28) |
| | Bongwha | 0 | 2 (7/20, 30) | 6 (6/29, 7/12, 8/3, 12, 26, 9/13) | 3 (7/9, 19, 29) |
| | Cheongsong | 2 (8/19, 9/23) | 2 (6/20, 8/19) | 0 | 2 (7/19, 9/18) |
| | Uiseong | 0 | 0 | 0 | 1 (7/18) |
| | Yecheon | 3 (7/10, 8/20, 9/13) | 3 (6/21, 7/16, 8/19) | 3 (7/12, 8/3, 12) | 2 (7/19, 7/30) |
| | Yeongyang | 3 (7/10, 8/18, 9/13) | 2 (6/20, 8/19) | 1 (7/12) | 2 (7/17, 7/29) |

Infection risk was calculated using hourly temperature, precipitation, and relative humidity data collected by automated weather systems of the Korean Meteorological Administration.
[a]Data on relative humidity were missing for these four locations.

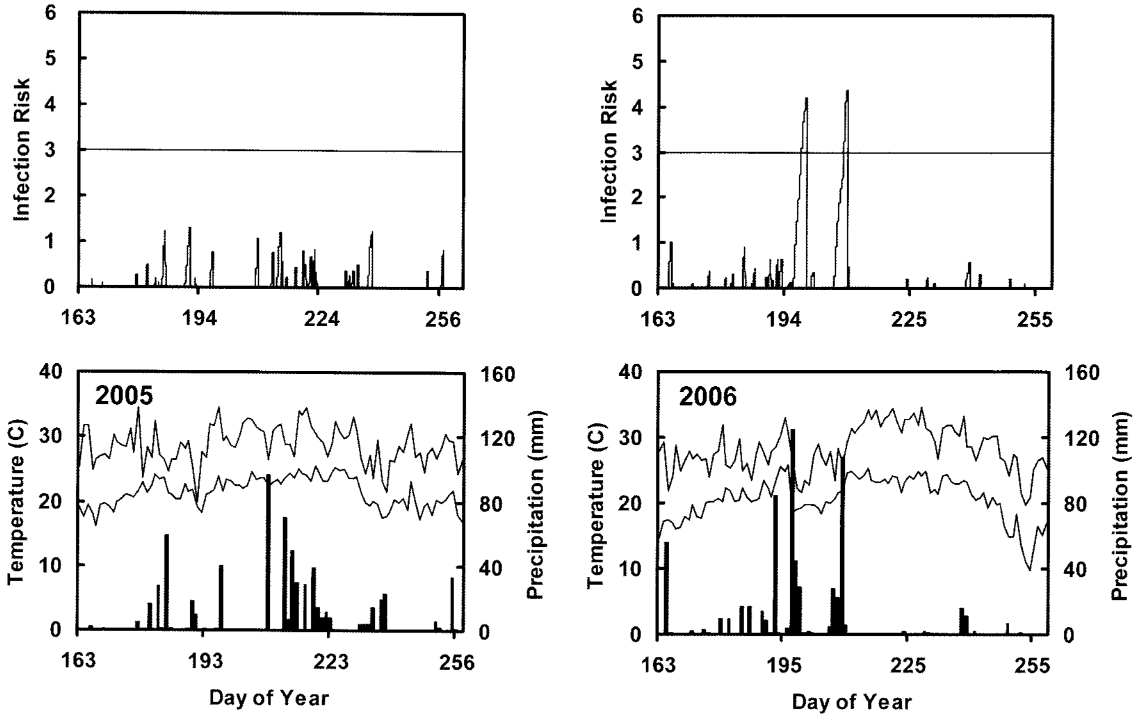


**Fig. 3.** Weather data and model-simulated infection risk (IR) using automated weather system data for the Asan, Chungnam, field in 2005 and 2006. IRs were calculated from hourly temperature and precipitation data. The upper panels show the infection risk and threshold value. The lower panels show rainfall (vertical bars) and daily maximum and minimum temperatures.

general, similar dates were recommended for different locations within the same province in the same year (e.g., 23 July and 19 August 2003 in Chungnam).

In the case of Asan, Taean, Yoeungam and Yeounggwang, neither wetness period nor relative humidity data were available (Table 2, asterisks). With IRs based on precipitation data only, these locations had one to two times fewer fungicide advisories than the other locations. That is, the difference in the calculated IR between locations with and without humidity data indicates that the model could predict anthracnose infection for high-humidity conditions without rain.

## Discussion

A disease-forecast system can help growers to determine risks of disease development and thereby to time more efficiently the deployment of control tactics (Bounds and Hausbeck, 2007; Gleason et al., 1997; Gugino et al., 2007). In Korea, pepper growers often apply fungicides for anthracnose 10 to 14 times, our field experiments and simulations based on weather data recommended only three to four applications if disease forecast based on weather data is available. Thus, the anthracnose-forecasting system can help growers to avoid unnecessary spraying when conditions are not favorable for anthracnose development. These results contribute to evidence that growers can reduce fungicide use substantially compared with traditional, calendar-based spray schedules with no added risk of yield loss (Funt et al., 1990; Gleason et al., 1995).

Based on the model, spray was applied to the experimental field on 29 July and 22 and 31 August in 2005, and 3, 13, and 22 July in 2006. The simulation based on the obtained meteorological data from pepper-producing counties recommended applications on 19 and 29 July in 2005 and 12 July and 12 August in 2006 (Table 2). The measurement locations for the field- and simulation-based experiments were within 10 km and thus can be compared (Figs. 2-3). The IRs based on field measurements of leaf-wetness periodwere 3-5 in 2005 and 10-12 in 2006 (Fig. 2). However, the IRs based on the simulated data from the nearest automated weather station were always lower than 3 in 2005 and 2 times (19 and 29$^{th}$ of July) higher than 3 in 2006 (Fig. 3). This is because automated weather stations do not measure the leaf wetness and wetness-period is simulated by precipitation data only. Because the anthracnose fungal pathogen is active only when free water is present and temperatures are conducive to its activity, the wetness-period is a key input for disease-forecast systems (Kim et al., 2006). The measurement of the wetness duration in each field is critical to create accurate disease-forecast systems (Gleason et al., 1995; Huber and Gillespie, 1992).

The measurement of leaf wetness-period can substantially alter the effectiveness of disease-forecast systems. The recent commercial service "E-Weather" can deliver site-specific, real-time estimates of wetness-period for disease-forecast systems in the USA (Gleason et al., 1997). The conventional weather monitoring by KMA does not include hourly wetness data. In order to apply in agricultural use of the weather information, wetness periods need to be monitored.

Anthracnose diseased plant and diseased fruits can vary greatly according to the weather conditions in each year. The rainy season in Korea generally spans from Julian day 170 to 210 and creates favorable conditions for disease infection. Anthracnose controls in the model treatment in 2005 were applied immediately after the rainy season, whereas those in 2006 were applied immediately before the rainy season. The results indicate that rain is not the main factor for IR. Because anthracnose develops rapidly after the pepper fruits are fully grown, spray timing is critical for disease control (Freeman et al., 1998).

Growers using this forecasting model to schedule fungicide applications should be aware of the system's limitations and be prepared for additional fungicide applications when environmental conditions conducive to disease or significant disease pressure from pathogens not included in the model occur (Byrne et al., 1997). Further, the model may be less effective in the early growing period when blossoms can become infected. Additional research is needed to incorporate epidemiological aspects of *C. acutatum* and create a more inclusive forecasting system.

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