Delaying the Onset of Fungicide Programs for Control of Apple Scab in Orchards with Low Potential Ascospore Dose of *Venturia inaequalis*

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ABSTRACT

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Conventional fungicide spray programs for the control of apple scab have long involved the application of fungicides prior to the pink stage of fruit-bud development. Our earlier studies, which showed a relationship between the relatively low levels of overwintering inoculum found in modern commercial orchards and the onset of scab epidemics, indicate that early-season fungicide sprays are not necessary in many commercial orchards in the northeastern United States. To test this hypothesis, experimental plots were established in several commmercial orchards in New Hampshire and New York, and tests were run from 1985 to 1991. The minimum delay of apple scab epidemics from the time of budbreak was forecast based upon estimates of potential ascospore dose (PAD) in these orchards by using a model developed in earlier research. PAD ranged from six to 45,450 ascospores per square meter, and the forecast minimum delay of the epidemics (Δt) based upon PAD ranged from 2 to 24 days after budbreak. Early protectant-spray programs were initiated either before Δt or between Δt and the first infection period following. Delayed protectant-spray programs were initiated after one to five infection periods had occurred following the initiation of the early program. Delayed protectant-spray programs provided control of fruit and foliar scab that was equal to that provided by earlier treatment in 27 of 30 orchards, despite the occurrence of one to five infection periods between the early and delayed fungicide treatments. At two of the remaining three orchards, the increased level of fruit scab, while statistically significant ($P \leq 0.05$), was less than 1.0%. Fruit scab at one of the 30 sites reached 10.7% when treatment was delayed beyond the time recommended by Δt, and PAD at this site was 19,700 ascospores per square meter, among the highest levels included in this study. At sites where PAD was low, the first fungicide application could be safely delayed to coincide with the control of arthropod pests at the tight-cluster to pink stage of fruit-bud development.

Apple scab, caused by *Venturia inaequalis* (Cooke) G. Wint., is controlled in conventional programs by the regular application of protectant fungicides, or by the application of fungicides with postinfection activity to address putative infection periods (3,18,19). It is widely assumed that the need for protection from primary infection in commercial orchards begins at or shortly after budbreak (3). This assumption probably developed from observations of the onset of apple scab epidemics in research orchards with large resident populations of *V. inaequalis* (12), and is undoubtedly valid when severely diseased trees are present in the orchards and the resultant overwintering inoculum is high. However, the incidence and severity of apple scab in modern commercial orchards is often extremely low (12,27), resulting in correspondingly lower levels of overwintering inoculum (12). Many studies have demonstrated a relationship between the density of the overwintering population of *V. inaequalis* at leaf fall and the incidence and severity of apple scab during the following growing season (1,4-6, 10,14,16,17,20,21). Recent research has provided a means to quantify the density of the overwintering inoculum and to forecast the delay of an apple scab epidemic (expressed as days after budbreak) based on inoculum dose (10).

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There are important advantages to be gained by forecasting the onset of apple scab epidemics. Chief among these is the opportunity to integrate the fungicide-application schedule with that for arthropod pests (12,27) when apple scab development is delayed several days after budbreak. Such delays are associated with the use of highly effective, modern fungicide programs and the resulting trace levels of foliar apple scab in autumn (12,27). An advantage of delaying the initial fungicide applications is the consequent reduction in total applications per season (12,27), which will potentially reduce both the cost of the disease-control program and the selection pressure for fungicide resistance. Our objective in the present study was to determine the relative efficacy of delayed protectant-fungicide programs in commercial orchards with measured levels of primary inoculum. Reports of our preliminary research in this area have been published (7-12,22-24).

MATERIALS AND METHODS

Orchard research sites. Commercial orchards selected in New Hampshire and New York typified the most common production systems of the northeastern region of the United States, i.e., mixed plantings of cultivars susceptible to apple scab grafted onto clonal dwarfing or seedling rootstocks and planted at low to moderate densities (Table 1). All of the orchard sites were well managed and were under effective disease-control programs in the year prior to their selection.

Experimental design, collection, and analysis of data. Potential ascospore dose (PAD) (10) was determined from an assessment of foliar apple scab incidence and severity in September and October, and an assessment of leaf-litter density in April (10). The orchards ranged in size from approximately 3 to 12 ha, and the estimate of PAD was a mean value for the entire planting. Apple scab was assessed on 20 randomly selected terminal shoots of 30 randomly selected trees at each site. The number of infected leaves and the number of lesions per infected leaf were recorded. PAD, expressed as the total seasonal production of ascospores per square meter of orchard floor, was estimated from the disease and leaf-litter assessment data using a previously described model (10). Based on the PAD at each site, the delay of an apple scab epidemic (Δt) was computed as previously described (10,12).

Replicated blocks were established prior to budbreak at each orchard site, and treatments were replicated three times in New Hampshire and four or five times in New York. Blocks in New Hampshire orchards contained 15 trees (three rows of five trees), while those in New York contained one to eight trees, depending on the size of the block. Weather instruments at each site or at nearby locations provided records of hourly temperature, humidity, rainfall, and leaf wetness. Experimental treatments in New Hampshire were applied by growers with air-blast equipment and consisted of 1) the normal protectant-fungicide program of the grower at each site, and 2) the same program with the first one to three sprays omitted. This protocol was also followed at sites in New York, but prebloom treatments were applied by our technicians with a hydraulic handgun sprayer. Beginning at full bloom, growers in New York applied all treaments with air-blast equipment. The selection of fungicides and the rates and dates of application were the same in the two experimental treatments, with the exception of the omission of the early fungicide applications. Uniformity was maintained with respect to fungicides used at a single site in one season, but growers at different sites and during different years used a variety of materials, including captan, mancozeb, dodine, benomyl, and thiophanate-methyl, to control apple scab and other fungal diseases. Because dodine and benzimidazole fungicides can act as eradicants, they were not used until several weeks after the first fungicide application in the delayed-spray blocks. Sterol biosynthesis inhibiting (SBI) fungicides, also eradicants, were not used at all. Protectant fungicides such as mancozeb and captan were selected for early-season treatments. Fungicides were applied at approximately 7–10-day intervals between budbreak and bloom, and at 2-wk intervals thereafter. In New Hampshire, within each block of trees, three McIntosh trees in the middle row were examined for foliar and fruit infection each year at fruit set and shortly before harvest. In New York, data were collected from all trees in the block. The percentage of terminal or cluster leaves infected and the percentage of infected fruit were recorded. Between 50 and 100 fruit and their subtending leaves, and the leaves of between 10 and 20 terminal shoots were examined per tree. The arcsine square roots of treatment means at each site were compared by t test ($P = 0.05$) to determine if delaying fungicide applications resulted in a significant increase in disease.

RESULTS AND DISCUSSION

Potential ascospore dose (PAD) within the commercial orchards in our study ranged from a minimum of six to a maximum of 45,450 ascospores per square meter (Table 2), resulting in computations of Δt of 2–24 days after budbreak (Table 2). Frequently, growers waited until several days after green tip to apply their first fungicide treatment, and in some instances they waited beyond the time recommended for the start of the delayed-fungicide treatment (Table 2). In 27 of 30 orchards, delayed protectant-spray programs provided equal control of fruit and foliar scab to that provided by earlier treatment, despite the occurrence of one to five infection periods between the early and delayed treatments (Table 2). At two of the remaining three orchards, the increased level of fruit scab, while statistically significant ($P = 0.05$), was less than 1.0% (Table 2). Fruit scab at one of the 30 sites reached 10.7% when treatment was delayed beyond the time recommended by Δt (Table 2).

The equivalent control of apple scab that was achieved even when the start of the fungicide program was delayed far beyond the time dictated by Δt indicates that the method by which Δt is calculated is often overly conservative. Indeed, Δt as it was used by us in an earlier paper (12) was intended to be a conservative estimate of the earliest date by which a spray program should be implemented based on PAD, assuming the most favorable conditions possible for epidemic development. Several factors contributed to a lengthening of the delay beyond that computed by the model. Less than optimal conditions for epidemic development, e.g., lengthening of the latent period, absence of infection periods, development of ontogenic resistance by foliage, etc., could all lead to delays of apple scab epidemics beyond those forecast when the infection rate is assumed to equal its theoretical maximum. Additionally, most of the New York orchards included in this research received applications of benomyl or thiophanate-methyl during June through August to control summer diseases. Benzimidazole fungicides are known to suppress the formation of pseudothecia, even when applied several weeks before leaf abscission (12,25,26), and may have effectively reduced PAD (and thereby increased Δt), contrary to our model forecasts. Resistance to these compounds, while widespread, is not universal. The frequency of resistant isolates in the New York orchards where benzimidazole fungicides failed to control apple scab ranged from 21 to 100% in 1986 (D. A. Rosenberger, *unpublished*). The orchards in New York that were selected for our study were not sites where resistance to benzimidazole fungicides had produced significant losses. Thus, we cannot eliminate a potentially significant impact of these compounds on the formation of pseudothecia. Similar suppression of ascocarp formation has been attributed to the use of SBI fungicides (12,26), and their widespread use in current disease-management programs for apple scab (12,27) may greatly decrease PAD and thus increase Δt beyond the forecast levels. Finally, more recent findings that ascospore release is often delayed for several days beyond both budbreak and the appearance of morphologically mature ascospores (13) could also partially explain the success both of our delayed treatments and of those of Wilcox et al (27).

We believe that these potential errors that are collectively involved in the computation of PAD and Δt do not argue against their use in disease-management programs. The actual delay of the epidemic should always be greater than that indicated by Δt, based only on the method by which Δt is calculated (12). The above potential sources of error, although unknown, will not cause the least desirable result: an apple scab epidemic that begins before the date forecast by

Table 1. Characteristics of commercial apple orchard sites in New Hampshire (NH) and eastern New York (NY) used to evaluate control programs for apple scab

State	Site	Cultivars	Rootstock	Year established	Trees per hectare
NH	NH-1	McIntosh, Cortland	M.7	1970–1972	262
	NH-2	McIntosh, Cortland, Delicious	M.7	1970	287
	NH-3	McIntosh, Cortland, Delicious	M.7	1968	262
	NH-4	McIntosh, Cortland, Delicious	M.7	1970	262
	NH-5	McIntosh, Cortland, Delicious	M.7	1975	262
	NH-6	McIntosh, Cortland, Delicious	M.106	1975	395
NY	NY-LC	McIntosh, Cortland	Seedling	1073	67
	NY-GC	McIntosh, Cortland	Seedling	1973	143
	NY-BC	McIntosh, Cortland	M.7	1980	326
	NY-MZ	McIntosh, Macoun	MM.106	1980	280

Δt. The benefits of delaying the onset of the spray program, i.e., the integration of arthropod and pathogen control, and the reduction of selection for fungicide resistance, have been obtained despite the imprecision of our forecasts of PAD and Δt.

Although most growers were able to delay the first fungicide application beyond Δt, the results obtained at site NH-3 in 1987 (Table 2) provide an example of the risks associated with doing so. Fruit scab at NH-3 exceeded 10% at harvest when the first fungicide treatment was delayed 17 days beyond Δt, and a single infection period occurred between the early and the delayed treatments (Table 2). PAD at site NH-3 (19,700/m^2/yr) was among the highest in our study (Table 2). In theory, measurements of initial inoculum, such as PAD, should be related to the amount of primary infection and thus to the need to initiate the disease-management program within a certain number of days after budbreak (10,12). Environmental favorability for secondary disease development and the efficacy of the fungicide applications, once initiated, will substantially affect the final amount of fruit scab that develops in the approximately 90–100 days between the end of the primary infection season and harvest.

The low incidence of fruit scab at most sites shown in Table 2 illustrates the high efficacy of the conventional disease-control programs of commercial orchards in the northeastern United States, despite the presence of an environment favorable to severe disease. A question frequently raised by commercial growers regarding our recommendations to delay the beginning of fungicide programs based upon PAD, apart from the immediate risk involved, relates to the sustainability of the program over several seasons; i.e., will there be a cyclical increase in PAD over several seasons as early-season fungicide sprays are eliminated? The results obtained at sites NH-1, NH-2, and NH-3 over a 4-yr period (Table 2) indicate that the program is sustainable, and that increased foliar infection and a resultant increase in PAD is unlikely, despite the decreased number of fungicide applications.

To minimize the risk of losses due to apple scab in our delayed-application program, it is advisable that the remaining fungicide applications be highly effective. The use of SBI fungicides has been investigated and discussed in earlier reports (12,24,27). SBI fungicides have postinfection, eradicant, and antisporulant activities that make them highly effective for control of apple scab. SBI fungicides were not used in our study, so that the delay of apple scab epidemics at lower PAD levels could be observed without possible confounding from the suppression of symptoms or the eradication of infections that occurred before the onset of the spray program.

SBI fungicides may be especially helpful in attempts to synchronize pesticide applications for diseases and arthropod pests in two applications at tight cluster and petal fall (12), because the time be-

Table 2. Incidence of apple scab on fruit of trees sprayed on a protectant schedule beginning shortly after budbreak or later, based on potential ascospore dose of *Venturia inaequalis*

Year	Site[a]	Leaf scab previous year[b] (%)	PAD[c]	Δt[d] (days)	Infection periods between early and delayed spray[e]	Days between green tip and application[f]		Fruit bud phenology at application[g]		Leaf scab[h] (%)		Fruit scab[h] (%)	
						Early	Delayed	Early	Delayed	Early	Delayed	Early	Delayed
1986	NH-1	0.16	75	18	5 (M,S,S,S,S)	12	56	2cmG	FS	0.0	0.0	0.0	0.0 NS
	NH-2	0.03	20	21	1 (M)	16	36	2cmG	PF	0.3	0.0 NS	0.3	0.0 NS
	NH-3	0.38	545	13	2 (M,S)	10	23	1cmG	P	1.3	3.7 NS	1.3	3.7 NS
	NH-4	0.24	231	15	2 (M,S)	14	26	TC	P	4.5	7.7 NS	7.6	7.3 NS
	NY-LC	0.22	180	16	1 (M)	19	28	TC	B	0.1	0.9 NS	T	0.1
	NY-GC	0.22	303	14	1 (M)	19	28	TC	B	0.1	0.1 NS	T	0.1
	NY-BC	0.05	45	19	1 (M)	19	28	TC	B	0.1	0.0 NS	T	0.0
1987	NH-1	0.27	410	14	3 (S,M,S)	8	25	1cmG	P	0.0	0.0	1.3	0.7 NS
	NH-2	0.10	119	17	3 (M,S,S)	6	42	1cmG	FS	0.1	2.4*	0.0	0.0 NS
	NH-3	2.40	19,700	4	1 (M)	7	21	1cmG	TC	0.0	0.4 NS	0.0	10.7*
	NH-4	2.90	26,500	3	2 (M,M)	7	27	1cmG	B	1.9	0.3 NS	4.7	6.0 NS
	NY-LC	0.79	902	12	1 (S)	15	27	TC	P	1.4	25.8*	0.2	1.5 NS
	NY-GC	0.71	699	12	1 (S)	15	27	TC	P	0.8	1.2 NS	0.0	0.4 NS
	NY-BC	0.38	381	14	1 (S)	15	27	TC	P	0.1	2.3*	0.1	0.1 NS
1988	NH-1	0.04	10	23	3 (M,M,S)	12	35	2cmG	PF	0.0	0.0	0.0	0.7*
	NH-2	0.06	19	21	3 (S,S,S)	15	39	TC	PF	0.1	0.5 NS	0.2	0.4 NS
	NH-3	0.20	91	18	3 (M,M,S)	0	26	GT	B	0.3	0.5 NS	0.2	0.4 NS
	NH-4	0.16	139	16	2 (S,S)	13	32	1cmG	B	2.7	5.4	5.3	5.9 NS
	NY-LC	5.20	3,236	9	1 (L)	2	23	1cmG	TC	T	0.2	T	0.0
	NY-GC	11.60	7,880	6	1 (L)	2	23	1cmG	TC	T	0.1	T	0.3
	NY-BC	1.60	1,351	11	1 (L)	2	23	1cmG	TC	T	0.0	T	0.0
	NY-MZ	1.50	571	13	1 (L)	2	23	1cmG	TC	T	0.1	T	0.5
1989	NH-1	0.04	6	24	2 (S,M)	7	16	1cmG	TC	0.3	0.6 NS	0.6	1.0 NS
	NH-2	0.45	595	13	3 (S,M,L)	13	33	2cmG	PF	0.0	0.1 NS	0.0	0.0 NS
	NH-3	0.83	2,684	9	2 (L,S)	8	26	1cmG	PF	0.1	0.3 NS	0.0	0.8*
1990	NH-2	0.01	8	24	3 (S,L,M)	7	25	1cmG	B	0.4	0.8 NS	0.0	0.0 NS
	NH-5	0.13	87	18	4 (S,S,L,M)	8	27	1cmG	B	0.0	0.1 NS	0.0	0.0 NS
	NH-6	3.90	45,450	2	2 (M,S)	0	9	GT	TC	2.8	4.0 NS	0.4	0.6 NS
1991	NH-1	0.01	10	23	2 (M,L)	19	39	P	PF	0.0	0.0	0.0	0.0 NS
	NH-5	0.01	10	23	2 (M,L)	21	45	P	1cmF	0.0	0.0	0.0	0.0 NS

[a] NH = New Hampshire, NY = New York.
[b] Percent of terminal leaves with scab lesions was measured at harvest in each year of the study.
[c] Potential ascospore dose expressed as ascospores per square meter of orchard floor per season.
[d] Forecast delay of the apple scab epidemic, expressed as days after budbreak.
[e] Apple scab infection periods *sensu* Mills: L = light, M = moderate, S = severe.
[f] Early = first fungicide application in grower's conventional program. Delayed = fungicide application delayed a minimum of days (>Δt) after budbreak (except NH-1 in 1989).
[g] GT = green tip, 1cmG = 1-cm green, 2cmG = 2-cm green, TC = tight cluster, P = pink, B = bloom, PF = petal fall, FS = fruit set, 1cmF = 1-cm fruit.
[h] Mean percent of terminal leaves at harvest (NH), cluster leaves at fruit set (NY), or fruit at harvest (NH and NY) with one or more lesions. NS = no significant increase of infection with delayed spraying ($P \leq 0.05$); * = significantly different means at $P \leq 0.05$; T = trace of infection (estimated <0.1%); and ND = no data collected.

tween these phenophases usually exceeds the protectant activity of conventional protectant fungicides. Nonetheless, the conventional protectant fungicides used by the commercial growers in our study provided excellent control of apple scab and other diseases when applied according to our experimental protocol, and the application of our results to disease-management programs is not dependent on the use of SBI fungicides.

Despite the demonstrated high efficacy of benomyl, dodine, and SBI fungicides when used against apple scab, and their suppressive effects on the formation of pseudothecia (12), their use in reduced-spray programs may be cause for concern because of the potential impact on PAD, in particular when SBI fungicides are applied either to existing lesions or as post-infection treatments. Hoch and Szkolnik (15) demonstated that such applications do not always kill the subcuticular stroma. The potential for regrowth of the stroma and formation of pseudothecia following treatment, in particular when fungicide treatments are terminated early in the growing season (12,27), has not been investigated.

Another potential risk in delaying fungicide applications based on PAD is related to the recent discovery by Becker et al (2) of overwintering conidia of *V. inaequalis* within apple-bud scales in New York. However, it is plausible that this source of inoculum poses no more risk in orchards with a low PAD than the risk posed by the ascosporic inoculum, since the reported frequency of bud infection was low on severely diseased trees (2), and the source of inoculum for bud infections is presumably the same as that for leaf infections. Furthermore, the success of our commercial orchard experiments and those of Wilcox et al (27) indicates that delaying the first fungicide application based on an estimate of inoculum dose is a sound practice. The major risk presented by conidial inoculum from bud infections would occur if conditions led to low estimates of PAD and an unexpectedly high incidence of bud infection. Further studies of the relationships among disease incidence and severity, PAD, and the incidence of bud infection would therefore be valuable.

Our study identified inoculum levels in many commercial orchards that were low enough to allow a delay of the first fungicide application to coincide with arthropod pest control at the tight cluster to pink stage of fruit-bud development (Table 2). Wilcox et al (27) suggested that a qualitative assessment of inoculum dose may suffice to determine the suitability of an orchard site for a delayed-spray program. A more precise estimate of PAD, however, requires less than 2 hr to prepare (10) and would reduce the risk associated with using a delayed-spray program in an orchard with an unexpectedly high inoculum dose. However, considering that leaf-litter density (7,10), the only variable other than disease incidence and severity measured to forecast PAD, generally ranges from 0.25 to 0.50, selecting a threshold level of disease incidence and severity (e.g., $\leq$0.5% leaf infection with one lesion per infected leaf) that generally corresponded to a PAD of $\leq$1,000 (10) would effectively identify orchards in which the first fungicide application could be safely delayed until the pink stage. In the northeastern United States, delaying the onset of the spray program beyond the pink stage would presently have minimal impact on fungicide use, because of the need to control other members of the complex of pests and diseases that attack apples at this critical stage of development (12).

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