A Stewardship Program for Using Fungicides and Antibiotics in Apple Disease Management Programs

ALAN L. JONES, Department of Botany and Plant Pathology and the Pesticide Research Center, Michigan State University, East Lansing 48824

There are many compelling reasons for using fungicides to control diseases on apples (*Malus domestica* Borkh.). No other disease control approach has been so thoroughly researched and evaluated in the field. Chemical control is an effective component of an overall management program and is often the only dependable method available. Chemicals provide flexibility in disease control programs with reasonable assurance of success. Nonchemical alternatives do not exist for the diseases of greatest economic importance.

Apples are a highly visible commodity to American consumers and have been the focus of recent pesticide issues. The daminozide (Alar) issue, concerns about the Environmental Protection Agency's (EPA) enforcement of the Delaney Clause, and the National Academy of Science's report on "Pesticides in the Diets of Infants and Children" have focused public attention on pesticide residues in apples and other fruits. The Clinton administration responded to these issues by submitting pesticide and food safety reform legislation to Congress and announcing the goal of having 75% of all farm acres using integrated pest management (IPM) practices within 7 yr. An IPM plan is needed for apples that will profitably cope with food safety and the environment in addition to traditional pest management (37).

Recently the EPA, the United States Department of Agriculture, and the United States Food and Drug Administration formed a partnership with a number of commodity groups, including the International Apple Institute, to promote environmental stewardship in pesticide use in the United States. This partnership represents the beginning of a new interaction between regulatory agencies, industry groups, and university researchers and extension staff. In this new paradigm, the regulatory agencies are prodding the industry and university staff to provide a proactive perspective on how pesticide issues can be managed in the future.

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This paper outlines approaches to voluntary reductions in fungicide and antibiotic use for the Michigan apple industry. It provides background information on disease problems, progress in reducing the use of fungicides, the feasibility of management strategies that require less use of fungicides, and priorities for research in disease-control alternatives. It is part of a comprehensive plan developed by a task force of university and industry representatives associated with the Michigan apple industry and represents a benchmark for future EPA-industry-university cooperation.

Apple Diseases of Significance in Michigan

Over 200 pathogens have been reported on apple (2), but only 10–15 of these have the potential to seriously damage the Michigan apple industry (Table 1). Weather conditions, such as high humidity, rainfall, and moderate temperatures, favor the development of many of these diseases; these conditions frequently occur together in Michigan from April through September. Fortunately, controls for most major diseases exist. The diseases are described elsewhere (20,24).

Among the currently important diseases, control of scab is essential if substantial disruption in apple production in Michigan is to be avoided. Although alternative methods of control, such as scab-resistant cultivars, might reduce dependence on chemical fungicides for scab control in the future, elimination of fungicide use is unlikely since sooty blotch and fly speck will increase in severity as fungicide use is reduced (31,38). Powdery mildew and fire blight are problems on a few susceptible cultivars. Disease management strategies for apple scab, sooty blotch, and fly speck are outlined below to illustrate the progress Michigan apple growers have made and are continuing to make to reduce the overall use of fungicides.

Apple scab, caused by *Venturia inaequalis* (Cooke) G. Wint., is a consistently important disease that can cause total crop loss. An illustration of the persistent threat of loss from scab is the annual occurrence for over 40 yr of 98–100% fruit infection on unsprayed trees in fungicide spray trials conducted in orchards at Michigan State University (MSU). Infections on fruit cause premature fruit drop and reduce fruit size and quality. Early defoliation from infections on leaves reduces fruit size and inhibits the formation of flower buds for the next year's crop.

Most of the fungicide used on apples in Michigan is applied for scab control. Treatments are initiated at the green-tip stage of bud development and are maintained on a 7-day schedule until mid-June, when they are applied about every 14 days until harvest. Generally, there are eight to 10 applications annually. Applications may be discontinued after about second cover if primary scab has been well controlled (98–100% control) and other fungal pathogens are not important. If primary scab has not been well controlled, fungicide applications are continued until harvest.

Sooty blotch and fly speck are diseases caused by different fungi: *Gloeodes pomigena* (Schwein.) Colby causes sooty blotch, and *Zygophiala jamaicensis* E. Mason causes fly speck. The environmental conditions that favor their development are very similar, and both diseases are often found together on apple fruit. Their presence on the fruit's surface lowers quality and subsequent market value. In orchards where these diseases occur, fungicides are applied on a 10- to 14-day schedule from first cover to harvest to protect fruit from infection. Sooty blotch and fly speck have increased in importance as sterol demethylation inhibitors (DMIs) have replaced captan and the ethylene-bisdithiocarbamate fungicides for apple scab control (21,52).

Resistance—A Major Problem Confronting Chemical Control

Unquestionably, resistance of plant pathogens to fungicides has become a serious threat to the stability and success of control strategies for several important diseases of apple. The development of fungicide resistance in populations of *V. inaequalis* has limited the number of fungicides that can be used effectively for scab control. Resistance to the benzimidazole fungicides benomyl and thiophanate-methyl was first identified in North America in Michigan in 1975, only

3 yr after benomyl was introduced for scab control (19,25). Because populations of resistant strains are distributed widely and are stable, benzimidazole fungicides are no longer recommended for the control of scab in Michigan orchards. The development of resistance to benomyl had great practical significance because no other fungicide has provided the level of scab control or flexibility in timing.

Dodine-resistant strains of *V. inaequalis* were detected in Michigan after their identification in New York State in 1969 (46). The research in New York was the first documented case of field resistance to a modern fungicide. Resistance developed where dodine was used exclusively for 10 or more years. In Michigan, strains of *V. inaequalis* resistant to both benomyl and dodine were detected where the fungicides were used in combination after many years of exclusive dodine use (25). In 1992, the continued presence of dodine-resistant *V. inaequalis* in Michigan apple orchards was confirmed (W. Köller and A. L. Jones, *unpublished data*). Although dodine is still registered for scab control, it is no longer efficacious against the scab pathogen in most Michigan apple orchards.

With the introduction of the DMI fungicides fenarimol (Rubigan) in 1987 and myclobutanil (Nova) in 1989, Michigan growers began to use a new class of fungicides for scab control. However, *V. inaequalis* resistance to DMIs has occurred after several years of intensive use in experimental and commercial orchards in other regions (5,17,40). Resistance is expected to develop eventually in orchards in the United States, and considerable research has been done already to establish the baseline sensitivity of scab populations to various DMI fungicides (27,39). Mixtures of DMIs with conventional protectant fungicides are used by many growers as a way of delaying resistance to DMI fungicides. Also, mixtures control fruit scab and certain other diseases better than DMIs alone. The withdrawal of several conventional fungicides from the marketplace due to reregistration costs or outright bans would hasten the development of resistance to DMI fungicides in *V. inaequalis*.

As fungicides lost their effectiveness for scab control due to the development of resistance, they were replaced in spray programs with new fungicides. It may not be possible to replace DMIs when resistance develops because very few fungicides with new modes of action are being developed for apple scab control.

The lack of alternative control measures, either chemical or nonchemical, is currently the situation with streptomycin and fire blight control in three areas of Michigan (30). Resistance to streptomycin in *Erwinia amylovora* (Burrill) Winslow et al was identified in 1990 after it had been used for nearly 40 yr for fire blight control in Michigan apple orchards (7). Where resistance to streptomycin has developed, growers are left with no effective chemical to control this serious disease.

Table 1. The relative importance of apple diseases in Michigan

Disease Scientific name	Loss without fungicide or antibiotics	Type of damage
Apple scab *Venturia inaequalis*	Severe[a]	Spots on leaves and fruit, leaf and fruit drop, weakening of trees[b]
Fire blight *Erwinia amylovora*	Severe	Killing of fruit spurs, shoots, branches, and trees[c]
Quince rust *Gymnosporangium clavipes*	Minor	Spots on leaves and fruit, deformed fruit, weakening of trees[c]
Cedar apple rust *G. juniperi-virginianae*		
Hawthorn rust *G. globosum*		
Powdery mildew *Podosphaera leucotricha*	Moderate	Distorted leaves, russeting of fruit, reduced shoot growth[c]
Black rot *Botryosphaeria obtusa*	Minor to moderate	Fruit decay, leaf spotting, cankers on wood
White rot *B. dothidea*	Minor	Fruit decay, cankers on wood
Sooty blotch *Gloeodes pomigena*	Moderate to severe	Blemishes on fruit. Worst on late-season yellow and green skin cultivars[d]
Fly speck *Zygophiala jamaicensis*		
Bitter rot *Glomerella cingulata*	Minor	Fruit decay
Blister spot *Pseudomonas syringae* pv. *papulans*	Minor to moderate	Spotting of fruit of Mutsu, Fuji, Cortland[d]
Brooks fruit spot *Mycosphaerella pomi*	Minor	Small sunken spots on fruit[e]
Cayx-end rot *Sclerotinia sclerotiorum*	Minor	Decay on blossom-end of fruit[f]
Moldy core and core rot *Alternaria* spp.	Minor	Rot of core, premature ripening, visible mold[g]
Nectria twig blight *Nectria cinnabarina*	Minor	Death of spurs, cankers. Severity cultivar dependent[h]
Bull's-eye rot *Pezicula malicorticis*	Minor to moderate	Decay of fruit after harvest[i]

[a] Could eliminate industry.
[b] Affects all commercially accepted cultivars.
[c] Severity depends on cultivar.
[d] Problem increasing.
[e] Problem in poorly sprayed orchards.
[f] No effective control.
[g] Problem on strains of Delicious.
[h] No chemical control.
[i] Controlled with preharvest sprays.

Progress in Reducing the Need for Fungicides and Antibiotics

Fruit growers in Michigan and throughout the Eastern United States have made significant progress in reducing the amount of fungicides used in apple production. Fungicide reductions have been achieved by improving the effectiveness of application equipment, eliminating unneeded sprays at the beginning of the season, improving the timing for applications later in the season, and using cultural practices wherever possible.

Application techniques. New and improved techniques for fungicide applications have played an important role in the development of apple disease management programs. Prior to the late 1940s and early 1950s, high-pressure sprayers and handguns were used to spray orchards. With the development and improvement of airblast sprayers during the 1950s, disease control improved with a parallel decrease in labor. By the 1960s, most major pathogens were under control and only maintenance programs were needed for orchards where inoculum levels were kept low.

The development of concentrate spraying enabled growers to reduce overall fungicide use even more. With the old standard of 400 gal of water per acre (3,740 L/ha) for trees 20–22 ft (6–7 m) tall planted in rows 35 ft (10 m) apart (28), there was excessive loss of fungicide into the environment through runoff from sprayed trees. With concentrate or low-volume spraying at 30–100 gal of water per acre (280–935 L/ha), comparable pesticide residues were obtained, with a 20–25% reduction in the amount of fungicide used and less runoff from sprayed trees. Today concentrate sprays are commonly used in apple disease management programs.

Further reductions in fungicide use resulted from the development of the alternate middle technique of spraying in the 1960s (28,29). Alternate middle spraying refers to the spraying of alternate sides of the tree at shorter spray intervals. The technique was based on findings that good spray coverage can be obtained with large airblast sprayers by spraying one side of the tree and that the effectiveness of fungicides with short residual activity can be increased by more frequent application (5–10 days) at low rates. The development and use of the tree-row-volume concept (6), coupled with an adjustment for canopy density (44,45), provided a satisfactory guide for determining the rate of fungicide needed in orchards with trees of various sizes and canopies of various densities.

These improvements in application technology, fungicide chemistry, and control strategies made it possible to adequately control diseases in many commercial orchards with less fungicide. As part of the reregistration process, whereby the EPA scrutinized the risks and benefits of pesticides, dose rates recommended on fungicide labels were reduced by 25% for several fungicides introduced when inoculum levels in orchards were high and dilute spraying was common. Thus, as a result of the reregistration process, growers were required through labeling to reduce fungicide use, shown to be possible by university and industry scientists.

Improved timing. Through accurate timing of fungicide applications, adequate disease control can be maintained while the total amount of fungicide used per season is reduced in all but exceptionally wet years. Timing involves the application of a fungicide 1 or 2 days before the onset of infection or the application of special kinds of fungicides after predicted infection periods. Most fungicides exhibit maximum protectant effectiveness when applied just prior to infection periods. Therefore, most Michigan apple growers try to utilize this approach in timing sprays to control apple scab, but the effectiveness of this strategy for reducing fungicide treatments depends on having accurate weather forecasts. Inaccurate weather forecasts contribute to unnecessary applications when predicted rains fail to develop or to missed applications when rains are unpredicted or arrive ahead of time.

Infections that occur before fungicides are applied may be controlled by after-infection fungicides applied 24–96 h after the beginning of a rain favorable for infection. Some fungicides must be reapplied 7 days later to ensure that the infections are eliminated (35). Temperature and wetness duration combinations necessary for infection to occur were defined by D. W. Mills in the mid-1940s (32,33). Although Mills' predictive system has been modified slightly by other researchers, the criteria established continue to form the basis for predicting scab infection periods and timing after-infection treatment. Widespread use of the Mills program was made possible by the development of airblast sprayers for spraying orchards quickly and thoroughly and by the development of fungicides with after-infection or presymptom curative control properties.

Through the use of microprocessor technology, researchers at MSU developed a battery-operated instrument that monitored environmental factors in an orchard and predicted apple scab infection periods (23). After predicted infection, it displayed a tailor-made list of fungicide options for growers to select from. An average of 3.3 fungicide sprays were saved per season in field tests conducted for 5 yr in Michigan and 3 yr in New York when spray programs based on after-infection fungicides were substituted for programs based on protectant fungicides (22). Independent studies conducted in Ohio demonstrated the economic benefits of this technology and confirmed the potential to reduce fungicide use through more precise scheduling of fungicide application (11,12).

A commercial version of the instrument developed and marketed by Reuter-Stokes, Inc., Cleveland (22), was not a commercial success. Virtually all growers in Michigan were influenced by predictions from these instruments because district extension horticultural agents collected and disseminated information from a few units located in each region. The networking approach was cost effective for growers, but because it limited instrument sales, adequate profits were not returned to the manufacturer.

In addition to identifying scab infection periods based on weather, it is important for growers to know when the primary inoculum is available for infection and when it is actually discharged. Fungicide sprays are often unnecessary if no ascospores are mature or if the supply of ascospores is exhausted. Control of the primary stage of apple scab markedly reduces or eliminates the need for control measures for secondary scab, particularly where the fruit are being grown for the processing market. In Michigan, several extension agents monitor one or two orchards in their district for ascospores with Rotorod samplers and make information on spore discharge available to growers via self-answering telephones (Code-A-Phone systems), fax networks, and radio. One advantage of using spore samplers is that the variable effects of weather (light, temperature, amount and intensity of rain, and prior drought periods) on discharge are reflected in the monitoring data. These techniques were evaluated and refined in the early 1970s (43) and continue to be used by extension personnel and IPM consultants in Michigan.

Integrated, reduced-spray (IRS) program. Beginning in the 1990s, a new strategy for reducing the number of fungicide sprays for scab control was introduced for use in orchards where inoculum levels are low due to excellent scab control the previous year (50). Reduction is achieved by eliminating unneeded sprays at the beginning of the season and by capitalizing on the postinfection control activity of back-to-back sprays with DMI fungicides. Four sprays timed to coincide with the phenologic tree stages of tight cluster, pink, petal fall, and first cover are used in the IRS program compared to six to seven sprays in a traditional protectant program. DMI fungicides must be used, preferably in combination with a protectant fungicide, and effectiveness requires good spray coverage. This program also controls powdery mildew until second cover.

The four-spray IRS program was the culmination of research on the quantification of ascospore dose in well-sprayed commercial blocks compared to unsprayed or poorly sprayed blocks and on the mode of action of the DMI fungicides. Although the scab fungus develops similarly in sprayed and unsprayed orchards, ascospore populations are not "critical" until tight cluster to pink in sprayed orchards compared to green tip in unsprayed orchards (13,14). Secondly, the DMI fungicides have excellent presymptom control activity when applied in back-to-back sprays (26,35). The extended presymptom activity of repeat applications provides the flexibility needed to coordinate early season disease, insect, and mite control applications.

Cultural practices. Apple growers use a number of standard cultural practices to improve fruit quality and disease control. For example, dormant and summer pruning to open up the tree canopy and thinning to separate fruit clusters help prevent sooty blotch and fly speck by facilitating drying of fruit after rain or dew (10,42). These practices also favor better spray coverage (9). Removing alternate hosts, such as brambles, from the orchard and surrounding hedgerows also helps to reduce the influx of fly speck inoculum (42). However, cultural practices are not adequate by themselves for disease control.

Prospects for Reductions in Use of Fungicides and Antibiotics

The potential for reduced use of fungicides on apples in the United States depends to a large extent on the disease complex to be controlled in various regions. There would be severe disruption in apple production if growers in the eastern United States were expected to reduce use of fungicides to levels employed in the West where disease problems are minor. Fungicide reduction is less likely in the East where apple scab and summer diseases are major problems.

Breeding for disease resistance. Development and planting of cultivars with multiple disease resistance could result in significant reductions in the use of chemical fungicides on apples in the future. The first crosses to incorporate apple scab resistance into a commercial cultivar were begun in Illinois over 55 yr ago when Rome Beauty was crossed with *M. floribunda*. Although more than 30 scab-resistant cultivars have been released from breeding programs in the United States, Canada, and Europe, they are not being widely planted nor have they been accepted in volume in the marketplace. A few Michigan growers are evaluating small plantings of these cultivars, but the new releases are largely unfamiliar to most growers and consumers, and most are inferior to the present commercial cultivars, especially for the fresh market.

Although apple cultivars with genetic resistance to scab will become more important if options for chemical control of diseases become limiting, it is unlikely that resistant cultivars will substantially or quickly replace chemical fungicides. Some scab-resistant releases also have resistance to powdery mildew, fire blight, and cedar apple rust, but most are susceptible to at least one of these diseases and to such diseases as sooty blotch, fly speck, black rot, and white rot. Failure to control sooty blotch and fly speck on the disease-resistant cultivar Liberty resulted in a significant reduction in economic returns for the fruit (38).

Due to physiologic variation in the scab pathogen, antiresistance strategies need to be developed to increase the durability of scab-resistant cultivars. Recently, a new race (race 6) of the apple scab fungus infected some scab-resistant cultivars in Europe (36). This breakdown in resistance emphasizes the need to reexamine the breeding strategies for this disease. Because of the limited evaluations made within breeding programs for susceptibility to other pathogens, resistance to a particular pathogen in one region may not provide resistance to that pathogen in another region. For example, Liberty was considered resistant to powdery mildew when released but is now considered highly susceptible to mildew (8). Widespread use of scab resistant apple cultivars is not expected for many year, and the substantial replacement of well-established susceptible cultivars by resistant ones is highly unlikely.

Genetic engineering of resistant cultivars. Although several apple cultivars with disease resistance have been developed by traditional breeding methods, creating new cultivars with the desired genetic characteristics is a time-consuming, laborious process. Sources of genetic resistance may not be available for the range of important diseases in each apple-growing region. Because of the development of an ever increasing array of molecular methods, scientists are no longer restricted to working with genes identified in apple. Beneficial genes from other crop plants or even from outside the plant Kingdom also can be incorporated into apple. Plants can now be manipulated to deliver the same mechanism of control as microorganisms, and microorganisms are now being viewed as potential sources of genes for disease resistance. A major advantage of this strategy is that existing commercial cultivars could be altered by introducing desirable characteristics, such as disease resistance. This is expected to be much quicker than breeding entirely new cultivars that are both resistant and of acceptable quality.

This approach is currently being used by Norelli et al (34) to introduce resistance to fire blight into apple. A gene from the giant silk moth (*Hyalophora cecropia*) was introduced into M.26 apple rootstocks. Transgenic M.26 that contained and expressed the gene had increased resistance to infection by *E. amylovora* when compared with the parent M.26. Such genetic alteration of the rootstock should not affect the quality of the fruit produced by the scion cultivar. In the future, plants may be genetically engineered to repel pathogens only when they are under attack. Although genetic engineering combined with breeding could substantially reduce use of chemical pesticides or result in control measures for diseases that are currently uncontrolled, progress in this area will be very slow because resistance to multiple diseases will be needed before fungicide load can be significantly reduced in many apple-growing regions.

Microbial pesticides. The growing interest in using microorganisms (bacteria, fungi, yeast, and viruses) for biological control of pathogens of apple is an outgrowth of public concern over chemical pesticides, including fungicides. No fungicide registered for disease control on apple has been replaced by a microbial pesticide. Without an unanticipated breakthrough in research, development of microbial fungicides for managing foliage and fruit diseases of apples is still decades away. Most microorganisms currently under study are not self-sustaining after they are introduced, or natural populations must be augmented to reach levels sufficient to combat pathogens. Therefore, they must be applied again and again to be effective. Applying them repeatedly involves formulations and application equipment identical to that used for chemical fungicides. The mechanism of biological control for many organisms currently being evaluated as microbial pesticides involves antibiotic production. In reality, microorganisms are delivering chemicals. Although the level of antibiotic involved is normally far less than the level of a chemical fungicide applied to control a particular disease, the public may still have considerable apprehension about consuming apples sprayed with biological control agents. Unlike chemical fungicides, microbial fungicides rarely provide multiple disease control. Unless microbial pesticides can be developed for the range of diseases on apples, it will be difficult to eliminate applications of fungicides for those diseases that are not controlled biologically.

Despite the problems outlined here, there are a few areas in which microbial pesticides may provide alternate means for controlling apple diseases. The apple scab pathogen overwinters in leaf litter. Destruction of the litter by mechanical, chemical, or biological methods, eliminating the overwintering inoculum, has been under investigation since the mid-1930s. Andrews and co-workers (16,53) in Wisconsin evaluated a large number of microorganisms found in the leaf litter and as residents on the surface of apple leaves and fruit as potential biocontrol agents. The fungus *Athelia bombacina* Pers. has demonstrated potential as a biological control agent for apple scab by inhibiting overwintering of the scab fungus in apple leaves. This biological control strategy is attractive because the trees and fruit are not directly treated with microbial pesticides. This strategy has not been evaluated in large-scale trials in orchards nor have economic benefits been determined. Removal of leaf litter may allow growers to control scab during the growing season with fewer fungicide applications, but benefits of this method may be limited because the scab pathogen also overwinters in apple buds (4).

Biological controls for fire blight have been under development since the early 1970s (15,49,51). Two bacteria, *Pseudomonas fluorescens* strain A506 and *E. herbicola* strain C9, are the most promising. Strain A506 is registered with the EPA but is not a commercial product. The antagonistic bacteria are applied to blossoms and colonize the flower stigma before the fire blight pathogen becomes established. Although bees have been used to deliver the bacteria to blossoms (18,47), bee vectoring of these antagonistic bacteria to flowers is not efficient enough to replace spraying of formulated microbial pesticides. The best control has been obtained with periodic rather than single applications. Since antagonistic bacteria have only provided up to 60% control of fire blight in controlled experiments, their use will need to be integrated with antibiotics. One strategy is to apply the biocontrols early in bloom and again near full bloom, followed by antibiotic sprays when the MARYBLYT model (41) or other models indicate that weather is conducive for fire blight. Importance of biological control of fire blight should increase as *E. amylovora* develops resistance to antibiotics. However, biocontrols have not yet been developed for the shoot blight phase of fire blight; this phase is a serious problem in Michigan during the summer.

Predictive models. Knowledge of weather, levels of inoculum, and fungicide efficacy are especially important factors to consider before deciding on a particular control strategy. Models that relate disease occurrence to inoculum availability, environmental conditions, and host susceptibility have resulted in improved disease control, particularly for apple scab and fire blight. The incorporation of these models and other management strategies into disease predictors or into expert systems (48) will provide an avenue for the widespread implementation of these disease management programs.

Refinement of existing models and the development of management models for other apple diseases is dependent on acquisition of a large data base on the biology and epidemiology of each disease and pathogen and the availability of effective chemical controls. Models recently proposed for cedar apple rust (1) and black rot (3) may provide the foundation for the development of new management programs for other diseases. Although data on the biology and epidemiology of these and other diseases are accumulating, a sufficient data base does not exist to construct predictive models.

Successful implementation of disease management models and programs also depends on grower attitudes and their willingness to accept new technology. Because of the high per-acre value of the crop, apple growers are inherently risk averse and need to be convinced that the risks involved in implementing new management programs are outweighed by their benefits. Thorough testing of new management strategies before release to growers is requisite to the development of successful management programs.

The availability of effective chemicals will continue to be critical to the development and implementation of disease management models. Fungicides with good postinfection and curative activity are necessary to take full advantage of models such as the Mills model for apple scab. For example, the DMI fungicides, because of their curative activity, are valuable for use in managing apple scab, mildew, and cedar-apple rust. However, there currently are no fungicides registered with postinfection activity against diseases such as sooty blotch, fly speck, black rot, bitter rot, and white rot. Even if models become available for scheduling sprays for these diseases, they may not be of practical value without fungicides to eliminate latent infections.

Pesticide management. In addition to reducing the number of chemical applications by monitoring infection periods as described above, new sprayer designs aimed at decreasing the amount of chemical applied in each application are needed. Reliable procedures to eliminate pesticide residues by postharvest treatments would ensure the safety of apples when growers are forced to apply chemicals late in the season.

Because of current design of orchard pesticide application equipment, the lower parts of trees are over sprayed to ensure adequate coverage in tops of trees. Michigan growers are beginning to use a sprayer that applies sprays in a uniform curtain of air that extends from the bottom to the top of the tree. This sprayer, developed at MSU by two agricultural engineers (G. Van Ee and R. Ledebuhr, *unpublished data*), improves delivery of the spray to the target site. Research is currently underway to establish how much chemical application rates can be reduced without affecting the level of disease control and how planting systems affect disease control practices with this sprayer. Research in this area could advance quickly with large-scale implementation within a few years.

Although reduced spray programs and longer preharvest intervals reduced detectable chemical residues in raw apples at harvest and in processed apple products, residues of some systemic fungicides were seldom eliminated even by processing (21). However, residues of certain nonsystemic chemicals were reduced and sometimes eliminated in processed products made from peeled apples compared to unpeeled apples (J. Cash, M. Zabik, and A. L. Jones, *unpublished data*). Washing fruit with warm water at pH 11 also was very effective in removing some chemicals but not others. Other postharvest techniques for lowering residues of fungicides prior to marketing or processing of the fruit need to be evaluated.

Summary and Conclusions

Disease management strategies and tactics developed over the past 20–30 yr have led to substantial reductions in the use of fungicides on apples. Label changes involving lowering of dosage rates resulted in a 25% reduction in use for several common fungicides, and further reductions of 5–15% are possible using various disease management practices, such as eliminating early season sprays or timing of sprays close to predicted infection periods. Combined, these practices result in a possible 30–40% reduction in fungicide use. Strategies currently being researched or under development include new cultivars and rootstocks with disease resistance, advances in sprayer technology, development of microbial pesticides, and new or improved models for timing fungicide and bactericide application. If these technologies are developed and implemented, a 40–50% reduction in overall pesticide use appears possible when compared to levels used in the early 1960s. Outbreaks of minor or new disease problems or the development of strains resistant to the DMI fungicides could make it difficult to reach this goal. Conversely, significantly higher reductions could occur longer term by undertaking a major research effort to introduce multiple disease resistance into currently accepted cultivars using genetic engineering.

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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. Anonymous. 1960. Index of plant diseases in the United States, USDA Agric. Handb. 165.
3. Arauz, L. F., and Sutton, T. B. 1989. Temperature and wetness duration requirements for apple infection by *Botryosphaeria obtusa*. Phytopathology 79:440-444.
4. Becker, C. M., Burr, T. J., and Smith, C. A. 1992. Overwintering of conidia of *Venturia inaequalis* in apple buds in New York orchards. Plant Dis. 76:121-126.
5. Braun, P. G., and McRae, K. B. 1992. Composition of a population of *Venturia inaequalis* resistant to myclobutanil. Can. J. Plant Pathol. 14:215-220.
6. Byers, R. E., Hickey, K. D., and Hill, C. H. 1971. Base gallonage per acre. Va. Fruit 60:19-23.
7. Chiou, C.-S., and Jones, A. L. 1991. The analysis of plasmid-mediated streptomycin resistance in *Erwinia amylovora*. Phytopathology 81:710-714.
8. Cimanowski, J., Dzieciot, W., and Kowalik, B. 1988. Evaluation of susceptibility of 22 apple varieties to apple scab (*Venturia inaequalis* [Cooke] Aderh) and apple powdery mildew (*Podoshaera leucotricha* [Ell et.Ev] Salm). Fruit Sci. Rep. 15:81-84.
9. Cooley, D. R., and Lerner, S. 1994. Summer pruning increases pesticide coverage in apple canopies. (Abstr.) Phytopathology 84:1370.
10. Cooley, D. R., Telgheder, C., Autio, W. A., and Gamble, J. 1992. Using summer pruning to reduce flyspeck and sooty blotch of apple in the Northeast. (Abstr.) Phytopathology 82:1075.
11. Ellis, M. A., Madden, L. V., and Wilson, L. L. 1984. Evaluation of an electronic apple scab predictor for scheduling fungicides with curative activity. Plant Dis. 68:1055-1057.
12. Funt, R. C., Ellis, M. A., and Madden, L. V. 1990. Economic analysis of protectant and disease-forecast-based fungicide spray programs for control of apple scab and grape black rot in Ohio. Plant Dis. 74:638-642.
13. Gadoury, D. M., and MacHardy, W. E. 1986. Forecasting ascospore dose of *Venturia inaequalis* in commercial apple orchards. Phytopathology 76:112-118.
14. Gadoury, D. M., MacHardy, W. E., and Rosenberger, D. A. 1989. Integration of pesticide application schedules for disease and insect control in apple orchards of the northeastern United States. Plant Dis. 73:98-105.
15. Ishimaru, C. A., Klos, E. J., and Brubaker, R. R. 1988. Multiple antibiotic production by *Erwinia herbicola*. Phytopathology 78:746-750.
16. Heye, C. C., and Andrews, J. H. 1983. Antagonism of *Athelia bombacina* and *Chaetomium globosum* to the apple scab pathogen, *Venturia inaequalis*. Phytopathology 73:650-654.
17. Hildebrand, P. D., Lockhart, D. L., Newbery, R. J., and Ross, R. G. 1989. Resistance of *Venturia inaequalis* to bitertanol and other demethylation-inhibiting fungicides. Can. J. Plant Pathol. 10:311-316.

18. Johnson, K. B., Stockwell, V. O., Burgett, D. M., Sugar, D., and Loper, J. E. 1993. Dispersal of *Erwinia amylovora* and *Pseudomonas fluorescens* by honey bees from hives to apple and pear blossoms. Phytopathology 83:478-484.
19. Jones, A. L. 1981. Fungicide resistance: Past experience with benomyl and dodine and future concerns with sterol inhibitors. Plant Dis. 65:990-992.
20. Jones, A. L., and Aldwinckle, H. S. 1990. Compendium of apple and pear diseases. American Phytopathological Society, St. Paul, MN.
21. Jones, A. L., Ehret, G. R., El-Hadidi, M. F., Zabik, M. J., Cash, J. N., and Johnson, J. W. 1993. Potential for zero residue disease control programs for fresh and processed apples using sulfur, fenarimol, and myclobutanil. Plant Dis. 77:1114-1118.
22. Jones, A. L., Fisher, P. D., Seem, R. C., Kroon, J. C., and Van Demotter, P. J. 1984. Development and commercialization of an in-field microcomputer delivery system for weather-driven predictive models. Plant Dis. 68:458-463.
23. Jones, A. L., Lillevik, S. L., Fisher, P. D., and Stebbins, T. C. 1980. A microcomputer-based instrument to predict primary apple scab infection periods. Plant Dis. 64:69-72.
24. Jones, A. L., and Sutton, T. B. 1984. Diseases of tree fruits. North Central Reg. Ext. Publ. 45.
25. Jones, A. L., and Walker, R. J. 1976. Tolerance of *Venturia inaequalis* to dodine and benzimidazole fungicides in Michigan. Plant Dis. Rep. 60:40-44.
26. Kelley, R. D., and Jones, A. L. 1981. Evaluation of two triazole fungicides for postinfection control of apple scab. Phytopathology 71:737-742.
27. Köller, W., Reynolds, K. L., and Parker, D. M. 1991. Baseline sensitivities of *Venturia inaequalis* to sterol demethylation inhibitors. Plant Dis. 75:726-728.
28. Lewis, F. H. 1980. Control of deciduous tree fruit diseases: A success story. Plant Dis. 64:258-263.
29. Lewis, F. H., and Hickey, A. L. 1972. Fungicide usage on deciduous fruit trees. Annu. Rev. Phytopathol. 10:399-428.
30. McManus, P. S., and Jones, A. L. 1994. Epidemiology and genetic analysis of streptomycin-resistant *Erwinia amylovora* from Michigan and evaluation of oxytetracycline for control. Phytopathology 84:627-633.
31. Merwin, I. A., Brown, S. K., Rosenberger, D. A., Cooley, D. R., and Berkett, L. P. 1994. Scab-resistant apples for the northeastern United States: New prospects and old problems. Plant Dis. 78:4-10.
32. Mills, W. D. 1944. Efficient use of sulfur dusts and sprays during rain to control apple scab. N.Y. Agric. Exp. Stn. Ithaca Bull. 630.
33. Mills, W. D., and LaPlante, A. A. 1951. Control of diseases and insects in the orchard. Pages 18-22 in: N.Y. Agric. Exp. Stn. Ithaca Bull. 711.
34. Norelli, J. L., Aldwinckle, H. S., Destéfano-Beltrán, L., and Jaynes, J. M. 1993. Increasing the fire blight resistance of apple by transformation with genes encoding antibacterial proteins. Acta Hortic. 338:385-386.
35. O'Leary, A. L., Jones, A. L., and Ehret, G. R. 1987. Application rates and spray intervals for apple scab control with flusilazol and pyrifenox. Plant Dis. 71:623-626.
36. Parisi, L., Lespinasse, Y., Guillaumes, J., and Krüger, J. 1993. A new race of *Venturia inaequalis* virulent to apples with resistance due to the Vf gene. Phytopathology 83:533-537.
37. Rajotte, E. G. 1993. From profitability to food safety and the environment: Shifting the objectives of IPM. Plant Dis. 77:296-299.
38. Rosenberger, D. A., Meyer, F. W., and Engle, C. A. 1994. Economic impacts of failure to control summer diseases on 'Liberty' apples. (Abstr.) Phytopathology 84:547.
39. Smith, F. D., Parker, D. M., and Köller, W. 1991. Sensitivity distribution of *Venturia inaequalis* to the sterol demethylation inhibitor fusilazole: Baseline sensitivity and implications for resistance monitoring. Phytopathology 81:392-396.
40. Stanis, V. F., and Jones, A. L. 1985. Reduced sensitivity to sterol-inhibiting fungicides in field isolates of *Venturia inaequalis*. Phytopathology 75:1098-1101.
41. Steiner, P. W., and Lightner, G. W. 1992. MARYBLYT: A predictive program for forecasting fire blight disease in apples and pears. Version 4.0. University of Maryland, College Park.
42. Sutton, T. B. 1990. Dispersal of conidia of *Zygophiala jamaicensis* in apple orchards. Plant Dis. 74:643-646.
43. Sutton, T. B., and Jones, A. L. 1976. Evaluation of four spore traps for monitoring discharge of ascospores of *Venturia inaequalis*. Phytopathology 66:453-456.
44. Sutton, T. B., and Unrath, C. R. 1984. Evaluation of the tree-row-volume concept with density adjustments in relation to spray deposits in apple orchards. Plant Dis. 68:480-482.
45. Sutton, T. B., and Unrath, C. R. 1988. Evaluation of the tree-row-volume model for full-season pesticide application on apples. Plant Dis. 72:629-632.
46. Szkolnik, M., and Gilpatrick, J. D. 1969. Apparent resistance of *Venturia inaequalis* to dodine in New York apple orchards. Plant Dis. Rep. 53:861-864.
47. Thomson, S. V., Hansen, D. R., Flint, K. M., and Vandenberg, J. D. 1992. Dissemination of bacteria antagonistic to *Erwinia amylovora* by honey bees. Plant Dis. 76:1052-1056.
48. Travis, J. W., Rajotte, E., Bankert, R., Hickey, K. D., Hull, L. A., Eby, V., Heinemann, P. H., Crassweller, R., McClure, J., Bowser, T., and Laughland, D. 1992. A working description of the Penn State apple orchard consultant, an expert system. Plant Dis. 76:545-554.
49. Vanneste, J. L., Yu, J., and Beer, S. V. 1992. Role of antibiotic production by *Erwinia herbicola* Eh252 in biological control of *Erwinia amylovora*. J. Bacteriol. 174:2785-2796.
50. Wilcox, W. F., Wasson, D. I., and Kovach, J. 1992. Development and evaluation of an integrated, reduced-spray program using sterol demethylation inhibitor fungicides for control of primary apple scab. Plant Dis. 76:669-677.
51. Wilson, M., and Lindow, S. E. 1993. Interactions between the biological control agent *Pseudomonas fluorescens* A506 and *Erwinia amylovora* in pear blossoms. Phytopathology 83:117-123.
52. Yoder, K. S., and Hickey, K. D. 1981. Sterol inhibiting fungicides for control of certain diseases of apple in the Cumberland-Shenandoah region. Plant Dis. 65:998-1001.
53. Young, C. S., and Andrews, J. H. 1993. Inhibition of pseudothecial development of *Venturia inaequalis* by the basidiomycete *Athelia bombacina* in apple leaf litter. Phytopathology 80:536-542.