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

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ABSTRACT

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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 frogeye 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 forecaster 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 frogeye 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 frogeye 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 frogeye 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, frogeye 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 8 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 (Benlate 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 diseased 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*

Pathogen	Infection thresholds[a]	Reference
B. obtusa	$WT^2 > 35.27$	(2)
V. inaequalis	$W + 47.61T^{-1} - 960.376777T^{-2} > 8.55681$	(11)
G. juniperi-virginianae	$W + 51.0314T^{-1} - 787.0190T^{-2} > 7.4485$	(1,13)

[a] W = duration of leaf wetness (hours) required for infection at a given temperature (T).

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 (*Zygophiala 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 i.a./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

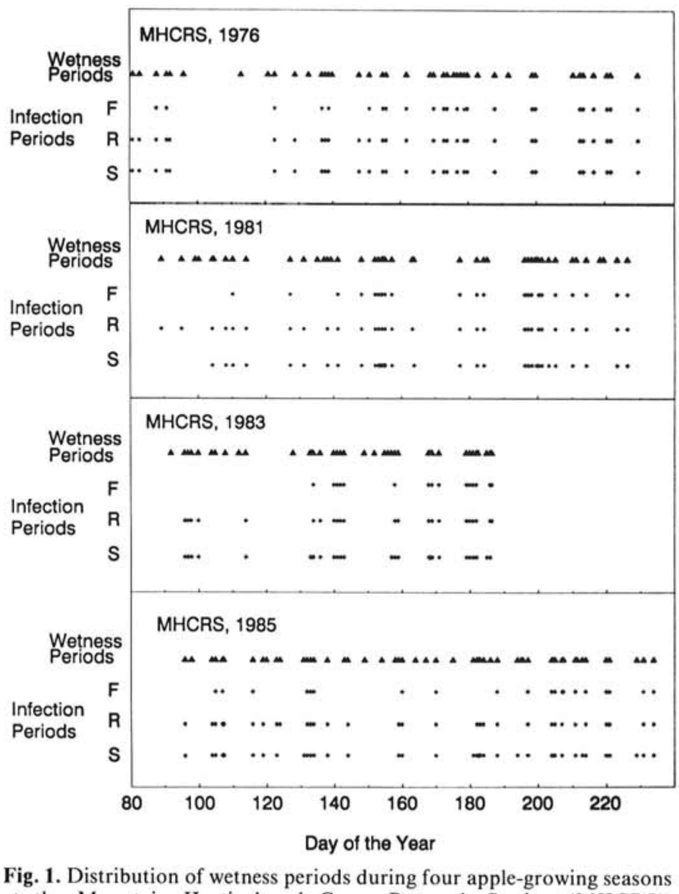

Fig. 1. Distribution of wetness periods during four apple-growing seasons at the Mountain Horticultural Crops Research Station (MHCRS), Fletcher, NC. Wetness periods (triangles) that would result in infection periods (asterisks) for frogeye leafspot (F), cedar-apple rust (R), and apple scab (S) are indicated. No 1983 data after day 186 were available.

in SAS language (15), which in turn output an hourly disease warning based on the infection criteria shown in Table 1.

Funnel spore traps were placed under two of the cages to confirm that spores of *B. 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% $CuSO_4 \cdot 5H_2O$ were placed in each bottle to prevent spore germination and bacterial growth. 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.

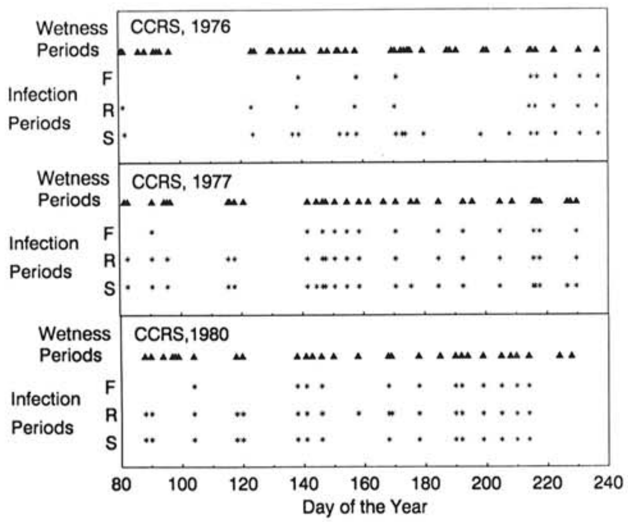

Fig. 2. Distribution of wetness periods during four apple-growing seasons at the Central Crops Research Station (CCRS), Clayton, NC. Wetness periods (triangles) that would result in infection periods (asterisks) for frogeye leafspot (F), cedar-apple rust (R), and apple scab (S) are indicated.

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

Place[a]	Year	Period analyzed[b]	Wetness periods	Infection periods[c]	Number of sprays	
					Advisory[d]	Calendar[e]
CCRS	1976	76–235	44	19	10	15
	1977	79–228	34	22	12	13
	1979	116–224	33	24	11	9
	1980	88–228	29	18	11	13
MHCRS	1976	76–229	41	30	14	14
	1977	118–230	43	29	10	9
	1981	89–226	47	37	14	13
	1982	116–229	44	36	13	10
	1983	92–186	38	27	8	9
	1985	96–234	53	41	15	14

[a] CCRS = Central Crops Research Station, Clayton, NC. MHCRS = Mountain Horticultural Crops Research Station, Fletcher, NC.
[b] Days of the year.
[c] Wetness periods resulting in apple foliage infection by *B. obtusa, G. juniperi-virginianae,* or *V. inaequalis*.
[d] Number of sprays per season. Advisory was based on infection criteria for the three diseases considered and a 7-day minimum interval between sprays.
[e] 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.

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 biweekly 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 penconazole 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 penconazole 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

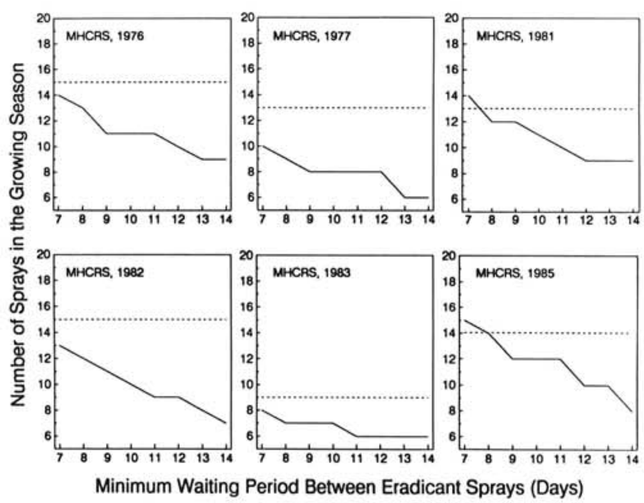

Fig. 3. Effect of increasing the minimum waiting time between fungicide sprays on the number of sprays advised in a weather-based advisory system (continuous lines), compared with the number of sprays required by a calendar-based schedule (dashed lines), in six apple-growing seasons at the Mountain Horticultural 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.

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 penconazole 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. & Schrenk) (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.

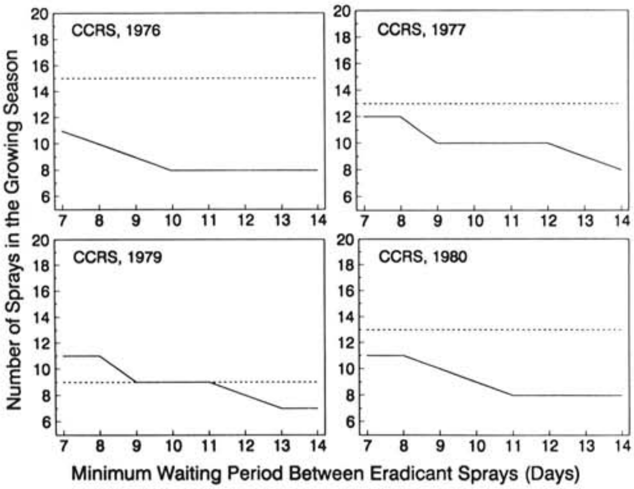

Fig. 4. Effect of increasing the minimum waiting time between fungicide sprays on the number of sprays advised in a weather-based advisory system (continuous lines), compared with the number of sprays required by a calendar-based schedule (dashed lines), in six apple-growing seasons at the Central Crops 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.

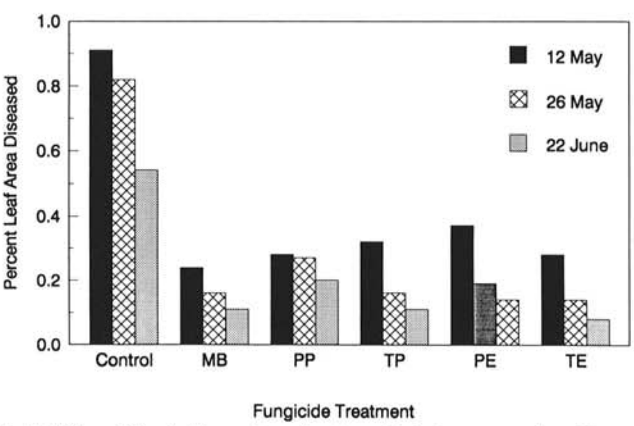

Fig. 5. Effect of fungicides and application schedules on severity of frogeye leafspot in the field at the Central Crops Research Station, Clayton, NC, on three dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = penconazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = penconazole 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.

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 when 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-virginianae* 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

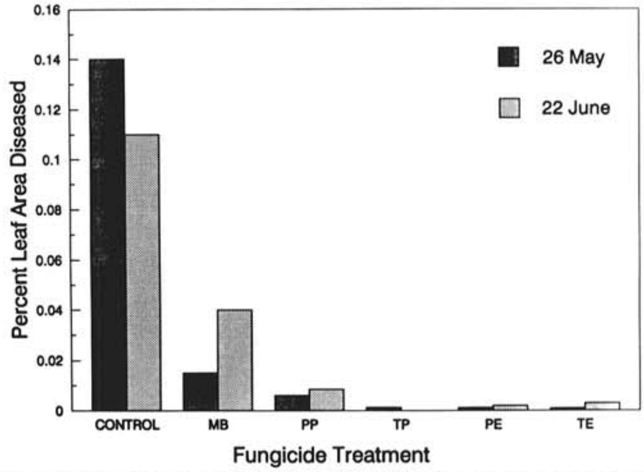

Fig. 6. Effect of fungicides and application schedules on severity of apple scab on foliage in the field at the Central Crops Research Station, Clayton, NC, on two dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = penconazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = penconazole 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.

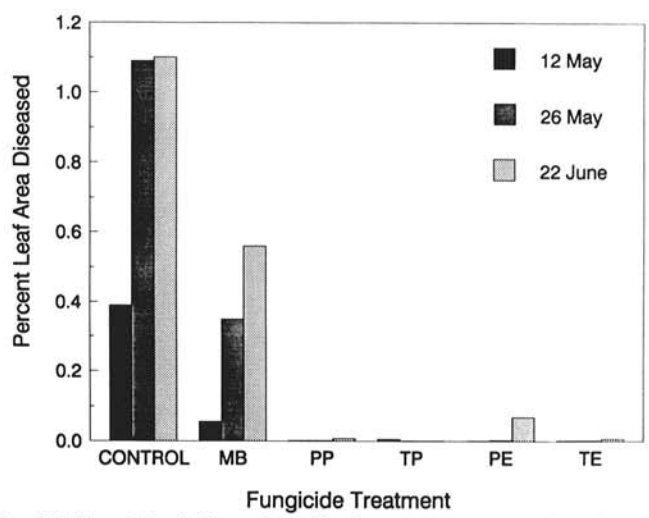

Fig. 7. Effect of fungicides and application schedules on severity of cedar-apple rust on foliage in the field at the Central Crops Research Station, Clayton, NC, on three dates in 1989. Control = insecticide only, MB = mancozeb + benomyl on a protectant schedule, PP = penconazole on protectant schedule, TP = tebuconazole on protectant schedule, PE = penconazole 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 forecaster 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

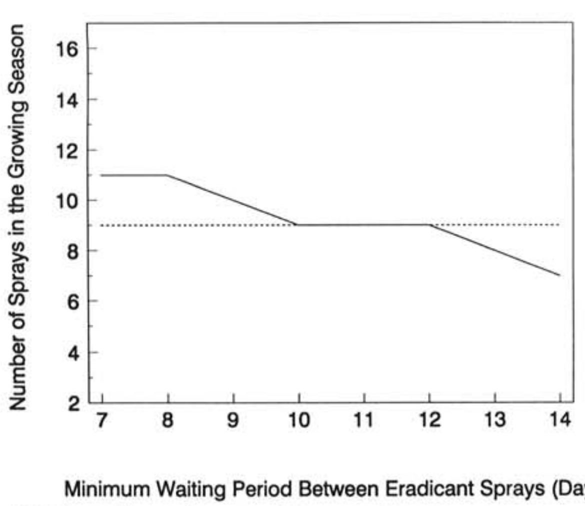

Fig. 8. Effect of increasing the minimum waiting time between fungicide sprays on the number of sprays applied in a weather-based advisory system (continuous line), compared with the number of sprays required by a calendar-based schedule (dashed line), in the 1989 apple-growing season at the Central 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.

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

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

		Percent reduction in disease incidence[b]		
Fungicide	Schedule[a]	Sooty blotch and flyspeck	Bitter rot	White rot
Penconazole	Forecast	81.6 a[c]	0.0 a[d]	35.9 a
	Calendar	81.3 a	0.0 a	48.6 b
Tebuconazole	Forecast	83.8 a	18.0 b	49.0 b
	Calendar	81.4 a	21.5 b	44.7 b
Mancozeb + benomyl	Calendar	98.7 b	0.0 a	36.9 a

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

[b]Compared to disease incidence in a nontreated control.

[c]Numbers followed by the same letter within each column do not differ significantly ($P = 0.05$ [$k = 100$]) according to the Waller-Duncan k-ratio t-test.

[d]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-virginianae*, and *V. inaequalis* for the duration of individual wetness periods

Wetness period no.	Duration[a] (hr)	Mean temperature[b] (C)	Diseases expected[c]	Disease severity observed[d] FELS[e] C	P	E	Rust C	P	E	Scab C	P	E
1	1	13.3	R	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4(19)3	15.6	None	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	11	13.9	R	0.6	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
4	11.5	24.4	F R S	*0.8*	*0.3*	*0.2*	0.0	0.0	0.0	0.0	0.0	0.0
5	2.5(2.5)17	21.2	F R S	0.6	0.1	0.0	0.0	0.0	0.0	0.9	0.0	0.0
6	9.5	25.5	F R S	*2.0*	*0.2*	*0.4*	0.0	0.0	0.0	*0.8*	*0.1*	*0.0*
7	12(4.5)20.5	25.8	F R S	*1.1*	*0.0*	*0.0*	1.0	0.0	0.0	*1.6*	*0.1*	*0.0*
8	6	26.1	F	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
9	10	24.2	F R S	0.6	0.2	0.2	0.2	0.0	0.0	0.1	0.0	0.0
10	19	26.1	F R S	*2.1*	*0.1*	*0.3*	0.0	0.0	0.0	0.4	0.0	0.0
11	14.5	24.4	F R S	0.2	0.1	0.0	0.1	0.0	0.0	0.7	0.0	0.0
12	14.5	20.1	F R S	*0.3*	*0.0*	*0.2*	0.0	0.0	0.0	0.0	0.0	0.0
13	15.5	24.1	F R S	*0.7*	*0.1*	*0.0*	0.0	0.0	0.0	0.3	0.0	0.0
14	18	26.6	F R S	*0.7*	*0.1*	*0.0*	0.4	0.0	0.0	0.2	0.0	0.0
15	2(5)21	24.4	F R S	*0.5*	*0.1*	*0.1*	1.1	0.0	0.0	0.2	0.0	0.0
16	11	26.4	F R	*0.4*	*0.0*	*0.1*	0.4	0.0	0.0	0.0	0.0	0.0
17	3.5(6)31	19.4	F R S	*0.7*	*0.1*	*0.0*	1.6	0.0	0.0	0.4	0.0	0.0
18	11.5	12.2	R	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] Interrupted wetness periods are represented as follows: hours before interruption—(duration of interruption)—hours after interruption.
[b] (Maximum temperature + minimum temperature)/2.
[c] According to infection criteria from Table 1. F = frogeye leafspot, R = cedar-apple rust, S = scab.
[d] 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.
[e] Frogeye leafspot.

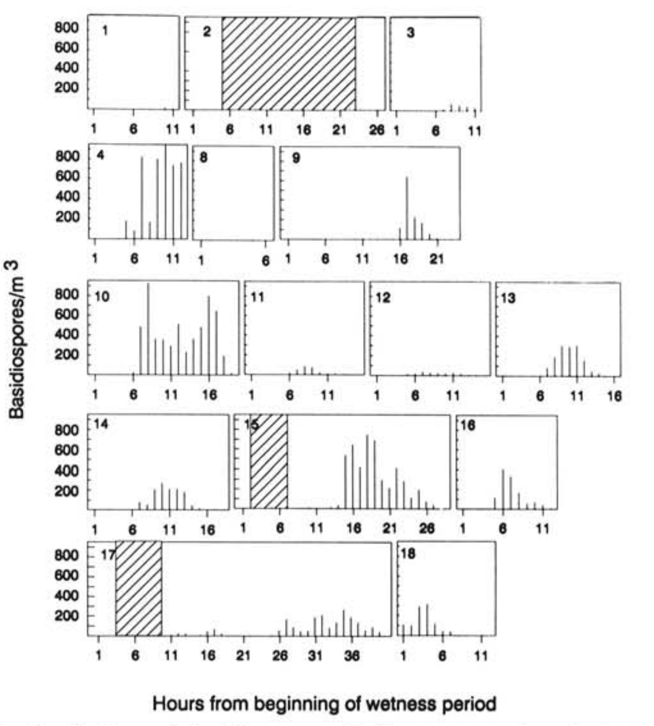

Fig. 9. Capture of basidiospores of *Gymnosporangium juniperi-virginianae* in 15 separate wetness periods. Shaded areas are dry periods. The enumeration of wetness periods corresponds to the enumeration in Table 4. Basidiospore trappings from wetness periods 5–7 were lost accidentally.

been anticipated to be sufficient in length for infection. Apparently, the time from the beginning of the wetness period to infection by *G. juniperi-virginianae* is longer than that predicted by the models (1,13). The two models combined here consider the period from teliospore to basidiospore formation and the requirements for apple foliage infection by basidiospores of *G. juniperi-virginianae*. 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-virginianae* 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-virginianae* in the air is necessary to increase the predicting ability of the cedar-apple rust model.

LITERATURE CITED

1. Aldwinckle, H. S., Pearson, R. C., and Seem, R. C. 1980. Infection periods of *Gymnosporangium juniperi-virginianae* on apple. Phytopathology 70:1070-1073.
2. Arauz, L. F., and Sutton, T. B. 1989. Temperature and wetness duration requirements for apple infection by *Botryosphaeria obtusa*. Phytopathology 79:440-444.
3. Arauz, L. F., and Sutton, T. B. 1989. Influence of temperature and moisture on germination of ascospores and conidia of *Botryosphaeria obtusa*. Phytopathology 79:667-674.
4. Arauz, L. F., and Sutton, T. B. 1989. Eradicant and protectant activity of fungicides against *Botryosphaeria obtusa* on apple foliage. (Abstr.) Phytopathology 79:1206.
5. Beisel, M., Hendrix, F. F., Jr., and Starkey, T. E. 1984. Natural inoculation of apple buds by *Botryosphaeria obtusa*. Phytopathology 74:335-338.
6. Brown, E. M., and Sutton, T. B. 1984. Apple disease control, 1983. Fungic. Nematicide Tests 39:1.
7. Coakley, S. M. 1989. Historical weather data: Its use in epidemiology. Pages 54-83 in: Plant Disease Epidemiology, Vol. 1: Genetics, Resistance, and Management. K. J. Leonard and W. E. Fry, eds. McGraw-Hill Publishing Co., New York. 377 pp.
8. Horsfall, J. G., and Barratt, R. W. 1945. An improved grading system for measuring plant diseases. (Abstr.) Phytopathology 35:655.
9. Jones, A. L., Lillevik, S. L., Fischer, P. D., and Stebbins, T. C. 1980. A microcomputer-based instrument to predict primary apple scab infection periods. Plant Dis. 64:69-72.
10. MacHardy, W. E., and Gadoury, D. M. 1989. A revision of Mills's

criteria for predicting apple scab infection periods. Phytopathology 79:304-310.
11. Mills W. D. 1944. Efficient use of sulfur dusts and sprays during rain to control apple scab. Ext. Bull. 630. Cornell University, Ithaca, NY. 4 pp.
12. Nardacci, J. F., and Sutton, T. B. 1982. Apple disease control in western North Carolina, 1981. Fungic. Nematicide Tests 37:12.
13. Pearson, R. C., Aldwinckle, H. S., and Seem, R. C. 1977. Teliospore germination and basidiospore formation in *Gymnosporangium juniperi-virginianae*: A regression model of temperature and time effects. Can. J. Bot. 55:2832-2837.
14. Roosje, G. S. 1959. Het schurftonderzoek in Nederland van 1955 t/m 1958. II. Laboratoriumonderzoek van infecties door ascosporen en conidien. Meded. Dir. Tuinbouw Neth. 22:441-447.
15. SAS Institute, Inc. 1985. SAS Language Guide for Personal Computers, Version 6 edition. The Institute, Cary, NC. 429 pp.
16. Saucier, W. J., and Bragg, A. W. 1983. Meteorological monitoring and analysis. Pages 13-20 in: Integrated Pest and Orchard Management Systems for Apples in North Carolina. G. C. Rock and J. L. Apple, eds. Tech. Bull. 276. N.C. Agric. Res. Serv., Raleigh. 240 pp.
17. Schwabe, W. F. S. 1980. Wetting and temperature requirements for apple leaf infection by *Venturia inaequalis* in South Africa. Phytophylactica 12:69-80.
18. Schwabe, W. F. S., Jones, A. L., and Jonker, J. P. 1984. Greenhouse evaluation of the curative and protective action of sterol-inhibiting fungicides against apple scab. Phytopathology 74:249-252.
19. Seem, R. C., and Russo, J. M. 1984. Simple decision aids for practical control of pests. Plant Dis. 68:656-660.
20. Sutton, T. B. 1983. Apple disease control, 1982. Fungic. Nematicide Tests 38:154.
21. Sutton, T. B., and Brown, E. M. 1986. Apple disease control, 1985. Fungic. Nematicide Tests 41:21-22.
22. Yoder, K. S., Cochran, A. E., II, Warren, C. M., and Ellis, A. E. 1989. Evaluation of experimental fungicides on three apple cultivars, 1988. Fungic. Nematicide Tests 44:47-48.