Fungicide Resistance of Apple Scab: Status Quo and Management Options

Wolfram Köller[1], Diana Parker[1], William Turechek[1], David Rosenberger[1], Wayne Wilcox[1], Juliet Carroll[2], Art Agnello[3] and Harvey Reissig[3]

[1]Department of Plant Pathology, New York State Agricultural Experiment Station, Cornell University, Geneva, NY 14456
[2]New York State IPM Program, Geneva, NY 14456
[3]Department of Entomology, New York State Agricultural Experiment Station, Cornell University, Geneva, NY 14456

This work was funded in part by the New York Apple Research and Development Program.

Starting with dodine in the early 1960s, five classes of scab fungicides have allowed the post-infection control of apple scab. Unfortunately, resistance has developed or will develop in all five classes. Work on measuring the levels of resistance to all available classes of post-infection fungicides began in 2002. The results of this project will provide an opportunity for growers to practice site-specific management of resistance (SMOR).

Apple scab caused by the fungus *Venturia inaequalis* is an important and recurring disease in all apple-growing regions of New York. In the absence of fungicides, the pathogen can defoliate apple trees prematurely. However, scab lesions on harvested fruits are economically much more important because of the 'zero-tolerance' for scab lesions on apples produced for the fresh market and an increasingly limited market for fruits with defects. Although some management practices, such as leaf litter management in the fall, can assist in the management of apple scab during the following season, fungicides will remain indispensable tools in the commercial production of apples in New York.

Highly effective scab fungicides became available in the early 1950s. Starting with the introduction of dodine in the early 1960s, all new fungicide classes have provided post-infection activities against apple scab. Unfortunately, we have found that the scab fungus has become or will become resistant to all classes of these post-infection fungicides. In this article, we will outline the current problems with resistance to scab fungicides along with management options that might help to avoid crop losses caused by unexpected outbreaks of resistance.

Qualities of Scab Fungicides and History of Resistance

There are two principally different types of scab fungicides on the market today, the protectant fungicides and the post-infection materials. Their inherently different qualities have an immediate impact on the control of apple scab but also on the development and management of resistance.

Protectant fungicides, such as ethylene bisdithiocarbamates (EBDCs) and captan, stop growth of the scab fungus by interfering with numerous steps important to the growth and survival of the scab fungus. Unfortunately, this multiple and nonspecific mode of action also determines the way these fungicides must be used. The scab fungus infects apples via microscopic spores that land on and attach to the surfaces of apple leaves and young fruits. The spores then germinate and penetrate through the surface barrier, after which the fungus will grow underneath the surface until new visible scab lesions appear, approximately two weeks later. Each of these scab lesions can produce 100,000 new infective spores shortly after lesions become visible.

The initial germination and penetration step of spores is rapid and can be completed in less than 24 hours. Any fungicide expected to stop the fungus after it already grows inside the apple host would have to penetrate through the outer surfaces of leaves and fruits in order to reach the fungus. This cannot be accomplished with protectant fungicides. If such nonspecific fungicides were allowed to penetrate into apple tissue, they would cause phytotoxicity. This, for example, is what happens if captan is used in combination with mineral oils. Mineral oils make plant surfaces more penetrable, allowing captan to enter and damage apple tissue.

The only effective way of managing scab with nonspecific protectants is to prevent the germination and penetration of spores. Because most growers find it impractical to apply fungicides within 24 hours after rain began (and because spraying in the rain is generally inadvisable), protectants must already be deposited on the surface before spores are disseminated during rain. The weather conditions conducive to infections are well defined (Mills table and its recent refinements), allowing growers to decide whether an infection took place and whether the application of a post-infection fungicide would be necessary. A sim ilarly precise timing of protectant sprays in advance of an infection period would require the accurate forecasting of such events at the local level, which remains somewhat unreliable. Therefore, routine prophylaxis remains the best option for the effective use of protectants. Strict prophylaxis necessitates the start of scab programs at 'green tip' and the continuation of sprays in weekly (or shorter) intervals up to '1st' or sometimes '2nd cover' in order to replenish fungicide deposits washed off by rain and to protect the new growth of leaves. Applying a purely protective fungicide after infections are established will have minimal effect. The load of secondary spores formed as a result of a missed protectant spray will be very high and much more difficult to control. To correct for a spray missed, subsequent applications of nonspecific protectants must provide excellent coverage, and they must be applied at high rates and / or at shortened intervals.

The EBDCs and captan, currently the most widely used protectants, are ineffective for the control of powdery mildew. However, the EBDCs control rust and some summer diseases in addition to scab, and captan is active on several summer diseases (Table 1).

Stopping the scab fungus after it is established inside leaves or fruits can only be accomplished with fungicides that can reach the pathogen underneath the surface. Such post-infection fungicides must be highly fungal-specific, because they will have to penetrate into the apple tissue without killing or damaging plant cells. Dodine, introduced in the early 1960s, was one of the first scab fungicides with pronounced post-infection activities, in addition to good protectant activity. Small necrotic lesions developed when dodine was applied up to seven days after infection, but they did not form new spores (pre-symptom activity). Although dodine provided no control of other apple diseases (Table 1) and could cause fruit russetting on light-colored cultivars, the fungicide was rapidly accepted as a new and convenient post-infection tool in the management of scab. However, in the early 1970s, control failures were noticed in many New York orchards, where dodine had been used for approximately 10 years on a full-season basis. It was found that the scab fungus had developed resistance. This discovery came as a surprise because resistance had never been observed for the EBDCs or captan. Lack of resistance to nonspecific protectants remains in effect today and is unlikely to become a problem in the future.

TABLE 1

Qualities of commonly used scab fungicides

Class	Common name(s)	Trade name(s)	Post-infection	Additional diseases
EBDCs	mancozeb	Dithane, Manzate, Penncozeb	no	rust, flyspeck, sooty blotch
	maneb, metiram	Manex, Polyram		
Captan	captan	Captan	no	black rot, white rot, flyspeck, sooty blotch
Dodine	dodine	Syllit	yes	none
Benzimidazoles	thiophanate-methyl	Topsin M, T-Methyl	yes	powdery mildew, black rot, white rot, flyspeck, sooty blotch
Sterol inhibitors (SIs)	fenarimol, myclobutanil, triflumizole	Rubigan, Nova, Procure	yes	powdery mildew, rust
Strobilurins	kresoxim-methyl, trifloxystrobin	Sovran Flint	yes	powdery mildew, rust, black rot, white rot, flyspeck, sooty blotch
Anilinopyrimidines (APs)	cyprodinil, pyrimethanil	Vangard, Scala	yes	none

The introduction of the benzimidazoles in the early 1970s, with benomyl (Benlate) as the first representative, offered a solution to the problem of widespread dodine resistance. Benomyl and later thiophanate-methyl provided post-infection control of scab and also controlled powdery mildew and several summer diseases (Table 1). Unfortunately, the scab fungus developed resistance to benzimidazoles even faster than to dodine, with first control failures reported after only four years of season-long use. In addition, the phenomenon of cross-resistance between different fungicides surfaced as a new problem. Individuals of the scab fungus resistant to benomyl were also resistant to thiophanate-methyl and *vice versa*.

It had been noticed that benzimidazoles continued to control scab in regions where they had been mixed with an EBDC in order to control apple rust. The concept of mixing benzimidazoles with a protectant was quickly adapted as a general anti-resistance strategy. Unfortunately, resistance to the benzimidazoles continued to develop even where they were used in mixture. By the early 1980s, the benzimidazoles failed to contribute to scab management in many orchards, and the protectant in the mixtures became solely responsible for the level of scab control achieved.

The third class of specific scab fungicides, the sterol inhibitors (SIs), was introduced in the late 1980s (Table 1). The SIs were highly effective in both after-infection and pre-symptom applications. For up to 96 hours after an infection period had started, they stopped the development of the pathogen inside the apple tissue without allowing visible symptoms to emerge (after-infection activity). Even when applied seven days after infection, only small necrotic lesions developed, but their conversion to sporulating lesions was prevented (pre-symptom activity). These excellent post-infection properties allowed the development and implementation of a 'delayed spray' program in orchards with very good scab control in the previous season. In such low-inoculum orchards, scab was effectively controlled with only four SI applications made at 'tight cluster', 'pink', 'petal fall' and '1st cover', a scheme that allowed growers to merge scab control with routine insect control in pre- and post-bloom applications. In addition to providing excellent scab control, the SIs also controlled powdery mildew and rust, thereby combining control of all major 'early season' apple diseases.

From the time the SIs were permitted in the US to be used in apple production, it was recommended that they should be applied in a mixture with protectants at half of their full 'stand-alone' rates. The rationale for this recommendation was to complement the protection of fruits – where the SIs had shown some weaknesses when used alone – and to add an anti-resistance component.

The first control failure in a commercial orchard caused by SI resistance was reported in 1995. In this Michigan orchard, the delayed spray program had provided good scab control for eight years. The same speed of resistance development was identified in an IPM test orchard at the Geneva Experiment Station where the same delayed program was used in scab management. The development of SI resistance has been slower in other orchards, but as described below, SI resistance is now established in many orchards in New York. Orchards resistant to one SI will be equally resistant to all other SIs available.

Two new classes of scab fungicides with post-infection activities became available in 2000: the strobilurins and the anilinopyrimidines (APs) (Table 1). For both classes, cases of control failures caused by resistance have not been documented in New York orchards. However, our assessments of resistance risks and the monitoring of orchard sensitivities leave no doubt that both classes are prone to resistance development, with cross-resistance apparent for all members of each class.

The Pathways of Resistance Development

Over the past two decades, we have been able to answer the question of how resistance to post-infection fungicides develops. Although the apple scab pathogen causes typical and apparently uniform scab lesions, the fungus exists in each orchard as a community of different individuals with different and distinct characteristics. The characteristics with importance to fungicide resistance are the different sensitivities individuals have to a new class of fungicides. Most of the individuals will be sensitive at the time the new fungicide is introduced, and their reproduction will be prevented. A few individuals of the scab fungus, however, will be able to survive treatments and will continue to multiply. In sprayed orchards, these individuals will have a clear reproductive advantage over their sensitive counterparts, and their preponderance in treated orchards will increase. This increase will first lead to an erosion of the initial efficacies in scab control and then to the stage of full resistance where economically acceptable scab control is no longer provided. Unfortunately, the transition from a noticeable erosion of performances to control failures is most often too short to be recognized by growers.

The speed of resistance development depends on the intensity of the fungicide used in individual orchards but also on the dose resistant individuals of the scab fungus will survive. For some fungicides, resistant individuals are entirely immune. They are not slowed down at any feasible application rate of the fungicide, and resistance will build up rapidly. The benzimidazoles are the classical example for this 'immunity' type of resistance. For other fungicides, resistant individuals continue to be inhibited at high doses, with the SI fungicides as an example. In such cases, emergence of resistance will be slower and more gradual, especially when application rates are kept at the high end of respective label rates.

Over the past 15 years, we also have learned how to measure the development of resistance in individual orchards. This task required both a quantitative sensitivity test and the development of data describing the two sensitivity extremes: baseline sensitivities prior to the first use of a new fungicide class and threshold sensitivities at which control failures will become a reality. We started to measure sensitivities and to monitor the development of resistance for the SIs from the time they were introduced, and we gradually added tests and data sets for all classes of post-infection fungicides currently available. We found that the status of resistance to the five classes of post-infection fungicides available was different from orchard to orchard, and that control failures were usually caused by outbreaks of resistance rather than by flawed practices of scab management.

Our findings opened an opportunity to manage resistance more effectively. Precise knowledge of the levels of resistance to all fungicide options in individual orchards would allow growers to design their own orchard-specific scab management program, with sufficient warning before control failures caused by resistance would become imminent. Although the sensitivity tests we had developed in the past have helped to better understand how resistance develops and how it can be managed, our tests were too costly and too complicated to be used in measuring the sensitivity of individual orchards on a broad scale.

Since 2002, we have simplified and unified our test procedures. The reproducibility and precision of the new test, as evaluated over two seasons, is sufficient to rank individual orchard sensitivities into four functional categories and, at the same time, to predict the expected performances of post-infection fungicide options:

Sensitive	good performance is expected
Slight shift	good performance is expected at high label rates
Strong shift	performance must be supplemented with another fungicide
Resistant	insufficient contribution to scab control to warrant further use

Our new test measures orchard sensitivities to dodine, the SIs, the strobilurins and the APs. A test for the benzimidazoles was omitted for reasons given below, but this test segment could be added easily if a need should exist.

Status Quo of Fungicide Resistance in New York Orchards

With the new sensitivity test in hand and the sets of crucial data established, we have measured the fungicide sensitivities of 13 commercial orchards across all major apple-growing regions in New York during 2003 and 2004 (Table 2). Although the number of orchard sites we tested is small, our results illustrate the current problems but also the opportunities for managing fungicide resistance. We will describe the status of resistance in New York orchards according to the history of fungicide introductions.

Dodine. Widespread resistance to dodine was first documented in the 1970s. During the past decade we verified that dodine-resistant individuals in scab populations were not immune to dodine. At the application rates recommended, however, full resistance to dodine was reached after a total of approximately 60 applications had been made in any given orchard. These 60 applications could be spread over 10 years with six applications per season or over 30 years with only two applications made per season. We found in surveys conducted in the mid 1990s that once dodine resistance had been established in an orchard, the proportion of dodine-resistant individuals did not decline to baseline levels even after dodine use had been discontinued for 20 years. We also found that some orchards expected by growers to be dodine-resistant were sensitive; whereas, some orchards expected to be sensitive to dodine contained large numbers of resistant individuals.

Our most recent survey of orchard sensitivities (Table 2) confirmed our previous results. Only four of the 13 commercial orchards we tested in New York were diagnosed as dodine-resistant, while nine orchards were sensitive or only slightly shifted. We also confirmed the longevity of dodine resistance once it was established in an orchard. Resistance was found even in young orchards after old orchards

TABLE 2

Sensitivities of the apple scab fungus in New York orchards. Orchards 1-13 are commercial orchards. 'McIntosh' and 'Empire' are experimental test orchards at the Geneva Experiment Station.

Orchard	Dodine	SIs	Strobilurins	APs
1	sensitive	strong shift	slight shift	sensitive
2	**resistant**	**resistant**	slight shift	strong shift
3	slight shift	**resistant**	sensitive	strong shift
4	sensitive	**resistant**	slight shift	strong shift
5	**resistant**	**resistant**	strong shift	**resistant**
6	sensitive	slight shift	slight shift	strong shift
7	slight shift	strong shift	slight shift	strong shift
8	**resistant**	**resistant**	slight shift	strong shift
9	sensitive	**resistant**	sensitive	slight shift
10	sensitive	slight shift	slight shift	strong shift
11	slight shift	strong shift	slight shift	strong shift
12	slight shift	**resistant**	slight shift	slight shift
13	**resistant**	**resistant**	strong shift	strong shift
'McIntosh'	strong shift	**resistant**	slight shift	strong shift
'Empire'	slight shift	**resistant**	sensitive	slight shift

with resistance problems in the 1970s had been replanted. In summary, the reintegration of dodine into scab management appears feasible and potentially advantageous in many orchards, but only if the dodine sensitivity of a particular orchard has been determined before dodine is applied.

Benzimidazoles. For several reasons, the benzimidazoles were not included in our recent orchard survey. The US registration for benomyl (Benlate) was voluntarily withdrawn by the manufacturer, leaving thiophanate-methyl as the single benzimidazole product available for scab control. Also, our surveys in the 1990s had indicated that benzimidazole resistance, once established in an orchard, remains stable. More recent test results indicated that the number of benzimidazole-resistant orchards could even have increased above the levels observed in our initial surveys. A reason for this increase might be that a mixture of thiophanate-methyl with captan has been widely used for the management of summer diseases. Because the end of the scab season and the start of the summer disease program often overlap, the scab fungus has remained under continuous selection pressure toward increasingly higher levels of benzimidazole resistance. As a result, thiophanate-methyl will not be an option for scab control in the majority of New York's apple orchards. In many orchards, powdery mildew has also developed resistance to the benzimidazoles, and the future role of thiophanate-methyl appears to be largely restricted to the management of summer diseases.

SIs. With their initially excellent after-infection and pre-symptom activities, and their activity against powdery mildew and rust, the SIs became the post-infection materials of choice during the 1990s. We found that mixing EBDCs at half of their full rates provided the additional control of fruit scab needed, but we also found that the selection of SI-resistant individuals of the scab fungus was not slowed by EBDCs in the mixtures. However, the speed of their selection could be slowed down with high rates of the SIs, because resistant individuals were not immune to the SIs.

When SI programs were started at 'tight cluster' with application rates at the low end of their label rates, 30-40 SI applications in total were sufficient to render an orchard SI-resistant. Our recent survey of orchards (Table 2) showed that SI resistance has now become widespread in New York. Only two of the 13 orchards we tested (15%) were rated 'slightly shifted', while eight orchards (62%) were diagnosed as SI-resistant. Control failures following SI applications had been experienced in three of the orchards, but SIs had not been applied in the other five SI-resistant orchards. Taking our sampling bias into account, the results suggest that approximately 40-50% of New York's orchards have reached the stage of SI resistance. Many other orchards showed strong sensitivity shifts. If SI resistance in these 'strongly shifted' orchards is not managed prudently (high protectant rates in mixtures with SIs and applied at shortened spray intervals), respective growers will experience unexpected control failures in the near future.

In fully SI-resistant orchards, the SIs in mixture with an EBDC can no longer be expected to contribute to scab management. Rather, the EBDC in the mixture will have to bear the full burden of scab control. The current EBDC labels allow either one of two use options: At a high rate (6 lb / acre) they can be applied up to four times and no later than bloom. At half of the rates (3 lb / acre) they can be used up to seven times and to within 77 days of harvest. The effectiveness of EBDCs at these low mixture rates was tested in the two SI-resistant experimental orchards 'McIntosh' and 'Empire' at the Geneva Experiment Station (Table 2). The high inoculum levels in these test orchards would be similar to those expected in commercial orchards where fungicide resistance has contributed to control failures. Our trial results are described in Tables 3 and 4.

In 1999, the scab program in the 'McIntosh' orchard was started at '1/2 inch green' and ended with '2nd cover', with a total of seven applications made (Table 3). Dithane alone at the low mixture rate provided poor control of leaf scab and commercially unacceptable control of fruit scab. Mixing Dithane with Rubigan had little effect on the level of scab control because the orchard was SI-resistant.

At the 'Empire' orchard examined in 2003, the program was initiated at 'green tip' with a protective spray five days in advance of the first scab infection period, and the program continued with six additional applications (Table 4). Dithane at the low rate provided a marginally acceptable level of scab control. Mixing Dithane with Nova at the four stages emphasized in the original 'delayed spray program' did not significantly improve scab control above the level achieved with Dithane alone, as expected from the status of SI resistance.

The trial results confirmed our previous predictions. Mixing SIs with an EBDC will not prevent the development of SI resistance. As the level of SI resistance rises over time, the EBDC will carry an increasingly greater burden of scab control provided by the mixture. When full SI resistance is reached, the SI will no longer contribute to the management of scab.

If the results of our most recent sensitivity orchard survey (Table 2) are representative of New York orchards, sole reliance on the low EBDC rate in mixture with SIs will be risky because the post-infection activity formerly provided by the SIs will be lost in SI-resistant orchards. In such orchards, only the Dithane com ponent in the mixtures can be expected to control scab. The risk a grower unaware of the situation will take is apparent from the result of a trial where the protective spray with Dithane at 'green tip' was omitted (Table 4). Scab lesions on cluster leaves developed freely, and the extreme load of secondary spores in the immediate vicinity of developing fruits caused a failure of fruit scab control.

In summary, the original security and convenience of the 'delayed four-spray SI program' will no longer be applicable in the majority of New York orchards. However, the SI fungicides remain effective in controlling powdery mildew and rust. In SI-resistant orchards, the timing of mildew and rust applications must be adjusted to these diseases. Sufficient scab control must be provided by another scab fungicide.

It must be noted that the status of SI resistance has by now surpassed the status of dodine resistance (Table 2). Unfortunately, four of the SI-resistant orchards were also resistant to dodine. In these orchards, reintegration of dodine into scab management programs will not be an option. The potential for double-resistance constitutes a problem. Although dodine could be reintroduced as a post-infection fungicide in early parts of the season, the longevity of dodine resistance might contribute to the false assumptions that an orchard is sensitive to dodine. Reliance on dodine in such cases will lead to severe control failures.

Strobilurins. In New York, the strobilurins became available in 2000. Our early risk assessment studies had suggested that resistance could develop as a gradual shift of orchard sensitivities (similar to dodine and the SIs), and/or as a mutation conferring the benzimidazole-type of immunity. Both predictions were confirmed for the apple scab fungus. Following an initially gradual sensitivity shift in Germany, immune mutants emerged after a total of 20-30 applications had been made. Cases of such orchard immunities are spreading slowly through Europe and, most recently, were detected in Chile. Fortunately, we have not yet found strobiluin-immune mutants in New York orchards. However, the initially gradual shifts of orchard sensitivities are clearly apparent in many orchards (Table 2).

We have tested the performance of the strobilurins in both of our SI-resistant test orchards. In trials at both orchards, the strobilurins provided the best control of scab (Tables 3 and 4), and good performance of strobilurins can be expected in SI-resistant orchards throughout New York State. However, several concerns relating to the future use of strobilurins have surfaced. Our experience suggests that the slight sensitivity shifts typical for New York orchards will diminish the after-infection activity strobilurins will provide. In comparison with the SIs, the strobilurins are excellent protectants but less potent in after-infection applications. When strobilurins are used 96 hours after infection in 'slightly shifted' orchards, as allowed by the product labels, their activity might not be sufficient to provide complete control of scab. In such orchards, strobilurins should be restricted to 48 hours post-infection action, and they should be applied at their highest label rates.

Strong shifts of strobilurin sensitivities were found in two of the commercial New York orchards we tested recently (Table 2). Incidentally, both orchards were also resistant to dodine and the SIs. In such orchards, strobilurins might have to be used on a strictly protective schedule, because post-infection action is no longer assured. Trials are under way to fully explore this additional restriction.

Another concern is the speed by which the initially gradual sensitivity shifts toward strobilurin resistance can turn into the stage of full immunity. Once this immunity stage is reached, the strobilurins will no longer contribute to scab control, and they will have to be used in

TABLE 3

Performance of fungicides in an SI-resistant experimental orchard (McIntosh) in 1999. Timing of applications (dilute) was 1, April 12 (1/2-inch green); 2, April 23 (tight cluster); 3, May 5 (pink); 4, May 13 (bloom), 5, May 20 (petal fall); 6, May 27 (1st cover), 7, June 7 (2nd cover).

			Scab incidence (%)		
Fungicides	Timing	Rate/100 gal	Cluster leaves (June 26)	Terminal leaves (August 1)	Fruits (August 17)
Untreated check			42.8	81.4	68.5
Dithane 75DF	1-7	1 lb	33.4	43.0	12.3
Rubigan 1E + Dithane 75DF	1-7	3 floz + 1 lb	26.0	46.8	8.5
Flint 50WG	1-7	0.67 oz	4.6	7.4	1.3
Vangard 75WG	1,2	1.67 oz			
Vangard 75WG + Dithane 75DF	3-7	1 oz + 1 lb	13.5	46.2	5.5
Vangard 75WG	1,2	1.67 oz			
Vangard 75WG	3-7	1 oz + 1 lb	22.8	49.7	30.3

TABLE 4

Performance of fungicides in an SI-resistant experimental orchard (Empire) in 2003. Timing of applications (dilute) was 1, April 16 (green tip); 2, April 24 (1/2-inch green); 3, April 30 (tight cluster); 4, May 7 (pink); 5, May 15 (bloom); 6, May 22 (petal fall); 7, May 29 (1st cover). The first infection period was on April 21.

			Scab incidence (%)		
Fungicides	Timing	Rate/100 gal	Cluster leaves (June 14)	Terminal leaves (August 20)	Fruits (August 20)
Untreated check			8.8	64.3	77.5
Dithane 75DF	1-7	1 lb	2.5	7.0	6.0
Dithane 75DF	1,2,5	1 lb			
Dithane 75DF + Nova 40W	3,4,6,7	1 lb + 1.5 oz	1.5	9.8	12.5
Dithane 75DF	2-7	1 lb	9.8	8.0	32.0
Dithane 75DF	1,2,5	1 lb			
Sovran 50WG	3,4,6,7	2 oz	0.0	1.5	0.5
Scala 60SC	2,3 4-7	3 fl oz 1 lb	1.8	11.0	12.0

mixture with another scab fungicide. The current anti-resistance strategy recommended by the strobilurin manufacturers and enforced in product labels is to limit the number of strobilurin applications to a maximum of four per season. This number might be too high to sustain the potency of strobilurins over many more seasons. At present, we recommend to use strobilurins when conditions demand after-infection activity in addition to a strong forward protection of leaves and fruits, and to restrict the number of strobilurin scab sprays per season to less than the four currently allowed applications. We also have good evidence that the transition from gradual sensitivity shifts to full immunity will be slowed when strobilurins are used at their highest label rates.

Anilinopyrimidins. The AP cyprodinil (Vangard) was introduced in 1999, and the AP pyrimethanil (Scala) will become available in 2005. Both APs provide up to 48 hours after-infection control of scab, but they lack activity on apple diseases other than scab. Both of these features are reflected in their product labels. APs used alone are only recommended for pre-bloom applications. Mixtures at lower rates with unrelated fungicides are allowed in later than pre-bloom applications.

In our testing of orchard sensitivities, we noticed that the AP sensitivities varied widely in commercial orchards where APs had never been used. We found that some of this variation was dependent on the status of SI resistance. Many SI-resistant individuals of the scab fungus were also less sensitive to the APs, suggesting that SI-resistant orchards can be less sensitive to the APs even before these fungicides were used for the first time.

Our 'McIntosh' and 'Empire' test orchards at the Geneva Station provided an opportunity to test the efficacy of APs in SI-resistant orchards. The recommended Vangard program was tested in our 'McIntosh' orchard (Table 3). Vangard was used alone up to 'tight cluster', followed by the recommended mixture of Vangard plus Dithane. The Vangard program improved the control of scab on cluster leaves and fruits slightly above the level achieved with Dithane alone. The relative contribution of Vangard for control of scab was tested by omitting Dithane from the mixture segment of the program. The results suggested that Vangard alone provided a very low and unacceptable level of scab control. Similar results were obtained during several other seasons. The results prompted us to designate the test orchard as 'strongly shifted' to the APs (scab control must be supplemented).

Our second SI-resistant 'Empire' orchard had remained more sensitive to the APs and was designated 'slightly shifted'. Here, the first of two Scala applications was applied 72 hours after-infection, after omission of the first application at 'green tip'. The levels of cluster leaf and fruit scab control achieved were higher than for the comparatively delayed 'Dithane alone' program, indicating a benefit from the after-infection action of the AP. However, the level of control achieved was not higher than for the Dithane program initiated with a spray at 'green tip' (Table 4).

Although APs had never been used in any of the 13 commercial orchards we tested (Table 2), only four were 'sensitive' or 'slightly shifted'. All other orchards were already 'strongly shifted' or even beyond the 'strong shift' designation derived from our 'McIntosh' test orchard where Vangard was largely ineffective. This new phenomenon of 'shifted sensitivities' prior to the use of a new class of fungicides might pose a future problem. Orchards where scab has developed resistance to several classes of fungicides may not be fully sensitive to a new class of fungicides before it is used. The variable performances of APs might be an example for this future challenge.

In New York, AP fungicides could find their best fit in the management of scab when after-infection activity is required in the early pre-bloom period. Unfortunately, respective AP activities are not expected to be sufficient in many orchards, and mixtures of APs with other fungicide will become important in order to supplement their performance, even in pre-bloom applications.

Management of Fungicide Resistance

Multiple resistance of the scab fungus to several post-infection fungicides has become a reality in New York. Although we have learned to cope with resistance in the past, our management strategies have only responded to control failures after they became evident. Unfortunately, the growers affected first had to shoulder the economic impact of control failures they could not foresee. This purely reactive practice of managing resistance to fungicides is both unsatisfactory and unsustainable.

To avoid the risk of crop losses caused by resistance, we need to develop tools that will allow the continued use of post-infection fungicides and, at the same time, protect apple growers from crop losses caused by unexpected outbreaks of resistance. The periodic measurement of orchard sensitivities to all fungicide options can provide reliable predictions. As noticed previously and confirmed in our recent survey, both the pattern and magnitude of resistance to scab fungicides is different from orchard to orchard. Therefore, resistance management must become a site-specific rather than a regional endeavor.

Orchard-specific measurements of resistance levels will have to be combined with reliable management alternatives. Unfortunately, all past strategies of resistance management – replacing one fungicide class with a new class, mixing post-infection fungicides with a protectant fungicide, or applying certain fungicide classes at high doses – have not accomplished the goal of protecting apple growers from sudden and unexpected crop losses.

Where do we go from here? At present, there are two solutions to the problem of fungicide resistance in the control of apple scab. Growers can revert to exclusive use of protectants (mostly EBDCs and captan), or they can implement site-specific management of resistance in order to adjust scab management programs before control failures become imminent.

The option of abandoning reliance on any of the post-infection fungicides would not be without consequences. As described above, sole reliance on nonspecific protectants will be 'unforgiving' when protective applications in advance of infection periods are missed. In addition, both captan and the EBDCs have been under continuous toxicological scrutiny as 'B2 carcinogens' (probable human carcinogens). They may be further restricted in order to protect pesticide applicators, orchard workers and consumers. Some apple buyers may be unwilling to accept fruit treated with these fungicides.

Under the 1996 FQPA mandate, captan was granted a Re-registration Eligibility Decision (RED) by EPA in 1999 and remains available for the management of apple scab. EPA is currently in the process of amending the RED for captan, which might downgrade (but not eliminate) the cancer risk associated with captan. For the EBDCs, the metabolite ETU, which is common to all EBDC products, has been affiliated with carcinogenic risks. The RED for EBDCs should be issued in 2005. Although EBDCs will probably remain available for use in apple production, some label changes might be imposed as a result of this most recent label review.

The critical scab management question for the immediate future is this: when and under what circumstances can apple growers rely on post-infection fungicides to stop scab when a protective spray was missed or its expected efficacy eroded during extensive rain? As apparent from our recent orchard survey, in two of the 13 orchards we tested (orchards 5 and 13), current post-infection choices are few, but in 11 orchards, some post-infection fungicides remain as viable alternatives to protectants. The question of which post-infection fungicides are expected to provide good scab control can only be resolved by measuring the level of resistance to all options available. Based upon this knowledge, management programs can be designed to use all active fungicides to their best advantage. Utilization of several viable classes of fungicides over a single season will prolong the useful lifetime of each class used because the speed of resistance development will be slower when such fungicides are used less frequently.

Our new sensitivity test was designed to accomplish the goal of measuring fungicide sensitivities in individual orchards. Once the sensitivities are known, the information can be used to predict the site-specific risk of control failures before they happen. Our limited experience with this site-specific management of resistance (SMOR) has been positive. Several growers managing the orchards described in Table 2 had experienced poor scab control or control failures after they had applied fungicides to which the scab fungus had become resistant. In those orchards, management changes based on the knowledge of orchard sensitivities to all fungicide options has restored effective scab control.

We plan to further develop SMOR as a service available to apple growers in New York. The costs for this service will have to be defrayed by the growers requesting the service, but the potential savings by avoiding unexpected crop losses caused by sudden and unexpected outbreaks of resistance would outweigh these costs. Major hurdles such as current uncertainties regarding the laboratory and organizational infrastructure required for conducting the sensitivity tests will need to be overcome before the service can be fully implemented.

Conclusions

Fungicides that allow post-infection management of apple scab have become valuable tools in the commercial production of apples. Unfortunately, the progress made has coincided with the emergence of resistance and the risk of sudden, unexpected and costly crop losses. We found that fungicide-resistant orchards remained resistant over several decades. This robustness of resistant individuals of the scab fungus makes it difficult to predict all levels of resistance in an individual orchard. Equally disturbing is the fact that multiple rounds of resistance development might have resulted in some orchard populations of the scab fungus that are now 'trained' to evade new fungicide challenges more quickly than in the past.

The current status quo might sound discouraging. Although apple growers in New York have the choice among nine scab fungicides with post-infection activities, only a fraction of these choices will provide reliable scab control because durable resistance to one or more of these options exists in many orchards. The options for managing scab without risking control failures are either the complete reliance on protectants or the site-specific management of resistance (SMOR) based upon measurements of sensitivities to all post-infection options available. Utilizing all available scab fungicides in full awareness of their limitations and their benefits will be the key to reliable control of apple scab in the future.

Acknowledgements

This research was supported, in parta by the New York Apple Research and Development Program, by Bayer CropScience and several other manufacturers providing fungicides. Any conclusions or recommendation are those of the authors and do not necessarily reflect the view of fungicide manufacturers. We wish to acknowledge the cooperation of all apple growers participating in this project, and the help of Kevin Iungerman in arranging meetings with several of the participating growers.

References

Köller, W., Wilcox, W. F., Barnard, J., Jones, A. L., and Braun, G. 1997. Detection and quantification of population shifts of *Venturia inaequalis* to sterol demethylation inhibitors. *Phytopathology*. 87: 184-190.

Olaya, G., and Köller, W. 1999. Baseline sensitivities of *Venturia inaequalis* populations to the strobilurin fungicide kresoxim-methyl. *Plant Dis*. 83: 274-278.

Köller, W., Wilcox, W.F., and Jones, A.L. 1999. Quantification, persistence and status of dodine resistance in New York and Michigan orchard populations of *Venturia inaequalis*. *Plant Dis*. 83: 66-70.

Köller, W., and Wilcox, W.F. 1999. Evaluation of tactics for managing resistance of *Venturia inaequalis* to sterol demethylation inhibitors. *Plant Dis*. 83: 857-863. Köller, W., and Wilcox, W.F. 2001. Evidence for the predisposition of fungicide-resistant isolates of *Venturia inaequalis* to a preferential selection for resistance to other fungicides. *Phytopathology*. 91: 776-781.

Köller, W., Parker, D. M., Turecheck, W. W., Avila-Adame, C., and Cronshaw, K. 2004. A two-phase resistance response of *Venturia inaequalis* populations to the QoI fungicides kresoxim-methyl and trifloxystrobin. *Plant Dis*. 88: 537-544.

Köller, W., Wilcox, W. F., and Parker, D. M. 2005. Sensitivities of *Venturia inaequalis* populations to anilinopyrimidines and their contribution to scab management in New York. *Plant Dis*.: in press.

Wolfram Köller is a research professor in the Department of Plant Pathology who specializes in fungicide resistance. David Rosenberger and Wayne Wilcox are professors in the same department who specialize in the management of tree-fruit and grape diseases respectively. William Turecheck was assistant research and extension professor in the Department of Plant Pathology until 2004, where he was the leader of Cornell's tree and small fruit disease extension program. He is now a researcher at the USDA-ARS Fruit Laboratory, Beltsville, MD, where he leads the strawberry disease program. Diana Parker is a research support specialist working with Wolfram Köller. Juliet Carroll leads Cornell's fruit IPM program. Art Agnello and Harvey Reissig are research and extension professors in the Department of Entomology specializing in tree fruit insect pest management. They also lead a project funded through a USDA-RAMP grant, which allowed the inclusion of our work on fungicide resistance.