Simultaneous Use of Infection Criteria for Three Apple Diseases for Timing of Fungicide Sprays

L. F. Arauz, T. B. Sutton, and L. R. Pope

Department of Plant Pathology, North Carolina State University, Raleigh, 27695-7616
Use of trade names does not imply endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones not mentioned.
Accepted for publication 14 June 1990 (submitted for electronic processing).

ABSTRACT


The feasibility of using criteria for infection by Botryosphaeria obtusa, Venturia inaequalis, and Gymnosporangium juniperi-virginianae on foliage of apple (Malus × domestica) in a combined weather-based forecasting system for frugeye leafspot, apple scab, and cedar-apple rust was evaluated through computer simulation and in a field study. Ten sets of historical weather data from two locations in North Carolina were analyzed. Using a 7-day minimum waiting period between eradicant sprays, eight to 15 fungicide applications per season were required. More applications were required with the forecast than with a typical calendar-based spray program for five data sets; the same number of sprays were advised for one data set; and less spraying was advised with the forecaster for four data sets. With a 14-day minimum waiting period between fungicide applications, six to nine sprays per season were advised. In a field trial, weather-based eradicant sprays of penconazole or tebuconazole resulted in similar levels of frugeye leafspot and lower levels of scab and rust as compared to the levels resulting from the standard calendar-based protectant program (mancozeb + benomyl at 2-wk intervals). However, more sprays were required in the weather-based program using a 7-day minimum waiting period between eradicant sprays than for the calendar-based program. Levels of all three diseases were similar in a 14-day protectant program using either tebuconazole or penconazole as compared to eradicant programs of the same fungicides. Apple seedlings were set outdoors and exposed to natural inoculum of B. obtusa, G. juniperi-virginianae, and V. inaequalis for 18 individual wetting periods to evaluate the effect of eradicant sprays on subsequent disease development. In all cases in which infection occurred, application of an eradicant spray of tebuconazole resulted in reduction of the three diseases as compared to that on a nonsprayed control.

The use of forecasting systems for disease management can result in more efficient pesticide use, reducing unnecessary expenses to growers and risks to the environment because fungicides are applied only when infection criteria are met. However, practical implementation of forecasting systems is limited by the fact that growers are usually faced with decisions concerning more than one disease. Thus, the likelihood that a forecasting system will be used in the field can be increased if multiple diseases are considered at the same time.

In this study we used models for three important early-season diseases of apple (Malus × domestica Borkh.) to develop and evaluate a forecasting system for simultaneously managing them with fungicide sprays. Mills (11) developed a system for predicting apple scab infection caused by Venturia inaequalis (Cooke) Wint., based on temperature and leaf wetness duration. The Mills system has been refined and utilized in apple-growing areas throughout the world (10,14,17). Similar systems have been developed for cedar-apple rust, caused by Gymnosporangium juniperi-virginianae Schwein. (1), and frugeye leafspot, caused by Botryosphaeria obtusa (Schwein.) Shoemaker (2). The possibility of using these models in a combined forecasting system increased with the introduction of ergosterol-biosynthesis-inhibiting fungicides, which show adequate after-infection activity against all three pathogens (4,18,22).

Thus, the objective of this study was to determine the feasibility of simultaneously using infection criteria for B. obtusa, V. inaequalis, and G. juniperi-virginianae on apple foliage in a fungicide advisory program for management of scab, cedar-apple rust, and frugeye leafspot. The possibility of reducing the number of fungicide sprays per season using weather-based infection predictions as spray criteria, as opposed to a standard protectant program, was investigated by examining sets of historical weather data by means of computer simulation. The combined forecast system was also evaluated in field studies.

MATERIALS AND METHODS

Computer study. Ten sets of historical weather data from two locations in North Carolina were analyzed: data for 1976, 1977, 1979, and 1980 at the Central Crops Research Station (CCRS) in Clayton, North Carolina, and data for 1976, 1977, 1981–1983, and 1985 at the Mountain Horticultural Crops Research Station (MHCRS) in Fletcher, NC. CCRS is located in the coastal plain of North Carolina; MHCRS is located in the mountains. Weather data were obtained from the records of the Integrated Pest and Orchard Management Systems for Apples in North Carolina. Instrumentation and methods used to collect weather data are described elsewhere (16). Each data set consisted of weather variables during the apple-growing season. Data for each wetness period included: beginning day of the year of the wetness period, initial hour, final day of the year, final hour, maximum temperature, minimum temperature, hours of relative humidity (RH) above 90% after the wetness period ended, and total rainfall. From these data the program calculated the duration of the wetness period in hours and the average temperature (maximum + minimum)/2 during the wetness period. These two parameters were used in determining infection periods. The occurrence of infection periods was determined on the basis of infection models (Table 1) developed for apple scab, frugeye leafspot, and cedar-apple rust. Equations for the apple scab model were derived by regression analysis of wetness duration and temperature combinations that result in light infection (11). The hours of RH > 90% were added to the wetness period as suggested by Jones (9), and wetness periods separated by 6 hr or less were added together (14). Although other models have been proposed for predicting apple scab infection periods (9), we elected to use Mills's model because of its successful use for many years. The equation that expresses the wetness duration required for light infection by G. juniperi-virginianae as a function of temperature was obtained by adding the hours required for basidiospore formation (13) and the hours required for light infection by basidiospores (1) at any given temperature and regressing the cumulative time on temperature. The equation for apple infection by B. obtusa is that given by Arauz and Sutton (2) for light infection. The
equation for prediction of frogeye leafspot was not modified, although ascospores and conidia of *B. obtusa* can continue to germinate at RH > 95% in the absence of free water (3), because it is likely that under field conditions apple foliage will remain wet if RH does not drop below 95% after a rain period.

A program to evaluate historical weather data was written in SAS language (15) for use in a microcomputer. The first part of the program outputs dates in the apple-growing season (from either green-tip or petal-fall, depending on the availability of historical weather data, to 2 wk before harvest) when infection periods occur for frogeye leafspot of apple, cedar-apple rust, and apple scab. If weather conditions were favorable for infection by any of the pathogens, an eradicant spray was advised if no sprays had been applied in the previous 7 days. We assumed, as has been shown experimentally (4,18,22), that the same fungicide or combination of fungicides would be effective against all three diseases.

The second part of the computer program evaluates the effect of extending the length of the period of protectant activity for the fungicides applied. This period was changed in 1-day increments, from 7 to 14 days. For each data set and duration of protection interval, the number of sprays per apple-growing season was output.

**Field experiment.** A field trial was conducted on 9-yr-old Golden Delicious trees at CCRS during 1989. Treatments consisted of applications of penconazole (Topas 10W, Ciba-Geigy Corporation, Greensboro, NC; 90 μg a.i./ml) or tebuconazole (Elite 45DF, Mobay Chemical Corporation, Kansas City, MO; 67 μg a.i./ml) in a weather-based eradicant program, in which the fungicides were applied only if infection criteria for apple scab, frogeye leafspot, or cedar-apple rust were met and the trees had not received a fungicidal spray in the previous 7 days. The same fungicides and a mixture of mancozeb (Dithane DF, Rohm and Haas Co., Philadelphia, PA; 659 μg a.i./ml) and benomyl (Bellite 50DF, Dupont de Nemours Co., Wilmington, DE; 110 μg a.i./ml), applied as preventive sprays every 14 days, were also tested. Control trees were not sprayed with fungicides. Treatments were applied to drip with a Swanson DA 500 airblast sprayer (Durand-Wayland, Inc., LaGrange, GA 30241) at 1,034 kPa and 1,935 L ha⁻¹. Treatments began at petal-fall (25 April, day of the year 115).

Leaf wetness duration was determined with a DeWit leaf wetness meter (Valley Stream Farms, Orono, Ont.) located in the orchard, within the canopy of a tree at approximately 1.5 m above ground level. Temperature and RH were measured with a hygrothermograph (Belfort Instrument Co., Baltimore, MD) located in a standard instrument shelter approximately 150 m from the orchard.

Inoculum sources were placed in the upper canopy of each tree included in the trial. They consisted of artificially inoculated apple twigs bearing pycnidia of *B. obtusa*, apple seedlings with sporulating lesions of apple scab, and freshly thawed galls of cedar-apple rust that had been collected in early spring and frozen to preserve viability (1). Inoculum sources were replaced as needed.

Ten terminals per tree were selected arbitrarily and tagged at the beginning of the season. Disease was assessed on these terminals on 12 and 26 May and 22 June. Percent leaf area disease was determined on the Horsfall-Barratt scale (8), with the aid of a leaf diagram.

**TABLE 1.** Thresholds used to predict infection of apple foliage by *Botryosphaeria obtusa*, *Venturia inaequalis*, and *Gymnosporangium juniperi-virginianae*

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Infection thresholdsa</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>B. obtusa</em></td>
<td>4.71T⁻¹ &gt; 35.27</td>
<td>(2)</td>
</tr>
<tr>
<td><em>V. inaequalis</em></td>
<td>4.71T⁻¹ &gt; 90.37677777T⁻² &gt; 8.56861</td>
<td>(11)</td>
</tr>
<tr>
<td><em>G. juniperi-virginianae</em></td>
<td>5.0314T⁻¹ &gt; 787.0190T⁻² &gt; 7.4485</td>
<td>(1,13)</td>
</tr>
</tbody>
</table>

*w* = duration of leaf wetness (hours) required for infection at a given temperature (7).

Incidence of fruit rots was determined by examining fruit that dropped onto the ground throughout the season and all fruit at harvest on 29 August. Severity of sooty blotch (*Gloeodes pomigena* (Schwein.) Colby) and flyspeck (*Zygothila jamaicensis* E. Mason) was determined by observing a subsample of 20 fruit per tree chosen arbitrarily at harvest.

The experiment was conducted in a randomized complete block design with three replications. Each experimental unit consisted of two trees.

**Microplot experiment.** Seedlings of 12 open-pollinated Delicious and 12 Golden Delicious apple trees (with 10-15 leaves) were placed outdoors under each of four wire mesh cages (195 cm long, 37 cm wide, 23 cm deep, raised 50 cm above ground level) with apple twigs bearing pycnidia of *B. obtusa*, crabapple (*Malus sylvestris* Mill.) leaves with sporulating scab lesions, and two freshly thawed cedar-apple rust galls with fully extended telial horns. A different set of seedlings was exposed to spore deposition for each wetness period. Four seedlings of each cultivar were sprayed with tebuconazole (101 μg a.i./ml) and allowed to dry before the wetting period (protectant treatment). Four seedlings were sprayed within 24 hr of the end of the wetness period, and the remainder of the plants did not receive any fungicide. After each wetness period, plants were placed in an air-conditioned chamber at approximately 20 °C and observed after 4-5 wk for symptom development. Percent leaf area diseased was determined by the Horsfall-Barratt scale (8), with the aid of a leaf diagram.

Temperature and RH were measured with a hygrothermograph, wetness duration with a DeWit leaf wetness meter, and rainfall with a top-weighing rain gage (Belfort Instrument Co., Baltimore, MD). In addition, electronic sensors for temperature and leaf wetness, connected to a micrologger (Campbell Scientific, Logan, UT), were placed close to the foliage of the seedlings. Data stored by the micrologger were processed through a program written.
in SAS language (15), which in turn output an hourly disease
warning based on the infection criteria shown in Table 1.

Fungus spore traps were placed under two of the cages to
confirm that spores of Sp. obtusa and V. inaequalis were released
during each wetness period. Each trap consisted of a 10.5-cm-
diameter funnel inserted into a 1-L plastic bottle. Twenty milliliters
of 10% CuSO₄·5H₂O were placed in each bottle to prevent spore
ermination and bacterial fouling. Bottles were changed at the
end of each wetness period. The number of spores in each bottle
was determined by filtering a 20-ml sample through a 25-mm
diameter gridded filter (1.2 μm pore size) and counting the number
of spores in three grids selected at random. Counts were adjusted
to spores per milliliter. Airborne basidiospores of G. juniperi-
virginianae were collected with a Burkard 7-day recording
volumetric spore sampler (Burkard Scientific Ltd.,Rickmansworth,Hertfordshire, England) placed within 3 m of
the inoculum sources. Only spores collected during wetness
periods were counted. Counts were adjusted to number of
basidiospores per cubic meter of air per hour. Each wetness period
was analyzed separately as a randomized complete block design
with four replications.

RESULTS

Computer study. Weather conditions resulting in infection
periods for frogeye leafspot, apple scab, and cedar-apple rust
in two locations in North Carolina were more frequent in late
or midseason than in early season (Figs. 1 and 2), especially
in the case of frogeye leafspot. Infection criteria for frogeye
leafspot were seldom met before day 110.

The number of sprays per season that resulted from
simultaneously using infection criteria for the three diseases
considered in this study and a 7-day minimum waiting period
between sprays are shown in Table 2. For comparison, the number
of sprays per season resulting from calendar-based spray programs
are included. Spray programs for MHCRS 1981–1983 and 1985
were obtained from actual spray records (6,12,20,21). The
remaining programs were theoretical spray calendars consisting
of weekly sprays from green-tip to petal-fall (approximately day
116) and bweekly applications thereafter, until 2 wk before
harvest. More sprays than in the standard program were advised
in five of the location-year combinations. In the data set MHCRS
1976, the same number of sprays were anticipated in the calendar-
based and the weather-based programs. Fewer sprays were
required with the weather-based advisory than in the preventive
schedule in the remaining data sets.

When the interval between eradicant sprays was increased from
7 to 14 days, the maximum number of sprays required was nine,
in MHCRS 1981 and 1976, and the minimum was six, in MHCRS
1977 and 1983 (Figs. 3 and 4). In all cases, fewer sprays were
required than in the calendar program.

Field study. Weather-based eradicant sprays of pencyclocarb
or tebuconazole resulted in similar levels of frogeye leafspot and
lower levels of apple scab and cedar-apple rust compared to the
levels resulting from the standard protectant program (mancozeb +
benomyl) at 2-wk intervals (Figs. 5–7). Severities of all three
diseases were similar in a 14-day protectant program of either
tebuconazole or pyraclostrobin compared to severities in the
eradicant programs of the same fungicides.

Eleven sprays were required in the weather-based program using
a 7-day minimum waiting period between eradicant sprays (Fig.
8); in contrast, nine sprays were required with the preventive
program. A theoretical number of seven sprays per season would

**TABLE 2. Simulated advisory of eradicant sprays for apples against
frogeye leafspot, scab, and cedar-apple rust, based on historical weather
data from two locations in North Carolina**

<table>
<thead>
<tr>
<th>Place</th>
<th>Year</th>
<th>Period analyzed</th>
<th>Wetness periods</th>
<th>Infection periods</th>
<th>Advisory</th>
<th>Number of sprays</th>
<th>Calendar</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCRS</td>
<td>1976</td>
<td>76–235</td>
<td>44</td>
<td>19</td>
<td>10</td>
<td>15</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>79–228</td>
<td>33</td>
<td>24</td>
<td>11</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>116–224</td>
<td>33</td>
<td>24</td>
<td>11</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>88–228</td>
<td>29</td>
<td>18</td>
<td>14</td>
<td>14</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1981</td>
<td>118–230</td>
<td>33</td>
<td>29</td>
<td>10</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td>MHCRS</td>
<td>1976</td>
<td>76–235</td>
<td>41</td>
<td>30</td>
<td>14</td>
<td>14</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>116–224</td>
<td>33</td>
<td>24</td>
<td>11</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1978</td>
<td>88–228</td>
<td>29</td>
<td>18</td>
<td>14</td>
<td>14</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>118–230</td>
<td>33</td>
<td>29</td>
<td>10</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>89–226</td>
<td>47</td>
<td>37</td>
<td>14</td>
<td>14</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1981</td>
<td>116–229</td>
<td>44</td>
<td>36</td>
<td>13</td>
<td>13</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1982</td>
<td>92–186</td>
<td>38</td>
<td>27</td>
<td>8</td>
<td>9</td>
<td>Calendar</td>
</tr>
<tr>
<td></td>
<td>1983</td>
<td>96–234</td>
<td>53</td>
<td>41</td>
<td>14</td>
<td>14</td>
<td>Calendar</td>
</tr>
</tbody>
</table>

*C CCRS = Central Crops Research Station, Clayton, NC. MHCRS = Mountain Horticultural Crops Research Station, Fletcher, NC.

†Days of the year.

‡Wetness periods resulting in apple foliage infection by Sp. obtusa,
G. juniperi-virginianae, or V. inaequalis.

§Number of sprays per season. Advisory was based on infection criteria
for the three diseases considered and a 7-day minimum interval between
sprays.

Table shows the number of sprays per season. Calendar program was based on weekly
sprays from green-tip to petal-fall and biweekly sprays thereafter until 2 wk before harvest.

Fig. 2. Distribution of wetness periods during four apple-growing seasons
at the Central Crops Research Station (CCRS), Clayton, NC. Wetness
periods (triangles) that would result in infection periods (asterisks) for
frogeye leafspot (F), cedar-apple rust (R), and apple scab (S) are indicated.

Fig. 3. Effect of increasing the minimum waiting time between fungicide
sprays on the number of sprays advised in a weather-based advisory system
(continuous lines), compared with the number of sprays required by a
calendar-based schedule (dashed lines), in six apple-growing seasons at
the Mountain Horticultural Crops Research Station (MHCRS), Fletcher,
NC. The calendar-based schedule consisted of weekly sprays from green-
tip to petal-fall and biweekly sprays thereafter until 2 wk before harvest.
Results from computer simulation.

1214 PHYTOPATHOLOGY
have been specified with a 14-day minimum waiting period based on the computer program.

Preventive and eradicant schedules of the demethylation-inhibiting fungicides tebuconazole and pencycymazole resulted in significant reductions of sooty blotch and flyspeck compared to levels found in the untreated control (Table 3), but the incidence of these diseases was significantly higher than in the standard protectant benomyl + mancozeb treatment. Incidence of white rot (Botryosphaeria dothidea (Moug.:Fr) Ces. & De Not) was significantly reduced by all fungicides (Table 3), regardless of the application schedule; however, none provided greater than 50% disease reduction. None of the fungicide treatments effectively controlled bitter rot (Glomerella cingulata (Ston.) Spauld. & Schenk) (Table 3). Incidence of black rot, also caused by B. obtusa, was generally low (<2%) and did not differ significantly among treatments. Scab and cedar-apple rust on fruit were virtually absent.

Fig. 4. Effect of increasing the minimum waiting time between fungicide sprays on the number of sprays advised in a weather-based advisory system (continuous lines), compared with the number of sprays required by a calendar-based schedule (dashed lines), in six apple-growing seasons at the Central Crops Research Station (CCRS), Clayton, NC. The calendar-based schedule consisted of weekly sprays from green-tip to petal-fall and biweekly sprays thereafter until 2 wk before harvest. Results from computer simulation.

Microplot study. Eighteen individual wetness periods were assessed (Table 4). Conidia of V. inaequalis and B. obtusa were captured by funnel traps during each wetness period. Frogeye leafspot and apple scab were observed in most cases where they were predicted from temperature and wetness duration data. Fewer wetness periods than predicted resulted in observed infection periods for cedar-apple rust. Also, trapping of basidiospores of G. juniperi-virginiana occurred later in the wetting period than anticipated (Fig. 9). In all cases in which infection occurred for any of the three diseases, the application of an eradicant or a protectant tebuconazole spray resulted in

Fig. 6. Effect of fungicides and application schedules on severity of apple scab on foliage in the field at the Central Crops Research Station, Clayton, NC, on two dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = pencycymazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = pencycymazole on eradicant schedule, TE = tebuconazole on eradicant schedule. Protectant schedule: biweekly sprays from petal-fall to 2 wk before harvest. Eradicant schedule: sprays within 48 hr after an infection period for either frogeye leafspot, cedar-apple rust (foliage infection), or apple scab (foliage infection) if no fungicide had been applied in the past 7 days, from petal-fall until 2 wk before harvest.

Fig. 5. Effect of fungicides and application schedules on severity of frogeye leafspot in the field at the Central Crops Research Station, Clayton, NC, on three dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = pencycymazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = pencycymazole on eradicant schedule, TE = tebuconazole on eradicant schedule. Protectant schedule: biweekly sprays from petal-fall to 2 wk before harvest. Eradicant schedule: sprays within 48 hr after an infection period for either frogeye leafspot, cedar-apple rust (foliage infection), or apple scab (foliage infection) if no fungicide had been applied in the past 7 days, from petal-fall until 2 wk before harvest.

Fig. 7. Effect of fungicides and application schedules on severity of cedar-apple rust on foliage in the field at the Central Crops Research Station, Clayton, NC, on three dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = pencycymazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = pencycymazole on eradicant schedule, TE = tebuconazole on eradicant schedule. Protectant schedule: biweekly sprays from petal-fall to 2 wk before harvest. Eradicant schedule: sprays within 48 hr after an infection period for either frogeye leafspot, cedar-apple rust (foliage infection), or apple scab (foliage infection) if no fungicide had been applied in the past 7 days, from petal-fall until 2 wk before harvest.
reduction of the three diseases as compared to disease in the nonsprayed control.

**DISCUSSION**

Historical weather data can be useful in helping to understand the epidemiology of disease, to improve disease control, and to evaluate the potential effects of climate change (7). In this study, the analysis of historical weather data sets provided information on the feasibility of implementation of a combined forecasting system for three apple diseases. This was accomplished by 1) analyzing the possibility of reducing the number of sprays per season and 2) indicating the prevalence of weather conditions favorable for the development of any of the diseases considered in different periods during the apple-growing season. This latter aspect indicates which disease would be the determining factor in the spray program at any given time in the season. Studies conducted in the field and in microplots analyzed the possibility of reduction of apple scab, frogeye leafspot, and cedar-apple rust by eradicant fungicide sprays, applied when infection criteria for any of the three diseases have been met. Reduction in disease severity was achieved both on a season-long basis and in separate infection periods.

The feasibility of reducing the number of sprays per season is decreased when several diseases are considered in a combined forecast because infection conditions are met more often than when individual diseases are considered. However, even in years when weather conditions are favorable for all three diseases, the number of sprays per season can be reduced if the fungicide application interval can be increased. With a 7-day minimum waiting period between eradicant sprays, reduction in the number of sprays per season was achieved only in relatively dry location-year combinations. However, by increasing the application interval, reduction in the number of sprays could be achieved even in wet seasons. An increase in the minimum waiting period between sprays, with continued acceptable control of apple diseases, requires effective eradicant activity as well as fungicidal protection of the foliage for more than 7 days. We have obtained evidence to support both conditions. Both tebuconazole and penconazole demonstrated good eradicant activity in the field study. Eradicant sprays of tebuconazole resulted in disease reduction similar to that obtained with protectant sprays in the microplot study, when infection periods were considered individually. Reduction in frogeye leafspot in the microplots was greater than that obtained in greenhouse conditions (4), probably because the inoculum levels were lower, the wetness periods shorter, and the time from inoculation to treatment also was shorter than in the greenhouse study. Experimental evidence shows that a 2-wk protection period against frogeye leafspot can be achieved with tebuconazole (4). However, to extend the protection period, a combination of tebuconazole or penconazole and a protectant fungicide such as captan is needed. These fungicide combinations are currently employed for extended protectant activity when sterol-inhibiting fungicides are used for apple scab control, and they would be necessary to provide control of summer diseases such as bitter rot, sooty blotch, and flyspeck.

Analysis of historical weather data indicated the seasonal distribution of wetness periods favorable for apple infection by any of the pathogens considered during the apple-growing season. Early in the season in North Carolina, especially before petal-fall, scab and cedar-apple rust would tend to be more prevalent than frogeye leafspot. Infection by *B. obtusa* is unlikely to occur because the weather conditions are unsuitable, even though tissue can be susceptible as early as the silver-tip stage (5). During midseason (May and June), weather conditions can be favorable for all three diseases considered here. However, during this period, inoculum availability for cedar-apple rust decreases as cedar-apple galls reach the “dark horn” stage (19). Late in the season (August and September under North Carolina conditions), weather would be favorable for scab and frogeye leafspot infections. However, because of the warm temperatures during the summer in the southeastern United States, survival of *V. inaequalis* is poor and the inoculum is often low. Foliage infection by *B. obtusa* is likely if actively growing tissue is present.

Our field experiment clearly demonstrated the need to take other potential diseases into consideration when implementing a forecasting system. Late in the season, the summer disease complex, especially fruit rots, is a major factor in deciding on the need for fungicide sprays in many warm, humid growing areas. In this study, fungicide applications resulted in poor control of these diseases. No information about black rot control was obtained because incidence of this disease was generally low despite the fact that inoculum of *B. obtusa* was provided to every tree considered in the field trial. A possible explanation is that initial infections of *B. obtusa* were overgrown by other fruit pathogens, especially *G. cingulata*, which affected more than 60% of the fruit. Information on conditions favoring infection by late-season pathogens and on fungicide schedules and combinations to reduce them could be incorporated into the forecast system considered here.

The accuracy of the models considered here in predicting infection periods was evaluated in the microplot study. Apple scab and frogeye leafspot were observed in most instances in which they were predicted. However, cedar-apple rust was observed only after wetting periods longer than those that had

![Figure 8](image)

**Fig. 8.** Effect of increasing the minimum waiting time between fungicide sprays on the number of sprays applied in a weather-based advisory system (continuous line), compared with the number of sprays required by a calendar-based schedule (dashed line), in the 1989 apple-growing season at the Central Crops Research Station, Clayton, NC. The calendar-based schedule consisted of biweekly sprays from petal-fall until 2 wk before harvest. Results from computer simulation.

---

**TABLE 3. Effect of fungicides and application schedules on summer diseases of apple**

<table>
<thead>
<tr>
<th>Fungicide</th>
<th>Schedule*</th>
<th>Sooty blotch and flyspeck</th>
<th>Bitter rot</th>
<th>White rot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penconazole</td>
<td>Forecast</td>
<td>81.6 a&lt;sup&gt;6&lt;/sup&gt;</td>
<td>0.0 a&lt;sup&gt;6&lt;/sup&gt;</td>
<td>35.9 a</td>
</tr>
<tr>
<td>Tebuconazole</td>
<td>Calendar</td>
<td>81.3 a</td>
<td>0.0 a</td>
<td>48.6 b</td>
</tr>
<tr>
<td>Mancoseb + benomyl</td>
<td>Calendar</td>
<td>81.4 a</td>
<td>21.5 b</td>
<td>44.7 b</td>
</tr>
</tbody>
</table>

* Schedules were: forecast, based on the combined forecasting system for apple scab, cedar-apple rust, and frogeye leafspot; calendar, every 14 days.

* Compared to disease incidence in a nontreated control.

* Numbers followed by the same letter within each column do not differ significantly (P = 0.05 [k = 1600]) according to the Waller-Duncan k-ratio test.

* No reduction in disease severity means that the treatment resulted in the same or greater disease severity than that of the untreated control.
TABLE 4. Effect of protectant and eradicant sprays of tebuconazole on infection of apple seedlings exposed to infection by B. obtusa, G. juniperi-virginiana, and V. inaequalis for the duration of individual wetness periods

<table>
<thead>
<tr>
<th>Wetness period no.</th>
<th>Duration* (hr)</th>
<th>Mean temperature* (°C)</th>
<th>Diseases expected†</th>
<th>Disease severity observed*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>FELS‡</td>
<td>Rust</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>P</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>13.3</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4 (9)3</td>
<td>15.6</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>13.9</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11.5</td>
<td>24.4</td>
<td>FRS</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.5 (2.5)17</td>
<td>21.2</td>
<td>FRS</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
<td>25.5</td>
<td>FRS</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12 (4.5)20.5</td>
<td>25.8</td>
<td>FRS</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>26.1</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>24.2</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>26.1</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>14.5</td>
<td>24.4</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>15.5</td>
<td>24.1</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>26.6</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>5 (2)21</td>
<td>24.4</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>26.4</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>3.5 (6)31</td>
<td>29.4</td>
<td>FR</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>11.5</td>
<td>22.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Interrupted wetness periods are represented as follows: hours before interruption—(duration of interruption)—hours after interruption.
†(Maximum temperature + minimum temperature)/2.
‡According to infection criteria from Table 1. F = frogeye leafspot, R = cedar-apple rust, S = scab.
§Percent leaf area affected. C = control (no fungicide), P = protectant application of tebuconazole, E = eradicant application of tebuconazole. Mean of four replications, three seedlings per replication and three leaves per seedling. For each disease and wetness period combination, an analysis of variance was performed if severity in at least two treatments was larger than zero. Cases in which differences between means were detected (LSD tests, P = 0.05) are indicated by italic numbers.
©Frogeye leafspot.

J. juniperi-virginiana. Possibly a lag occurs between formation of basidiospores and their accumulation in the air in sufficient numbers so that infection sites can be reached by randomly dispersed spores. This lag would depend on temperature, the amount of inoculum, and the distance from the inoculum source to the host tissue. In most cases in our study, basidiospores of G. juniperi-virginiana were first observed in the spore trap 5–6 hr after the beginning of the wetness period, but most spores were trapped after 7–8 hr or later (Fig 9). Further information on factors influencing accumulation of basidiospores of G. juniperi-virginiana in the air is necessary to increase the predicting ability of the cedar-apple rust model.

LITERATURE CITED

criteria for predicting apple scab infection periods. Phytopathology 79:304-310.