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Assessing new methods of integrated pest management for apple orchards in the Midwest and phenology of sooty blotch and flyspeck fungi on apples in Iowa

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Assessing new methods of integrated pest management for apple orchards in the Midwest and

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This thesis is dedicated to those I love dearly: Jen, Pa, Ma, Jake, Andy, & Grams.

TABLE OF CONTENTS

CHAPTER 1. GENERAL INTRODUCTION

THESIS ORGANIZATION

This thesis consists of four chapters. The first chapter provides background information about the development of apple pest management strategies and the ecology of sooty blotch and flyspeck fungi and states the research justification and objectives. The second chapter, a manuscript in preparation for *Plant Disease*, describes the timing of appearance of sooty blotch and flyspeck signs and development of associated fungi of the disease complex. The third chapter, a manuscript in preparation for *HortTechnology*, describes the development of integrated pest management strategies for disease-resistant, fully-dwarfed apple trees. The final chapter provides a summary of the research and general conclusions.

LITERATURE REVIEW

Apple (*Malus* x *domestica* Borkh.) production in the Midwest requires intensive pest management systems in order to produce acceptable yields of fresh-market-quality fruit. Current pesticide-intensive management practices pose substantial risks due to rising input costs, growing pesticide resistance, human health hazards, environmental degradation, and increasing government restriction on pesticide use. Because of these limitations, new methods of pest control are needed to achieve sustainability in apple production.

Several important apple pests pose problems for growers in the Midwest including codling moth, apple scab, sooty blotch and flyspeck (SBFS), and weeds. New techniques for managing these key pests must meet several criteria in order to be adopted by growers:

acceptable pest control, applicator and consumer safety, minimal environmental impact, ease of use, and affordability.

The apple disease complex known as SBFS is comprised of many species whose ecology is poorly understood. A better understanding of this diverse disease complex is a necessity as component species can respond differentially to climate, fungicides, reservoir hosts, and geographic location.

Apple pest management in the Midwest

In the Midwest, conventional management of apple pests is generally achieved by the application of chemical pesticides on a calendar-based schedule. Diseases and insect pests are controlled with synthetic chemical fungicides and insecticides applied at 7- to 10-day intervals from green tip until petal fall, and at 10- to 14-day intervals after fruit set (18, 38, 39, 40). Weeds are often controlled by sprays of synthetic chemical herbicides in strips beneath the orchard canopy (105). As a result, apples are among the most pesticide-intensive fruit crops grown in the United States, requiring 12 to 20 applications of insecticides, fungicides, and herbicides per growing season (33, 42, 68, 69, 71, 105).

Conventional pesticides used in apple production can result in toxic pesticide residues on apples, increasing resistance of pest organisms, and outbreaks of secondary pests (62). As knowledge about the health risks and environmental degradation linked with agricultural chemical inputs increases, concerns are rising over the risks associated with these practices (61). Many widely used fungicides such as mancozeb, chlorothalonil, and captan are suspected cancer-causing agents (84). Organophosphates, a class of insecticides widely used in apple production, can also endanger human health (76, 90).

Sustainable agriculture requires pest management strategies which are holistic in nature (21), encompassing many tactics. On the other hand, growers adopting new strategies prefer those that cause minimal disturbance to existing production schemes (84). Regardless, orchard management costs must be minimized, since the profit margin for fresh apples is narrow (84) and competition from other apple-growing regions around the world continues to increase (1).

Integrated pest management tactics

Integrated pest management (IPM) is a multidisciplinary strategy for pest control that seeks to achieve long-term effectiveness, affordability, and minimal environmental disruption (34). IPM tactics include genetic resistance, cultural controls, chemical application, and biological controls. Used in conjunction, these methods are more likely to be effective at controlling pests than reliance on a single technique, such as calendar-based pesticide spraying (2, 89, 98), and may also reduce development of pesticide resistance.

Implementation of IPM strategies has reduced the quantity of pesticides applied while controlling pest organisms acceptably (62). Despite many IPM success stories, however, some growers are reluctant to adopt integrated approaches to fruit management. A perceived risk is associated with the adoption of new technologies; loss of marketable yield due to an ineffective management strategy can far outweigh any benefits of saved sprays (14, 29). IPM programs can also be information intensive, requiring the grower to learn new technologies and management strategies. This can act as a deterrent to growers who are already very busy managing other aspects of their operations (2, 98). Furthermore, not all new technologies are beneficial to the bottom line (84). To be acceptable, however, an effective IPM program must not only control pest organisms, but also be cost-effective.

Partial budgeting, an economic tool used to determine costs from among differing management strategies while holding many crop production practices constant, has proven to be useful for comparisons of standard pest management and IPM programs (98). The use of partial budgeting to estimate changes in costs and revenues from various pest management options can be used to inform decisions about adoption of new techniques.

Apple scab management

Apple scab, caused by the ascomycete fungus *Venturia inaequalis* (Cooke) G. Wint., is the most economically damaging pathogen in humid apple-producing regions worldwide (63). Fungicides for scab management can comprise more than 10% of total production expenditures (92). The scab fungus overwinters on fallen leaves in the orchard; ascospores produced in these leaves are primary inoculum for leaf and fruit infections in the spring. Conidia produced on living leaves re-infect host tissues throughout the season (31). The conventional method of control is to apply fungicides at 7- to 10-day intervals from green tip through the petal fall stage (31, 33).

IPM programs for scab control usually focus on reduction of primary inoculum levels, or reducing fungicide sprays using predictive models to determine disease onset, or both. One of the first methods of predicting scab risk was proposed by Mills (74). Duration of wet periods and air temperature during at-risk periods were used as determinants of disease risk. Mills summarized these data into a chart, referred to as the Mills table. This technique allowed apple growers to apply fungicides when they would be most useful for scab management, as opposed to standard protectant sprays applied by the calendar. The Mills table has undergone continuous modification since its conception (56, 64), and some growers use it to predict when fungicide spray applications are needed.

A related, subsequent scab management strategy which reduced fungicide use was the integrated, reduced-spray program developed in New York (104). This program paired sterol demethylation inhibitor (DMI) fungicide sprays with insecticide and acaricide applications and used the phenological stages of tree development to help determine application interval. A key insight in this program was that, in orchards that experienced excellent scab control the preceding year, overwintering inoculum levels were so low that the initial fungicide spray of the season could be delayed until tight cluster. This saved two early-season sprays. This management tactic was tested in Iowa and was found to save an average of three sprays annually, while providing excellent disease control (41).

Although the NY reduced-spray program was widely adopted by growers, development of resistance to DMI fungicides turned out to be a serious flaw in the program. Scab resistance to DMI fungicides appeared during the early 1990s in orchards in New York (57, 58) and in Germany (59). The development of DMI resistance was more rapid when the NY reduced-spray program was used, effectively ending the program as a viable strategy (84). Pathogen resistance to the current classes of scab control fungicides has created an urgent need for alternative methods of scab management (69).

Studies from Vermont and New Hampshire suggested that fungicide sprays for scab management could be delayed until the pink stage of phenological development if predicted ascospore counts were at sufficiently low levels. Ascospores were estimated from the number of scab infected leaves monitored during the preceding fall and were used to determine an action threshold by which sprays are either delayed or carried out on a normal schedule the following spring (15). The researchers found that delayed spraying based on autumn ascospore estimates managed scab effectively, even in weather conditions which promoted scab development. In New Zealand, however, research indicated that there may be little incentive for growers to reduce fungicide applications because the cost of chemicals is relatively small when compared to increased harvest and grading costs associated with higher levels of scab infection which may occur in plots where scab was managed using reduced-spray programs (14).

Cultural techniques to reduce disease levels through elimination of primary inoculum, which include removal or destruction of leaves on the orchard floor, have had some success. In New Hampshire, flail mowing or application of urea fertilizer in November and April were used to destroy leaf litter and the scab psuedothecia they contained. These methods achieved reductions in scab risk by 80-90% and 50-66%, respectively (95). These inoculum reduction practices may be expensive and impractical for some commercial operations, and can never fully eradicate all sources of primary inoculum (69).

Scab-resistant apple cultivars

A strategy which can minimize the use of fungicides and reduce the need for weather monitoring is the use of scab-resistant apple cultivars (33, 69). Although many scab-resistant apple cultivars are commercially available, none are widely planted (63). Cultivars with scab resistance incorporate several dominant resistance genes, most of which are located at the V*f* locus of the apple genome. Genetic resistance to the apple scab pathogen was originally found in a crabapple, *Malus floribunda* 821, which was subsequently crossed with the commercial apple cultivar Rome Beauty in the 1950s. Several apple scab resistance breeding programs in North America incorporated acceptable yield and palatable fruit with the genetic resistance of *M. floribunda 821* (69). A number of scab-resistant cultivars are also resistant to other diseases, including cedar apple rust (caused by *Gymnosporangium juniperi-virginianae* Schw.), fire blight (caused by the bacterium *Erwinia amylovora* (Burrill) Winslow), and powdery mildew (caused by *Podosphaera leucotricha* (Ell. And Evherh.), which can make them even more appealing to growers (31, 33).

Apples from scab-resistant cultivars are not widely accepted by U.S. consumers due to their unfamiliarity with them and their loyalty to traditional varieties (69). Nevertheless, in consumer taste tests conducted in Vermont, several scab-resistant cultivars scored highly in aroma, texture, appearance, sweetness, and taste, and consumers surveyed reported a willingness to purchase these fruit (24). In a report from Iowa, scab-resistant cultivars Redfree, Goldrush, and Liberty all received high rankings during yield and quality evaluations, suggesting that they may have potential for commercial production (42).

A potential complication of integration of disease-resistant apple cultivars is persistence of other diseases when traditional scab fungicide sprays are eliminated. One example is the sooty blotch and flyspeck complex, a group of fungi that cause blotches and spots on the cuticle of apple fruits (103). This disease, along with others, will require at least some post-petal-fall fungicide applications to maintain marketable fruit, even on scab-resistant cultivars (33, 69, 85, 86).

Codling moth management

Codling moth (*Cydia pomonella,* Linnaeus) is one of the most serious insect pests of apple worldwide (9, 35, 99). Consumer tolerance of codling moth is low: one damaged apple out of 100 is commonly considered unacceptable (10).

In the spring, codling moth adults emerge from cocoons in and around apple orchards. Adults mate within a few days and lay eggs on the surface of fruit. Upon hatching, codling moth larvae burrow through the peel, generally entering at the calyx, and tunnel into the flesh of the fruit. Eventually the larvae emerge, drop to the orchard floor, and search out places to spin a cocoon, pupate, and finally reach the adult stage (60). Codling moth development is dictated by several factors, including geography and weather conditions at a particular location (52).

Traditional codling moth management can take the form of calendar- or phenology-based insecticide sprays such as organophosphates. Apple producers have used organophosphate insecticides since the mid-1960s. In recent years, however, declining effectiveness, new U.S. Environmental Protection Agency restrictions, and an increased knowledge of environmental toxicity have sharply restricted the use of organophosphate insecticides for codling moth control (4, 20, 40, 60, 98). Organophosphates are non-selective insecticides and will kill natural enemies of insect pests as well as target organisms (20, 25, 35). Also, codling moth resistance to the organophosphate azinphos-methyl has been observed in Missouri orchards (23).

IPM programs have attempted to minimize reliance on conventional insecticides and search out other techniques of codling moth management. An alternative to spraying organophosphates every 10 to 14 days is to base spray timing on insect development indicators such as degree days (DD) and pheromone trap captures (25, 40, 43, 49, 79).

Glenn (44) first introduced the DD concept as a way to track codling moth development. The DD is an accumulation of thermal units corresponding to insect growth. A first step in determining DDs is to take the sum of the daily maximum and daily minimum temperatures and divide by two. The base temperature, 10° C, is subtracted from the result and the outcome is summed daily. Because temperature is one of the most important factors in codling moth development, this daily summation of DDs has been widely used to determine when codling moth egg hatch, larval activity, and subsequent generations are likely to occur (44, 83).

Biofix, the date of first sustained capture of adult moths, for codling moth is determined when three to five male codling moths are caught weekly in pheromone traps. Insecticide applications based on trap captures and DDs can significantly reduce the number of sprays needed for codling moth management (82). Important thresholds which signal sprays correspond with the emergence of codling moth larvae from eggs. This occurs at 250 DD for the first generation and 1250 DD for the second generation (10).

An integrated approach to codling moth control can help to manage insecticide resistance. Scouting and weather monitoring can be used to discern key emergence times for precision pesticide applications. Reduced-risk organophosphate alternatives such as neonicotinyl insecticides can be utilized. Other integrated methods include sanitation, biological pesticides, natural enemies, pheromone-based mating disruption, and insect growth regulators (10, 19, 22, 25, 31, 40, 60).

Codling moth granulovirus

Codling moth granulovirus (CpGV) has shown promise as a useful tool for codling moth control (35, 60). Because CpGVs are extremely selective and have no re-entry or pre-harvest restrictions, they are useful as biological control agents (60). An additional advantage is that CpGV can be applied to apple fruit using conventional spray application methods. Codling moth larvae must ingest CpGV for infection to occur. Once inside the host organism, the virus multiplies and infects body tissues, killing the host in five to 10 days (4). This delay can allow continued feeding on an infected host, however, which can produce scars on the surface of the fruit.

Several formulations of CpGV are commercially available. When used alone, these commercial formulations decreased live larvae numbers as well as adult trap captures during successive generations at test sites and commercial orchards in the Pacific Northwest (4).

Weekly applications of CpGV are recommended for adequate insect control (40). As with all insecticides, growers using CpGV should integrate it with other insecticides and cultural forms of pest control to avoid risk of resistance development (5, 6, 102). In Washington, the virus was combined with applications of the organic insecticide spinosad in pear and apple orchards. Spinosad reduced codling moth damage at harvest when compared to stand-alone use of the CpGV, and using both decreased fruit damage at harvest and reduced trap captures in subsequent seasons (5). In Europe, granulovirus products are used alongside conventional chemicals, usually as a management technique for second-generation codling moth in areas where codling moth pressure is not as high as during the primary generation. However, populations of codling moth in organic orchards in both the U.S. and Europe have developed resistance to CpGV (6, 102).

Weed management

Weeds and other flora compete with apple trees for nutrients and water, especially in newly established orchards (100). A weed-free area beneath the tree row of young orchards can serve to bring the trees into production more rapidly (73). Weed competition can become less important as trees mature and vegetative growth diminishes later in the summer (70). In the northeastern U.S., for example, the period from May to mid-July was found to be critical for resource competition between developing trees and understory weeds (66, 70).

In apple orchards in the eastern half of the U.S., understory vegetation is managed in several ways. A common method is to maintain the tree-row understory free of weeds by calendar-based application of pre- or post-emergence chemical herbicides (66). This method is relatively inexpensive and resource competition is effectively decreased, but soil degradation and environmental toxicity may occur (65, 73).

Another method is to plant the area beneath the tree to turf grass or other cover crops and then mow or apply herbicides for broadleaf control as needed. This method minimizes soil degradation, but the turfgrass competes with the tree for water and nutrients (73). Of concern in orchards are grassy weed species, as fruit trees are particularly sensitive to competition posed by these weeds (53).

Other methods, including weed flaming, soil cultivation, biological control, and several different kinds of synthetic and natural mulches are available for orchard understory weed management (16, 50, 66, 72). Cultivation can pose problems for weed control because turning the soil can bring new weed seeds to the soil surface (77).

Mulch as a weed management strategy

Before the advent of chemical herbicides, mulching was a common way to control weeds and reduce resource competition in orchards (73). Weed seeds are prevented from germinating and growth of emerging seedlings is suppressed by covering the soil surface with mulch (17). Mulching in the orchard understory can have several additional positive impacts, including enhanced soil fertility and organic matter, conserved soil moisture, and increased tree growth (46, 47, 68).

Covering bare soils with mulch and increasing organic matter can also enhance populations of beneficial insects, nematodes, and bacteria (3, 32, 37, 46). High daytime soil temperatures can be detrimental to soil-dwelling beneficial predators of insect pests, and soil-covering residues such as mulch can mitigate temperature and moisture extremes (3). In order for mulches composed of organic matter to be most effective, they must be in place before the germination of weed seeds, and must be at least 10 to 15 cm deep (53).

There are also drawbacks to using mulch as a weed suppressant. Some types of mulch can offer cover for rodents, provide disease-conducive conditions, and be expensive to apply and maintain (67, 72). As mulch made of organic matter decomposes, it can tie up soil nitrogen, making it unavailable to trees (53). Another downside is that, when perennial weeds appear, they cannot be managed effectively by using mulches (17, 50).

In a high-density orchard in British Columbia, Canada, mulching increased growth and yield of trees after five years in a newly established orchard, despite daily irrigation and yearly fertigation of all groundcover treatments (75). Mulches, including shredded office paper, shredded office paper amended with biosolids, alfalfa straw, and black plastic mulch, were compared to an herbicide-treated, bare-soil check. The researchers suggested that differences in growth were attributable to an increase in water conservation and subsequent decrease in water stress of trees with mulch groundcovers. Another Canadian study examined the effects of mulching, cultivation, and permanent vegetative groundcover on soils in an organic, dwarfing-rootstock, scab-resistant orchard. It was concluded that straw and geotextile (landscaping fabric) mulches were superior to cultivation and cover crops because they increased soil water content, soil aggregate stability, and tree growth (101). In a New York soil study comparing sod, mulch, and pre- and post-emergence herbicide applications to herbicide-treated tree rows, organic hardwood bark-chip mulch reduced nitrogen losses, increased organic matter, and sustained excellent fruit yields compared to several other treatments (67).

In New York, hardwood bark mulch significantly improved availability of calcium and potassium, and increased soil pH, organic matter, and cation exchange capacity of an apple orchard understory after 12 years (105). Merwin et al. (72), based on results of a New York groundcover management study, suggested that added benefits of wood chips or shredded bark mulches can compensate for their higher establishment and maintenance costs compared to an herbicide-treated orchard understory.

Sooty blotch and flyspeck management

Sooty blotch and flyspeck (SBFS) is one of the most prevalent late-season apple diseases worldwide in production regions with warm, moist summers (96). This disease complex is comprised of over 70 putative species of fungi (13, 28). Fungi in the SBFS complex colonize the epicuticular wax layer of the apple fruit and produce dark brown to black blotches traditionally referred to as sooty blotch, as well as groups of tiny black specks traditionally referred to as flyspeck. Collectively, the fungi causing sooty blotch or flyspeck signs are generally characterized by grouping them into one disease complex abbreviated as SBFS in the current literature (12, 13, 29, 30).

Consumers are often unwilling to purchase apples blemished by SBFS, resulting in fruit which are no longer viable for fresh market sale. This downgrading of fruit can result in substantial economic losses for a grower (86, 103).

Management of SBFS combines cultural methods and the application of fungicides. Cultural controls include pruning (27) in order to promote rapid drying of the canopy, thereby enhancing spray penetration and creating a less favorable environment for disease development. Locating orchards on elevated sites can also speed drying (26). Fungicides have been used since the late 1800s to manage SBFS (26). Currently, benzimidazole, strobilurin, and pthalimide fungicides are used in combination with ziram or captan on a 10-to- 14-day interval starting 7 to 10 days after petal fall and continuing until harvest (40). This can result in four to eight sprays annually, depending on cultivar maturity date (40, 96, 103).

SBFS weather-based warning systems

Using information gathered by weather monitoring equipment, a grower can establish a time when a fungicide application for SBFS management will be of most use, instead of pre-emptive applications which can be costly, wasteful, and time consuming (18). These warning systems can help to achieve sustainability in orchard pest control systems by lowering pesticide inputs (7) and reducing fuel consumption.

A SBFS warning system developed in North Carolina by Brown and Sutton (18) utilized leaf wetness duration (LWD) recorded by mechanical wetness sensors. A threshold sum of 270 hours of LWD, including only periods with ≥4 hours of consecutive wet hours, was found to be most useful for determining when SBFS would appear on apples. Summing of LWD hours was initiated by the first rain occurring at least 10 days after petal fall (18). When this warning system was modified in Kentucky using electronic LWD sensors, the threshold sum of LWD required for the most effective application timing of the second-cover spray fungicides was 175 hours after the first-cover spray (51, 91).

Field trials in the Midwest using the 175-hour LWD model for SBFS have shown promise. In a three-state study, SBFS control using this model did not differ significantly from calendar-based spray applications in 11 of 12 site years in university research orchards and saved up to four sprays per season. In cooperator orchards, however, use of the warning system resulted in higher incidence of SBFS than in conventionally sprayed plots in 12 of 28 site-years (7). This result suggested that the LWD warning system developed in NC and KY needed to be modified for adaptation to environmental conditions found in the Midwest.

In field observations in IA and WI, Duttweiler et al. (29) found that cumulative hours of relative humidity ≥97% were a more accurate indicator of the timing of appearance of SBFS signs than cumulative LWD. Duttweiler's model predicted disease incidence with higher accuracy than models based on LWD, temperature, rainfall, or combinations of these variables.

Sooty blotch and flyspeck etiology, phenology, and identification

SBFS etiology

Most species in the SBFS complex have been identified only recently. Until the early 20th century, both sooty blotch and flyspeck were thought to be caused by a single species, *Dothidea pomigena* (88). Subsequently, Colby (26) separated sooty blotch and flyspeck, identifying the causal species as *Gloeodes pomigena* (Schwein.) Colby and *Schizothyrium pomi* (Mont. & Fr.) Arx., respectively.

Colby (26) noted a wide diversity of colony morphology types within sooty blotch; these were referred to as mycelial types. Groves (48) examined colony variations within *Gloeodes pomigena* and divided the mycelial types into four groups: punctate, ramose, fuliginous, and rimate. Several other researchers examined mycelial variation within *G. pomigena* in response to environment (8, 54). Nevertheless, sooty blotch continued to be described as caused by a single species.

Sutton and Sutton (94) characterized incidence and severity of mycelial types of sooty blotch at several orchards in North Carolina and observed that they responded differently to temperature, rainfall, and humidity. Severity and incidence of each type varied from one region to another; higher levels of the ramose mycelial type were associated with higher average temperature, whereas predominance of the punctate mycelial type coincided with cooler temperatures. Because distribution of SBFS mycelial types was associated with environmental conditions and geographic location, it was hypothesized that sooty blotch might include several different species.

This hypothesis was confirmed when Johnson et al. (55) described three new sooty blotch species: a ramose mycelial type, *Geastrumia polystigmatis* Batista and M.L. Farr; a fuliginuous mycelial type, *Leptodontium elatius* (G. Mangenot) de Hoog; and a punctate mycelial type, *Peltaster fructicola* E.M. Johnson et al. in North Carolina. They proposed that delineation of additional sooty blotch species was likely.

Flyspeck was once thought to have been caused by *Schizothyrium pomi* and its presumed anamorph *Zygophiala jamaicensis* (12). Isolates of flyspeck have been observed on various hosts and subsequently named for the host on which they were found. However, it has been revealed that these isolates were morphologically similar to *S. pomi* (12).

Flyspeck signs on apple in 14 U.S. states were recently discovered to include four separate species of *Zygophiala* (12). Parsimony analysis, backed by *in vitro* morphology and cultural characteristics, revealed three previously undescribed species.

Many new species are currently being added to the SBFS disease complex. Batzer et al. (13), using morphological descriptions combined with phylogenetic analysis of portions of ribosomal DNA, found 30 new putative species of SBFS in addition to the four which were previously described. Batzer described several new mycelial types: compact speck, discrete speck, and ridged honeycomb. Díaz Arias (28) determined that distribution of SBFS species varied regionally across 14 eastern and central U.S. states. It was hypothesized that species distribution within a region was influenced by climate, fungicide use, and nearby reservoir host species. It was also observed that mycelial growth of several clades of SBFS had differing sensitivity to fungicides *in vitro* (97).

SBFS phenology

The ecology of SBFS is poorly understood (30, 39, 103). Although the distribution of some species varies among regions, and environmental conditions play a large role in SBFS development, information about phenological patterns in the appearance of SBFS species on apples is needed. Phenology is the study of recurring sequential biological events, such as a plant's fruiting stages or a disease's development. There are many component species which compose the SBFS disease complex and it has been shown that not all the species behave in a like manner and some may be more important in one region than another (28, 94, 97).

Warning systems for SBFS could potentially be improved if patterns of species appearance over the course of a growing season were more clearly understood. When managing SBFS, the species appearing first on an apple becomes extremely important, because once an apple is blemished, it becomes unfit for fresh market sales. Other species might become especially important for management decision making later in the season, or even during cold storage of harvested apples.

SBFS identification

Identification of SBFS fungi using traditional mycological methods is challenging. Differentiating species by colony mycelial types on apple peels is usually not possible. When cultured, many SBFS fungi grow slowly, and are therefore readily overgrown by other fungi. Signs of a SBFS species produced *in vitro* may look completely different from signs of the same species on fruit. Fruiting structures and spores of SBFS fungi rarely develop on peels or in culture, further complicating traditional identification methods (11, 13, 48, 54). With recent advances in DNA-based fungal identification methods, however, genus and species identification can now be done much more quickly and accurately.

One such identification method uses restriction fragment length polymorphism (RFLP) of DNA products that were amplified by polymerase chain reaction. Sun et al. (93) used this technique to identify several primers that amplified 14 species and seven genera of the most common SBFS fungi. Primer specificity was obtained by pairing a Capnodiales order-specific reverse primer, Myc1-R, with a universal forward primer for fungi, ITS1-F. The amplified products were then digested using the restriction enzymes *Hae*III and *Alu*I. The resulting banding patterns on agarose gel can be used to determine genus or species of a particular isolate.

Duttweiler et al. (30) validated the use of this assay and further refined it by extracting fungal DNA directly from the colonies on apple peel, circumventing the need for time-consuming agar-plate isolation. This technique was applied to 24 known SBFS species in nine genera. Fourteen unique banding patterns were observed, and no genera shared the same pattern. Duttweiler and co-workers identified 60% of SBFS isolates from three Iowa orchards to the genus level. This technique, coupled with a RFLP banding pattern library, can provide a useful resource for rapid identification of some SBFS species and genera. Researchers who wish to identify genera or species of SBFS for ecological or management studies can now do so much more quickly.

THESIS OBJECTIVES

The research presented here had two objectives. The first objective was to evaluate new combinations of integrated pest management strategies for apple pests – scab, codling moth, the sooty blotch and flyspeck fungal complex, and weeds in an orchard of scab-resistant cultivars. The second objective was to determine the timing of appearance of species of sooty blotch and flyspeck fungi on apples in Iowa orchards.

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CHAPTER 2. PHENOLOGY OF SOOTY BLOTCH AND FLYSPECK FUNGI ON APPLES IN IOWA

A manuscript in preparation for submission to *Plant Disease*

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ABSTRACT

Sooty blotch and flyspeck (SBFS) is a complex of >60 fungal species that blemish the surface of apple fruit in humid regions worldwide. Blemishes become visible in mid-to late summer, reducing the value of fresh fruit. To test the hypothesis that SBFS species appear on apples at characteristic times during the growing season, 22-37 apples were monitored weekly for appearance of SBFS colonies at each of three Iowa orchards in 2006 and seven orchards in 2007. Colonies were marked with colored pens to denote the date of appearance. After harvest and storage of apples at 4° C for 3 months, SBFS colonies on each fruit were counted and classified by morphology, and a representative subset of colonies with subtending peel was removed and pressed. Fungal DNA, extracted from colonies scraped from the surface of the peel, was amplified with primer pair ITS1-F/ Myc1-R. Polymerase chain reaction products were digested with *Hae*III, and fragment patterns were observed with gel electrophoresis and compared to a library of previously identified SBFS species. Colonies that could not be identified using band patterns were sequenced and compared to other species using BLAST. Sterile mycelia spp. RS1 and RS2 were the first to appear in all but one of the Iowa orchards surveyed where SBFS signs were observed. *Dissoconium aciculare* consistently appeared on fruit during the week prior to harvest, and additional colonies of this species appeared during storage. The species that were most prevalent in Iowa orchards were also the most abundant. Knowledge of species prevalence and chronology of appearance on apple fruit could lead to improved SBFS management strategies.

Additional keywords: Capnodiales, fungal diversity, restriction fragment length polymorphism

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INTRODUCTION

Sooty blotch and flyspeck (SBFS) fungi blemish apple (*Malus* x *domestica* Borkh.) and pear (*Pyrus communis* L.) fruit in humid climates worldwide (23). Signs of SBFS fungi commonly appear during the latter part of the fruit maturation period. Because apples with SBFS blemishes are generally unsuitable for fresh-market sale, substantial economic losses can occur when fruit are downgraded to processing use (4, 19, 25).

Before the early 20th century, SBFS was thought to be caused by a single pathogen, *Dothidea pomigena* (Schwein.). Colby (7) described separate species as the causal agents of sooty blotch (*Gloeodes pomigena* (Schwein.) Colby) and flyspeck (*Schizothyrium pomi* (Mont. & Fr.) Arx.). Colby also noted a range of colony morphology types within *G.*

pomigena and referred to them as mycelial types. Groves (13) further divided the mycelial types of *G. pomigena* into fuliginous, punctate, ramose, and rimate. These differences in morphology were attributed to variations in environment rather than SBFS genetics (17). In 1997, Johnson et al. (18) described three new sooty blotch species in North Carolina: *Geastrumia polystigmatis* Batista and M.L. Farr; *Leptodontidium elatius* (G. Mangenot) de Hoog; and *Peltaster fructicola* E.M. Johnson et al. Recent surveys of 39 orchards in the eastern half of the United States, coupling genetic analysis with morphological characterization, revealed that >60 species cause SBFS on apple (2, 3, 9).

Many SBFS component species and genera can be identified quickly utilizing a polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) technique (11, 21). In contrast to the several months required to isolate and purify SBFS isolates before DNA extraction, amplification, sequencing, and sequence analysis, the PCR-RFLP method requires only hours to identify an isolate to the species or genus level, and has a much higher percentage of positive identifications than traditional methods that require isolation in pure culture (11).

Environmental biology of the SBFS complex is poorly understood (3, 25). Díaz Arias (8) presented evidence indicating that composition of the SBFS assemblage may differ according to geographic region and fungicide use. In the Southeast U.S., signs of SBFS species were noted to appear at characteristic times during a growing season, but species in that study were not identified conclusively (22).

Determining the timing of appearance of SBFS species in a particular region may pave the way for development of more cost-effective management factors by placing the focus of management on key SBFS species. The objective of this study was to determine phenology of SBFS species in Iowa apple orchards.

MATERIALS AND METHODS

Locations. In 2006, three orchards were monitored near Gilbert (42°06'N 93°35'W), Cambridge (41°52'N 93°28'W), and Fort Dodge (42°33'N 94°11'W), Iowa (IA). In 2007, four orchards were added near Jefferson (41°59'N 94°24'W), Iowa Falls (42°31'N 93°12'W), Pella (41°40'N 92°87'W), and Nevada (41°55'N 93°27'W), IA. A monitoring plot in each orchard consisted of a block of five to 15 trees located in one to three adjacent rows. Trees were cv. Golden Delicious, except that cv. Liberty was monitored at Iowa Falls in 2007 and cv. Honeygold at Fort Dodge in 2006. In order to facilitate SBFS development, no fungicides were applied after petal fall, but conventional insecticide-spray schedules (12) were maintained throughout the season.

Data collection. Beginning in mid-July, apples in each test block were inspected weekly for the presence of SBFS signs. When colonies first appeared in each orchard, 30 to 45 apples displaying signs were arbitrarily selected; each was marked with red flagging tape attached to an adjacent spur so that it could be found easily. Newly appearing colonies on these apples were marked with a ball-point pen using different colors or shapes each week. After harvest, marked apples were placed in plastic fruit storage bags and stored at 4° C for 3 months.

Colony characterization. Using a dissecting microscope, SBFS colonies on 22 to 37 apples per orchard were classified by mycelial type (33) and the number of colonies of each type was recorded. Representative colonies were excised from the fruit along with the subtending peel. On most apples, a few colonies of the most commonly occurring mycelial types were collected, as well as all colonies of less common or unique mycelial types. All colonies selected for analysis were visually separate from other colonies on the fruit in order to minimize contamination by multiple isolates. Excised colonies were labeled according to mycelial type, origin, and date of appearance, then pressed between paper towels until dry. Dried peels were photographed and stored at room temperature in individual wells of 24-well culture plates for up to 4 weeks.

DNA extraction. Fungal DNA was extracted from peels into tubes containing 50 µl Prepman Ultra Sample Preparation Reagent (Applied Biosystems, Foster City, CA), vortexed, and placed in a thermocycler (Model PCT-100, MJ Research Inc., Waltham, MA) (11). Microcentrifuge tubes with DNA and Prepman Ultra were then centrifuged at 13,000 rpm for 10 sec. Both precipitate and liquid were retained and tubes were stored at -20° C until amplification.

Polymerase chain reaction and restriction enzyme digestion. After samples of DNA were amplified with polymerase chain reaction (PCR) using Capnodiales-specific primers ITS1-F/Myc-1R (21), restriction fragment length polymorphism (RFLP) was performed using *Hae*III endonuclease and product was observed on agarose gel (11). If isolates failed to amplify using PCR on the first attempt, 5% DMSO was added to the PCR master mix, or a 10-fold dilution was applied to the DNA extract. If either the addition of DMSO or dilution failed to work, they were attempted simultaneously. If samples still did not amplify, the amount of SBFS isolate DNA used during amplification (2 µl) was doubled and re-assayed in a 50-µl reaction mixture.

Purification and sequencing. When restriction digest gel patterns did not match those of previously identified SBFS fungi (11), sample DNA was purified, then sequenced at the DNA Sequencing and Synthesis Facility of Iowa State University using primers ITS1-F/Myc-1R. As a quality control measure, several DNA samples from confirmed isolates of species RS1 and RS2 were also purified and submitted for sequencing, confirming identification of isolates from these species. After Sequence Navigator (Applied Biosystems, Foster City, CA) was used to edit the sequences, they were compared with known SBFS and non-SBFS species using BLAST (NCBI, Bethesda, MD). Sequences were aligned with all similar sequences obtained from SBFS surveys conducted in 2000 and 2005 (3, 8). Phylogenetic analysis using PAUP (Sinauer Associates, Inc. Publishing, Sunderland, MA) was used to detect new SBFS species.

Data analysis. The number of sampled colonies of each taxon was estimated by extrapolating species or genus identifications of colony DNA subsamples to the mycelial type associated with each subsample, under the assumption that each species produced a single characteristic mycelial type (3). Time of appearance of each taxon was then determined by averaging the estimated number of newly appearing colonies over the number of apples sampled at each location for each observation date. To test the hypothesis that the prevalence of SBFS taxa was correlated with its incidence, Spearman's rank correlation was used to analyze data. SBFS incidence was calculated as the mean number of colonies per apple, prevalence was calculated as the number of orchards where SBFS taxa appeared.

RESULTS

The Sun-Duttweiler PCR-RFLP technique (11) identified 86% of colonies sampled in 2006, and 65% in 2007, to either genus or species (Table 1). The primer pair ITS1-F/MYC1-R amplified 92% and 85% of DNA samples in 2006 and 2007, respectively. Non-SBFS

Cladosporium spp. were detected in 0 and 2% of the 2006 and 2007 samples, respectively, and 2% of the PCR products were not cut by *Hae*III.

Several SBFS species appeared in a characteristic sequence during both growing seasons (Figures 1 and 2). The majority of first-appearing signs were sterile mycelia spp. RS1 and RS2 at all three 2006 locations and five of six locations in 2007 (Table 2). At one location in 2007, *Schizothyrium pomi* was the first species to appear. Sterile mycelia spp. RS1 and RS2 continued to appear in greater numbers than other colony types until harvest, whereas *Dissoconium aciculare* colonies increased in abundance during cold storage (Figures 1 and 2).

Sterile mycelia spp. RS1 and RS2 could be distinguished from each other using the PCR-RFLP method, but not by using morphological characteristics on the peel, since signs of the two putative species were visually identical in appearance; therefore, separate numerical estimates of putative species RS1 and RS2 were not possible. Several other groupings of closely related putative species could not be distinguished from one another using the molecular tools used in this study, including *Xenostigmina* spp. P3 and P4, and *Pseudocercosporella* spp. (Table 3); therefore, these species were grouped in the phenology assessment.

Sterile mycelia spp. RS1 and RS2 were most prevalent and were present at all locations where SBFS was found, whereas *Ramularia* sp. P5 and several *Peltaster* spp. appeared in only a few orchards (Table 3). Sterile mycelia spp. RS1 and RS2 also had the highest incidence, with an estimated average of nearly 13 colonies per apple (Figure 3). *Dissoconium aciculare*, the next most prevalent species, was present at nine locations with an average incidence of seven colonies per apple. Other species, such as *Peltaster* spp. and

Zygophiala wisconsinensis, were detected at only one or two locations and averaged less than one colony per fruit. Species prevalence was directly proportional to incidence (Spearman's rank correlation coefficient $p<0.005$, $r=0.85$).

DISCUSSION

These findings are the first evidence that species in the SBFS complex become visible on fruit at characteristic times during the growing season. In addition, this research is the first to demonstrate that the most prevalent SBFS species on apples also have the highest incidence. If borne out by surveys in additional orchards and years, it may be possible to anticipate which SBFS species appear first and most abundantly on apples, and therefore may be particularly important in loss of fresh-market value due to blemishing. In Iowa, sterile mycelia spp. RS1 and RS2 may be the most important SBFS species to manage since they were generally the first to appear and were the most abundant in all orchards surveyed.

Such insights could focus epidemiological studies on the most prevalent early-appearing species, potentially yielding new insights that could improve the efficiency of SBFS management. For example, the Brown-Sutton-Hartman warning system advises timing of a fungicide spray shortly before the first SBFS signs appear (5, 6, 14, 15, 20). Therefore, the first-appearing SBFS species may be the most important for refining such warning systems. The fact that the geographic range of RS1 and RS2 is restricted to the Midwest (2, 8), and that these species are apparently most prevalent, abundant, and early-appearing in Iowa orchards, may suggest an explanation for occasional failures of the Brown-Sutton-Hartman warning system that have occurred in the Midwest (1). This warning system was initially validated in North Carolina and Kentucky, where the SBFS complex is dominated by different species (8). If the environmental biology of the predominant SBFS species in the

Southeast U.S. differs markedly from that of RS1 and RS2, it could explain why the warning system failed to perform consistently in the Midwest. However, comparison of the environmental biology of the predominant Southwest U.S. species with that of RS1 and RS2 is needed to evaluate this hypothesis.

Revealing the prevalence and incidence of SBFS species in orchards may also have implications for selection of fungicides. Tarnowski et al. (24) showed that species in the SBFS complex had >10-fold differences in sensitivity to thiophanate-methyl, a widely used fungicide against SBFS. If the most prevalent and abundant SBFS species in each region differ markedly in sensitivity to fungicides, determining these important species could influence fungicide selection and enhance the efficacy of fungicide sprays.

Species of SBFS appearing towards the end of the season may be important from a management perspective as well. Although fruit had probably been inoculated prior to harvest, *Dissoconium aciculare* developed visible signs on fruit during storage despite cold temperatures (4° C) (Figures 1 and 2). Hernández (16) found that *D. aciculare* mycelium grew relatively rapidly on water agar while incubated at 10° C for 7 weeks, whereas growth of other SBFS species was sharply curtailed at this temperature. As a low-temperature-tolerant species, *D. aciculare* could proliferate on apples stored at 4° C, even when relatively few or no colonies of this species are evident at harvest. Consequently, previously umblemished apples could exhibit *D. aciculare* signs upon removal from storage, causing unforeseen economic loss.

Although the present study demonstrated the value of the Sun-Duttweiler PCR-RFLP method for ecological studies of SBFS, several limitations were also noted. Several of the RFLP banding patterns from colonies sampled in the present study did not match any of the existing library of 14 banding patterns (11). These new patterns were assumed to indicate either newly discovered SBFS fungi or non-SBFS fungi which amplify with the ITS1-F/Myc1-R primer set. The discriminatory power of the method could potentially be enhanced by adding to the library, and by using additional primers (21) and restriction enzymes.

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Table 1. Amplification products of primers ITS1-F/Myc1-R and *Hae*III restriction fragment length polymorphism (RFLP) analysis of DNA samples from SBFS colonies on apples in 2006 and 2007.

	2006		2007	
Results	**No. of colonies**[x]	**% of colonies**	**No. of colonies**[y]	**% of colonies**
PCR product	149	92	481	85
RFLP patterns matching previously identified SBFS	140	86	367	65
New RFLP patterns[z]	6	4	92	16
RFLP patterns matching *Cladosporium* bands	0	0	10	2
Product not cut by *Hae*III	3	2	12	2

[x] Colony total was 162
[y] Colony total was 564
[z] RFLP patterns which did not match previously identified (11) SBFS species or *Cladosporium* bands

Table 2. Date of first appearance of the most abundant species associated with the first-appearing SBFS signs at orchards in Iowa in 2006 and 2007.

Location	Date of First Appearance	Putative Species[y]
2006		
Gilbert	21 Aug	Sterile mycelia spp. RS1/RS2
Fort Dodge	25 Aug	Sterile mycelia spp. RS1/RS2
Cambridge	24 Aug	Sterile mycelia spp. RS1/RS2
2007		
Gilbert	9 Aug	Sterile mycelia spp. RS1/RS2
Fort Dodge	N/A[z]	N/A
Cambridge	25 Aug	Sterile mycelia spp. RS1/RS2
Nevada	7 Aug	Sterile mycelia spp. RS1/RS2
Pella	16 Aug	Sterile mycelia spp. RS1/RS2
Iowa Falls	8 Aug	Sterile mycelia spp. RS1/RS2
Jefferson	14 Aug	*Schizothyrium pomi*

[y] At some locations, other SBFS signs were visible with sterile mycelia spp. RS1/RS2 at first appearance, but were present in relatively small numbers.

[z] No SBFS signs were observed in the test plot for the duration of the season.

Table 3. Total number of SBFS colonies by species and location in 2006 and 2007.

Location		*Schizothyrium pomi*	*Dissoconium aciculare*	Sterile mycelia spp. RS1/RS2[x]	*Pseudocercosporella* spp.[x]	*Colletogloeum* sp. FG2	*Xenostigmina* spp. P3/P4[x]	*Zygophiala wisconsinensis*	*Peltaster* sp. P2.4	*Peltaster fructicola*	*Peltaster* sp. P2.1	*Peltaster* spp. P2.1/2.2[x]	*Ramularia* sp. P5	Compact speck spp. CS1/CS2[x]	Unknown Punctates[y]
2006	Gilbert	77	594	500	107	85	130	0	0	0	0	9	1	47	60
	Cambridge	18	180	383	9	64	22	0	0	0	0	21	0	0	22
	Fort Dodge	54	71	604	83	111	53	0	0	0	0	0	44	47	0
2007[z]	Gilbert	11	56	244	34	18	12	0	0	0	0	0	0	0	0
	Cambridge	6	98	279	4	0	1	0	0	0	0	0	0	0	0
	Iowa Falls	22	56	142	52	20	4	2	0	0	0	4	0	0	7
	Nevada	175	312	660	192	111	88	1	4	91	2	2	3	0	0
	Jefferson	110	24	87	9	10	61	0	0	0	1	5	1	0	24
	Pella	100	267	230	84	90	75	0	0	4	0	3	0	0	31

[x] In 2006, no distinction could be made between species based on *Hae*III digests. Species belonging in this category were grouped.

[y] Colonies appearing as punctate mycelial types, but having RFLP patterns which did not match known SBFS species.

[z] In 2007, no signs of SBFS appeared on apples at Fort Dodge.

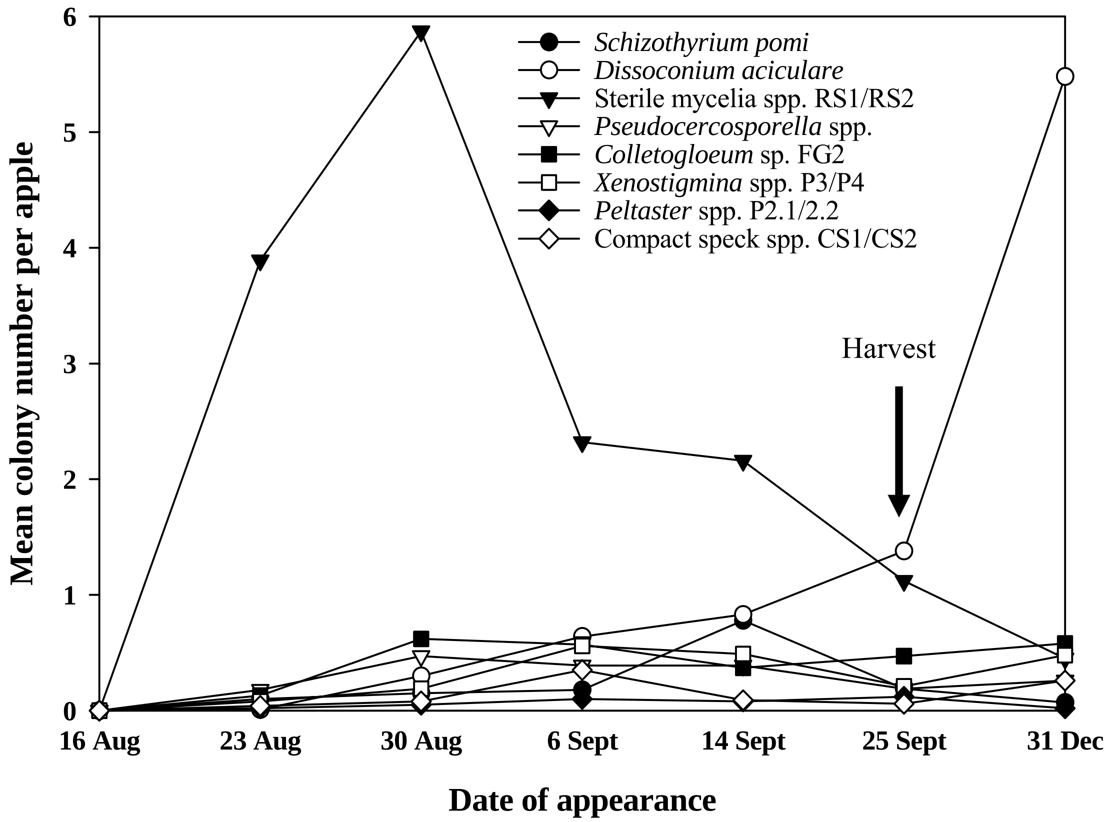

Figure 1. Mean number of newly appearing SBFS colonies per apple in 2006 from three Iowa orchards.

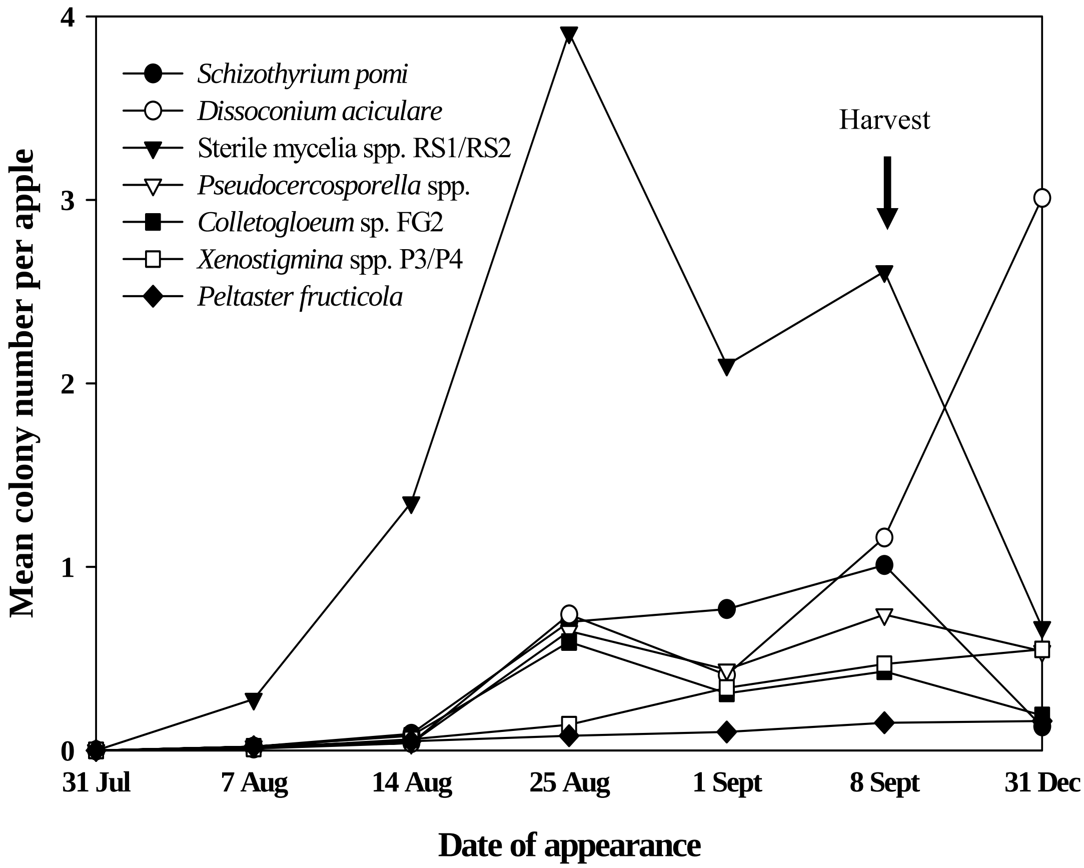

Figure 2. Mean number of newly appearing SBFS colonies per apple in 2007 from six Iowa orchards. No SBFS signs were present at Fort Dodge.

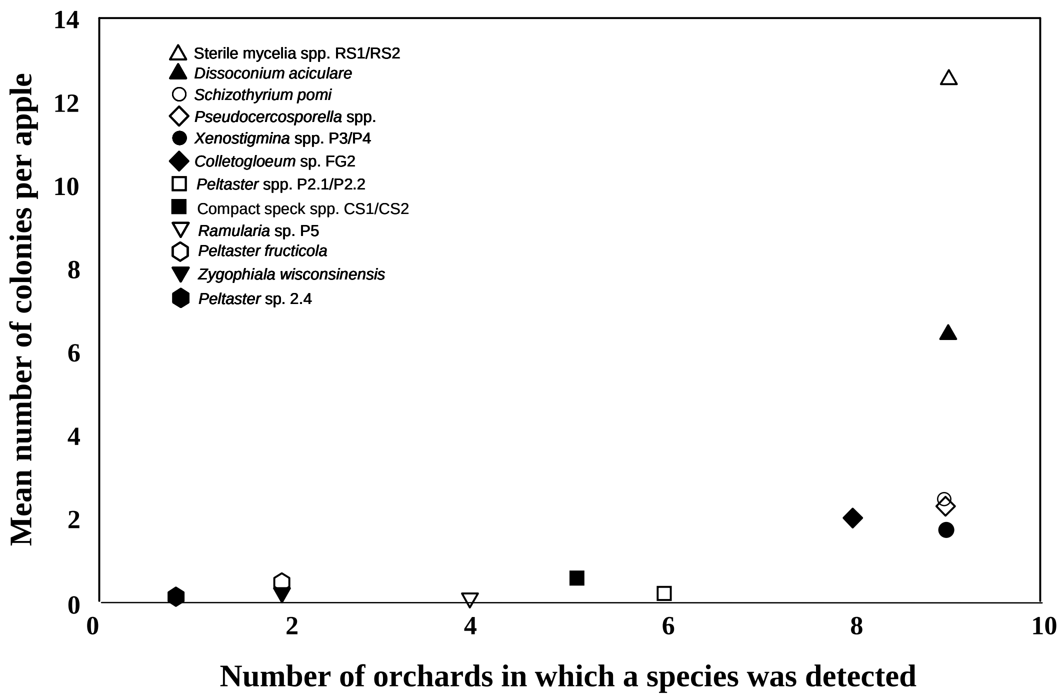

Figure 3. Mean colony number per apple by number of orchards where the colony type was detected. For each of 12 SBFS taxa, mean number of colonies per apple (incidence) was plotted against number of orchards in which it was found (prevalence) for nine orchard years (2006 and 2007).

CHAPTER 3. ASSESSING NEW INTEGRATED PEST MANAGEMENT STRATEGIES FOR APPLE ORCHARDS IN THE MIDWEST

A manuscript in preparation for submission to *HortTechnology*

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ABSTRACT

Four management strategies were compared in an Iowa apple orchard for management of codling moth, sooty blotch and flyspeck (SBFS), weeds, and other pests. In an orchard block with three apple scab-resistant cultivars (Redfree, Liberty, and Goldrush), two new integrated pest management (IPM) systems that incorporated weather-based disease-warning systems and alternative pesticides (Treatments 3 and 4) were compared to an existing IPM regime (Treatment 2) and a conventional system with calendar-based timing of fungicide and insecticide sprays (Treatment 1). At harvest, mean incidence (%) of fruit with disease or insect injury was recorded and marketable and cull fruit were counted and weighed. The two new IPM strategies were as effective as calendar-based and existing-IPM treatments for most apple pests, and yields were equivalent. A partial budget analysis

indicated that Treatment 4 was the least expensive for larger orchards and Treatment 3 was the most expensive for all orchard sizes. Treatment 4 had the least pesticide applications during the 2008 growing season. Active ingredients, spray rates, and applications of pesticides were used to develop an environmental risk rating for each treatment. New IPM treatments lowered ecological risks compared to calendar-based spraying and existing IPM. Composted hardwood mulch was also compared with bare soil for weed control efficacy; mulch suppressed weed coverage and biomass compared to bare soil and required fewer herbicide applications.

INTRODUCTION

In the eastern half of North America, production of fresh-market-quality apples (*Malus* x *domestica* Borkh.) entails an intensive regimen of pesticide sprays (16, 20, 21, 36, 37, 38, 54). Insect pests and diseases are generally managed with synthetic chemical insecticides and fungicides which are applied at approximately 7- to 10-day intervals from green tip until petal fall and at 10- to 14-day intervals thereafter until shortly before harvest (7, 18, 19, 20). Weeds are often managed by applications of synthetic chemical herbicides in tree-row strips (54). As a result, apple is one of the most pesticide-intensive crops in the United States, with 12 to 20 applications of insecticides, fungicides, and herbicides annually (16, 21, 37, 38, 54).

Pesticide-intensive apple management has been challenged by public concern over the use of potentially dangerous chemicals in food production (32, 41, 43, 46), rising international competition, low profit margins (1, 43), and pest resistance (33). Because of these intensifying environmental, economic, and social problems, new methods of integrated pest management (IPM) are needed to achieve adequate pest control while facilitating applicator and consumer safety, minimal environmental impact, and economic viability.

Several studies have developed methods to quantify the risks associated with pesticides (29, 33, 42). A system designed by Kovach et al. (29) rates pesticides by assigning points in proportion to the degree of environmental risks. These risks include potential groundwater leaching, danger to fish, birds, and beneficial insects, and impact on consumers, applicators, and farm workers. Ecological risks and benefits are often overlooked in apple pest management studies, but are arguably as meaningful to society as fruit yield and quality (42).

Apple scab, one of the most economically damaging diseases in humid regions worldwide, is caused by the fungus *Venturia inaequalis* (Cooke) G. Wint. In conventional scab management, fungicides are applied every 7 to 10 days during the spring from green tip to petal fall (15, 16), and can comprise ≥10 % of apple production costs (49). Scab-resistant cultivars can minimize the use of demethylation-inhibiting and other resistance-prone fungicides (16, 37). Although they are commercially available, scab-resistant cultivars are not widely planted (34) or recognized by consumers (37).

Sooty blotch and flyspeck (SBFS) is a late-season apple disease that occurs widely in regions with warm, moist summers (51). Signs of SBFS fungi appear as dark colonies on the apple surface. Current SBFS management combines intensive fungicide applications with cultural methods such as pruning (9, 10, 20). Weather-based warning systems for SBFS that can result in fewer fungicide applications while maintaining disease control were developed in the southeastern U.S. and validated in the Midwest (14).

Codling moth, *Cydia pomonella* (Linnaeus), is a major insect pest of apple worldwide (2, 17, 52). Even a single codling-moth-damaged apple in 100 is considered unacceptable to U.S. consumers (3). Traditional codling moth management often relies on organophosphate insecticide sprays timed by the calendar (20). Using IPM approaches, organophosphate applications for codling moth have been reduced by development of degree-day models (8, 20), mating disruption (20, 30), and sprays of codling moth granulovirus (17, 30).

Newly established orchards are vulnerable to weed competition (53), especially during May and June (35). The application of composted hardwood bark mulch to the soil surface has shown promise in suppressing weeds, conserving moisture, and enhancing soil quality (5, 23, 24, 36, 39).

The objective of the present research was to compare effectiveness, cost, and environmental risk of new combinations of integrated pest management tools with conventional calendar-based management methods for apple scab, sooty blotch and flyspeck, codling moth, and other pests on three scab-resistant apple cultivars. In addition, composted hardwood mulch was compared to bare soil for impact on weeds, tree growth, and soil quality.

MATERIALS AND METHODS

Field location and tree characteristics. A 0.36-ha orchard block at the Iowa State University Horticulture Research Station near Gilbert, IA, established in May 2004, had cultivars Redfree, Liberty, and Goldrush on M9 rootstock with 3-m spacing within rows and 6 m between rows. The orchard was planted in five blocks, each including 12 subplots that consisted of five adjacent trees of the same cultivar. In each block, cultivars were randomly assigned with four replicate subplots for each cultivar. Soil composition was Nicollet-

Webster-Clarion loam and clay loam. Trees were trained to the vertical axis system on a two-wire trellis.

2006 canopy treatments. In 2006, the first bearing year, six treatments were applied in a randomized complete block design to five-tree segments of the same cultivar within each of five replications. Subplots were assigned randomly across cultivars. Treatment rows were alternated with guard rows that were maintained using calendar-based pesticide sprays. The six apple pest management treatments were: 1. Calendar-based pest management, 2. Conventional IPM, 3. New IPM A, 4. New IPM B, 5. New IPM C, and 6. New IPM D (Table 1). Dates of various thresholds which determined spray dates are shown in Table 1 of the Appendix. Pesticides were applied to run-off using a hand-operated backpack sprayer (Solo Model 473, Newport News, VA). Spray rates are shown in Table 2 of the Appendix.

2007 & 2008 canopy treatments. Results of the 2006 trial indicated an interaction between treatment and cultivar. In 2007 and 2008, therefore, the experiment was redesigned as a randomized complete block design with four treatments equally replicated among cultivars in each of five replications. Treatments were assigned randomly in each cultivar and data were analyzed separately by cultivar.

The four treatments were as follows: 1. Calendar-based pest management, 2. Conventional IPM, 3. New IPM A, and 4. New IPM B (Table 2). Various thresholds which determined spray dates are shown in Table 1 of the Appendix. Pesticide application method was the same as in 2006. Spray rates and products are shown in Table 3 of the Appendix.

Canopy pest monitoring. A datalogger (WatchDog Data Logger 450, Spectrum Technologies Inc., Plainfield, IL) in the center of the plot monitored hourly mean temperature and relative humidity. A wetness sensor was placed at 1.5-m height under the tree canopy facing north at a 45° angle to horizontal. In Treatments 3-6 in 2006 and Treatment 3 in 2007-2008, a SBFS warning system called the Brown-Sutton-Hartman system was utilized (6, 7, 24, 25, 47). After the first-cover fungicide spray was applied, periods of leaf wetness duration (LWD) ≥4 hours were accumulated until a threshold total of 175 hours was reached; the 2nd-cover fungicide spray was then applied. In Treatment 4 in 2007 and 2008, the interval between 1st- and 2nd-cover fungicide sprays was a threshold of 192 cumulative hours of relative humidity ≥97 % (14).

In Treatment 2 in 2006 and Treatments 2 and 4 in 2007 and 2008, a degree-day model was used to time insecticide sprays for codling moth. Pheromone traps (Pherocon 1CP, Trécé Inc., Adair, OK) were used to monitor codling moth populations. Biofix was determined as the first date when ≥5 males were caught per trap per week (4). Degree days (base 10° C) were summed to determine when to apply insecticides for codling moth (2).

Canopy pest data. Immediately prior to harvest in 2006 and 2008, 20 apples per tree from the center three trees of each five-tree subplot were assessed for incidence of codling moth and plum curculio injury, apple scab symptoms, and SBFS signs. If there were <20 apples per tree, all apples on the tree were examined. Apples were chosen arbitrarily from the interior and exterior of the tree canopy in each year. In 2007, after a spring frost eliminated much of the apple crop, all apples from each five-tree subplot were assessed for insect damage.

In 2006 and 2008, canopy pest damage and yield were analyzed using PROC GLM ANOVA for randomized complete block designs (SAS Institute, Inc., Cary, NC). In 2007, because data were taken from every apple in a five-tree subplot, data were analyzed using a non-parametric Friedman’s test for randomized complete block designs (12).

Ecological risk rating of treatments. Treatments in 2007 and 2008 were assigned values on a rating scale called the Field Environmental Impact Quotient (FEIQ), indicating ecological risks as outlined in Kovach et al. (29). As new pesticides were introduced and formulations changed, point values were updated (29). The point value for each pesticide is proportionate to the ecological risk associated with its use. Total risk for each treatment was determined for each cultivar using the sum of FEIQs for each pesticide used in the treatment (Tables 4 and 5 in Appendix). FEIQ for each pesticide was determined by the following equation: (EIQ) x (percent active ingredient) x (dose/hectare) x (number of applications) (29). *Cydia pomonella* granulovirus was not assigned a rating in previous studies, so an EIQ value (6.7) was developed based on the same parameters used by Kovach et al. (29).

Economic analysis of canopy pest management strategies. A partial budget, calculated from results of the canopy pest trials in 2008, was used to compare the cost and revenue of pest management strategies (26). To assess possible economies of scale, partial budgets were projected for orchard sizes of 0.4, 2.0, 4.0, 8.1, and 16.2 ha (16). In 2007, only treatment costs were determined.

Costs of pesticides were obtained from United Agri Products and FMC Corporation, two commercial pesticide suppliers in the Midwest, during November of 2007 and May of 2008. Additional pesticide prices were estimated from a price sheet for Maine apple growers (28) and the North Dakota Field Crop Insect Management Guide (27).

Tractor and sprayer prices were estimated using an enterprise budget for medium density orchards (44). Machinery costs per hour reflected both variable and fixed costs. Variable costs included fuel, lubrication, and repairs and maintenance. Fixed costs included depreciation, interest, and insurance. A new four-wheel drive, 70 horsepower tractor cost

$31.58 per hour. A new 400-gallon, power takeoff driven airblast sprayer cost $23.44 per hour. Total equipment cost was $66.02 per hour which includes an $11.00 per hour wage for a machinery operator (13).

Spray time in a commercial orchard was determined by consulting several apple producers and research horticulturists. Spray time was estimated at 20 minutes per 0.4 ha (Lynn Schroeder, Iowa State University Horticulturist, personal communication; Greg Baedke, Community Orchard, Fort Dodge, IA, personal communication). Spray preparation time was estimated to be 15 minutes, and clean-up was estimated as 30 minutes. Clean-up times were assumed to be the same for all orchard sizes. However, multiple mixing times were required for larger orchards because the sprayer needed to be filled several times.

Weather-monitoring equipment was assumed to have a 5-yr lifetime, with an amortization rate of 20 percent (Cynthia Turski, Spectrum Technologies Inc., Plainview, IL, personal communication). Although the number of required codling moth traps increased for larger orchards, only one datalogger and thermograph were required for all orchard sizes examined.

At harvest, the number of marketable and cull fruit were counted and weighed for trees in each treatment. Apples were graded and separated as <5.0, 5.0-6.3, 6.3-8.1, and >8.1 cm in diameter. Yield data were recorded from the middle three trees of each five-tree subplot in 2006 and 2008, and from all five trees per subplot in 2007.

Returns of $3.31 per kilogram were assumed for all cultivars, based on a May 2008 telephone survey of prices which local Iowa growers said they received for fresh market apples. Price per kilogram was applied to average yield per tree in 2008. Average yield per tree was then multiplied by the number of trees per hectare (727). To calculate net returns, production costs (pesticides, machinery, monitoring equipment, spraying and scouting labor) were subtracted from the total fresh market value of fruit.

Groundcover treatments. In 2006-2008, mulching was compared to a bare-ground control in five replications; each subplot consisted of a five-tree row segment. Within each replication, the same cultivar was used for mulched and bare-ground subplots. Mulched subplots received a 15-cm-deep layer of composted hardwood mulch (Source: All Seasons Mulch, Ames, IA) in a 2-m-wide strip beneath the tree canopy in June 2006 and June 2008. The mulch had been composted for at least 1 year before use. A mulch-free zone was maintained within a 30-cm radius of tree trunks.

Two-meter-wide strips beneath the canopy were maintained free of weeds from the beginning of May until the beginning of July. An initial herbicide application was made at the beginning of each season to both bare-ground and mulched subplots. Herbicide sprays were applied using a boom sprayer when the tallest weeds had reached 12.5 cm in height. After mid-July, weeds were controlled by periodic mowing. Table 6 in the Appendix summarizes the products, rates, and timing of weed management tactics utilized in this study, and amount of pesticide active ingredient used each spray.

In 2007 and 2008, soil temperature was measured at 5-and 10-cm depths in one subplot of each bare-ground and mulched soil treatment using thermistors (Model 107, Campbell Scientific, Logan, UT). Soil volumetric water content was measured at depths of 0 to 15 cm and 15 to 30 cm using TDR sensors (Model CS616, Campbell Scientific).

A baseline soil chemical test was performed on 19 July 2006 and in mid-July 2007 and 2008. Two samples were collected from each bare-ground and mulched subplot. The first sample was a composite of five soil cores beneath each tree in a five-tree segment from of 0 to 15 cm depth, and the second sample was from a depth of 15 to 30 cm (Figure 1 in Appendix).

Soil samples were submitted to the Iowa State University Soil and Plant Analysis Laboratory (Ames, IA) and tested for percent organic carbon, organic matter, nitrogen, pH, nitrate nitrogen, and ammonium. A Mehlich-3 extraction was performed for total parts per million P, K, Ca, Mg, and Mn.

Before bud break in 2007 and 2008, growth was assessed for the center three trees in each subplot. Trunk diameter was measured 15 cm above the graft union. Tree height and limb spread from north to south were recorded before bud break in mid-March of 2007 and 2008 using a measuring tape.

Leaf nutrients were analyzed in mid-July of 2007 and 2008. Twenty leaves from each of the five trees in a subplot were chosen arbitrarily from mid-sections of terminal shoots and combined as one sample per subplot. Leaf samples were then submitted to the Iowa State University Soil and Plant Analysis Laboratory (Ames, IA) and tested for P, K, Zn, Fe, Mn, Ca, and Mg (parts per million), N (percent of leaf biomass), and moisture content (percent of leaf biomass).

Weed species data was collected monthly from May to September of 2007 and 2008 along 13 transects per subplot, yielding 130 data points per subplot. At each point, presence or absence of weeds was noted; if present, the tallest weed was identified to species.

Weed biomass was assessed in early August of 2006, and early September of 2007 and 2008 using 0.1 m^2 quadrat that was placed randomly at five locations in each subplot. Weeds harvested from five subsamples in each subplot were combined, oven-dried for 3 days at 65° C, and weighed.

In 2006, weed cover was analyzed using PROC GLM ANOVA for randomized complete block designs. In 2007 and 2008, data were analyzed using a repeated measures technique using the PROC MIXED procedure and the Tukey-Kramer adjustment for a randomized complete block design. Weed biomass data were analyzed using PROC GLM ANOVA for randomized complete block designs. Tree vigor, soil chemical properties, and leaf nutrient data were analyzed with an ANOVA using the mixed procedure in SAS for randomized complete block designs.

RESULTS

Number of pesticide sprays. In 2006, the total number of pesticide sprays ranged from 21 in Treatment 5 to 14 in Treatment 2. The number of spray trips (incorporating tank mixes of two or more pesticides) ranged from 16 in Treatment 5 to nine in Treatment 4 (Table 3). In 2007 and 2008, cv. Redfree had the fewest sprays as it was the earliest to be harvested, followed by cvs. Liberty and Goldrush (Table 3). Treatments 1 and 2 had fewest trips through the orchard in 2007, but Treatments 2 and 4 had the fewest total pesticide sprays because many fungicide and insecticide applications could be combined in Treatments 1 and 2, but not in Treatment 4. Treatment 4 had the fewest trips and sprays in 2008 for all cultivars.

Yield. In 2006, Treatment 1 had the smallest number and weight of marketable apples per tree, whereas Treatment 2 had the highest marketable weight and number (Table 4). In 2007, when few apples were harvested due to the spring frost, marketable and cull apple weight and number did not differ significantly among treatments (Table 4). In 2008, there was no difference among treatments in cv. Redfree marketable fruit weight and number

(Table 4). Treatment 3 had more cull apples than other treatments for Liberty apples. For Goldrush apples, Treatment 2 had less marketable fruit weight than Treatments 1 and 4.

Insect and disease damage. No scab damage on fruit was evident during the study (Sisson, unpublished data); this was expected due to scab resistance of the three cultivars (Table 5). In 2006, Treatments 1, 2, and 3 had significantly lower incidence of SBFS than Treatment 5. Treatment 5 also had less codling moth damage than Treatment 4. In 2007, there were no differences among any treatments for incidence of codling moth, SBFS, or plum curculio (Table 5). No SBFS was observed on Redfree apples. In 2008, no SBFS or plum curculio was observed on Redfree, and codling moth damage was minimal (Table 5). In Treatment 3, cv. Liberty had significantly more SBFS than Treatments 1, 2, and 4, and in Treatment 4, Goldrush had a significantly higher incidence of SBFS signs than Treatments 1 and 2; however, incidence of SBFS was <1 % in all treatments.

Field EIQ. New IPM Treatments 3 and 4 had the least ecological risk compared to calendar-based spraying (Treatment 1) and conventional IPM (Treatment 2) using the FEIQ system (Table 6). In 2007, New IPM treatments scored >40 % lower than calendar-based and >30 % lower than conventional IPM for cultivar 'Redfree,' while New IPM treatments showed nearly 50 % less ecological risk than calendar-based spraying for cultivar 'Goldrush.' In 2008, in part because early-season spraying differed from 2007, New IPM B (Treatment 4) scored nearly 75, 70, and 70 % lower for cultivars 'Redfree,' 'Liberty,' and 'Goldrush,' respectively, than calendar-based spraying (Treatment 1).

Economic analysis. Per hectare cost of pest management in 2008 (Table 7) was highest for Treatment 3 at all orchard sizes because of weekly insecticide sprays. Treatment 4 was the most profitable at larger orchard sizes (Table 7). Generally, profits were higher and costs were lower for larger orchard sizes in all treatments. 2007 treatment cost was highest in Treatment 3, followed by Treatments 3, 2, and 1, respectively (Data not shown).

Weeds. Mulched plots required spot treatments of herbicide throughout the season to manage localized outbreaks of weeds, but bare-ground plots required herbicide applications over the entire ground surface (Table 5 in the Appendix). Mulched plots required approximately 20 and 25 % less herbicide than bare ground plots in 2007 and 2008, respectively. Mulched plots had significantly less weed coverage than bare-ground plots on more than half the sampling dates (Table 8), usually late in the growing season. In July of 2007, common purslane (*Portulaca oleracea*) covered nearly 50% of sampling points in bare-ground plots, whereas none was found in mulched plots. Common purslane continued to appear in bare-ground plots in higher amounts than mulched plots for the rest of the season in 2007 and in 2008. In contrast, barnyard grass (*Echinochloa crus-galli*) covered significantly more of the mulched than bare-ground subplots in July, August, and September of 2007, and June of 2008.

Mean weed biomass was significantly lower in mulched than bare-ground plots all three field seasons (Figure 1). Differences were most notable in August 2006, when weed biomass in bare-ground plots was nearly 250 g/m^2 and mulched plots had < 50 g/m^2.

Trunk diameter, tree height, and limb spread did not differ significantly for trees in bare-ground and mulched plots in 2007 or 2008 (Table 9). Limb spread was less in 2008 than 2007 because of winter pruning which occurred in December of 2007.

Average weekly soil temperatures beneath bare ground fluctuated more than temperatures beneath mulched plots (Figure 2). Soil temperatures remained cooler under mulch, usually by at least 2° C, until near the end of the growing season, when the difference began to narrow.

Volumetric water content beneath mulched plots at 15- and 30-cm depths was higher than under bare-ground plots throughout most of the season (Figure 3). In 2007, volumetric water content was generally higher at a depth of 30 cm than at 15 cm in mulched plots. Mean soil nutrient levels, organic matter, and pH varied widely among bare-ground and mulched plots in all three years (Table 7 in Appendix). Total percent carbon, nitrogen, and organic matter were nearly identical between treatments in 2006, but in 2007 they all increased in mulched relative to bare-ground plots, and these differences were statistically significant in 2008.

In 2007 and 2008, means of foliar nutrients and foliar moisture content did not differ significantly between bare-ground and mulched plots (Table 8 in Appendix).

DISCUSSION

This research is the first systems-level assessment of scab-resistant apple cultivars in the Midwest. Because there were few differences in pest damage and yield among treatments, treatment cost, number of sprays, and ecological risks were examined to compare treatments. This method indicated that not only was Treatment 4 (New IPM B) least costly for orchard sizes 2 ha and above, it also required the fewest sprays and had the lowest total FEIQ in 2008. The fact that as many as nine pesticide sprays were saved in Treatment 4 compared to Treatment 1, while effectively managing pests and diseases, shows that there are viable alternatives to standard calendar-based pesticide application for sustainable production of apples in the Midwest.

The IPM alternatives offer additional benefits besides reduced pesticide sprays and lower production costs, including less time spent spraying and less environmental and consumer exposure to pesticides, as reflected in lower FEIQ ratings (Table 10). Lower FEIQ ratings occurred because active ingredients in pesticides used in New IPM treatments are less harmful to applicators and beneficial organisms, and disease-resistant cultivars, weather-based warning-systems, and scouting decreased frequency of insecticide and fungicide sprays in these treatments. Kovach et al. (29) indicated that IPM treatments had smaller FEIQ scores than either organic or conventionally sprayed treatments. Research from New Zealand also suggested that IPM strategies may address key pest management and economic problems associated with conventionally sprayed and organic treatments (50). These studies exhibit results consistent with the present study: that IPM treatments may be better for the environment and the bottom line than calendar-based spray applications.

Minimizing pesticide risk is an important part of sustainable agriculture. These benefits are sometimes overlooked but are as valuable to society as fruit yield and quality (42). Attempts have been made to organize and quantify the environmental impact of pesticides common in fruit production beyond number of sprays and amount of active ingredient used (29, 33, 42) but quantifying external benefits of pesticide reduction remains complex, sometimes limited by lack of information and conflicting conclusions from different risk rating systems (33).

This study is apparently the first to assess the impact of using composted hardwood mulch for orchard weed management in the Midwest. In the present study, weeds were suppressed in the orchard understory by the use of organic composted hardwood mulch coupled with spot herbicide treatments, indicating that mulch may be a workable weed management alternative to bare soil maintained solely by herbicides. However, mulching can be expensive (22), and perennial weeds were able to grow well in mulched plots. Common purslane, an annual whose seeds are very small, is more sensitive to the physical barriers to germination which mulch provides, unlike larger-seeded or perennial weeds (11, 31).

The fact that soil moisture remained consistently higher beneath mulched plots, even though all plots were drip irrigated, indicates that mulch may help to buffer water loss during the Midwest's periodic droughts. Studies in British Columbia and New York also showed that mulching helped increase soil moisture, even in irrigated plots (35, 40). Mulching could prevent damage to trees, yield, and fruit size during water-limited growing seasons, especially since most orchards in the Midwest are not irrigated. Mulch also moderated temperature fluctuation, showing that this weed reduction tactic also serves to temper environmental extremes. Region-specific soil studies are important as soil type and climate differ drastically between regions in the United States.

Significantly higher soil carbon, nitrogen, and organic matter in 2008 in mulched plots compared to bare soil suggested that mulching can gradually enhance these desirable soil characteristics. Potential benefits can include increased distribution of water in the soil, better water entry into soil, resistance to erosion, and enhanced fruit yield and quality (22, 48). Future work in this area should extend mulch and bare-ground evaluations to encompass more years and field sites. For example, in New York, a 12-year groundcover management study found that mulched plots doubled soil organic matter in that time (54). In the present study we began to observe significant organic matter increases in mulched plots only in the third year after mulching began, so it is reasonable to assume that organic matter would continue to rise if the study were continued. Likewise, if weeds are decreased over a period of years, as occurred in the mulched plots, it is likely that less weed seed will enter the soil seed bank over time (45), thus requiring less herbicide to manage weeds in mulched plots in the future.

The new IPM strategies in this study need to be tested further at several locations and more years of data are needed before such tactics can be recommended in apple production. However, the systems-level approach used in this study, taking into account not only pest management and yield, but economic and ecological impact, may pave the way for future system studies attempting to address the so-called “external” risks of pest management inherent with apple production in the Midwest.

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Table 1. Treatment application intervals and spray materials for apple pests in 2006.

Treatment	Scab fungicide sprays	SBFS fungicide sprays	Codling moth insecticide sprays
1: Calendar-based	**7-10 days, captan[q] + myclobutanil[r]**	**14 days, captan + thiophanate-methyl[s]**	**14 days, phosmet[t]**
2: Conventional IPM	**Delay 1 spray until tight cluster, then 7-10 days, captan + myclobutanil**	**14 days, captan + thiophanate-methyl**	**250 & 1250 degree days after biofix[u], phosmet**
3: New IPM A	**No control**	**Single use of LWD WS[v], then every 14 days, captan + thiophanate-methyl**	**7 days, *Cydia pomonella* granulovirus[w]**
4: New IPM B	**No control**	**Multiple use of LWD WS[x], captan + thiophanate-methyl**	**14 days, *Cydia pomonella* granulovirus**
5: New IPM C	**No control**	**Multiple use of LWD WS and kresoxim-methyl[y] 1st spray, then captan + thiophanate-methyl**	**7 days, *Cydia pomonella* granulovirus & 14 days spinosad[z]**
6: New IPM D	**No control**	**Multiple use of LWD WS and Sovran 1st, 2nd and alternate sprays with captan + thiophanate-methyl**	**14 days, *Cydia pomonella* granulovirus & spinosad**

[q] Captan Pro 50 WP Fungicide (378.2 g active ingredient(ai)/ha). Drexel.
[r] Nova 40 W Fungicide (19.3 g ai/ha). Dow Agrosciences.
[s] Topsin M 70 WDG Fungicide (72.48 g ai/ha). Cerexagri-Nisso.
[t] Imidan 70 W Insecticide (360.9 g ai/ha). Gowen.
[u] Biofix occurs when $\geq$ 5 adult male moths are trapped per week.
[v] Timing of 2nd-cover fungicide spray determined by a warning system (WS) for SBFS based on accumulation of 175 hours of leaf wetness duration (LWD) since date of application of first-cover fungicide spray; after 2nd-cover spray, fungicides were applied every 14 days until harvest.
[w] Cyd-X Insecticide (0.4 ml ai/ha). Certis USA.
[x] Timing of 2nd-cover fungicide spray determined by a warning system (WS) for SBFS based on accumulation of 175 hours of leaf wetness duration (LWD) since date of application of first-cover fungicide spray; after 2nd-cover spray, the warning system was reset. 3rd-cover and subsequent sprays occur every 175 hours LWD.
[y] Sovran (20.95 g ai/ ha). BASF.
[z] SpinTor 2 SC (11.5 ml ai/ha). Dow Agrosciences.

Table 2. Treatment application intervals and spray materials for apple pests in 2007 & 2008.

Treatment	Scab fungicide sprays	SBFS fungicide sprays	Codling moth insecticide sprays
1: Calendar-based	**7-10 days, captan[q] + myclobutanil[r]**	**14 days, captan + thiophanate-methyl[s]**	**14 days, phosmet[t]**
2: Conventional IPM	**Delay 1 spray until tight cluster, then 7-10 days, captan + myclobutanil**	**14 days, captan + thiophanate-methyl**	**250 & 1250 degree days after biofix[u], phosmet**
3: New IPM A	**No control**	**Warning system based on LWD[v] , then every 14 days, captan + thiophanate-methyl**	**7 days, *Cydia pomonella* granulovirus[w]**
4: New IPM B	**No control**	**Warning system based on RH[x], then every 14 days captan + thiophanate-methyl**	**Degree days, 16-18 days, 7 days, trap captures, *Cydia pomonella* granulovirus, novaluron[y], & thiacloprid[z]**

[q] Captan Pro 50 WP Fungicide (378.2 g active ingredient(ai)/ha). Drexel.
[r] Nova 40 W Fungicide (19.3 g ai/ha). Dow Agrosciences.
[s] Topsin M 70 WDG Fungicide (72.48 g ai/ha). Cerexagri-Nisso.
[t] Imidan 70 W Insecticide (360.9 g ai/ha). Gowen.
[u] Biofix occurs when $\geq$ 5 adult male moths are trapped per week.
[v] Timing of 2nd-cover fungicide spray determined by a warning system (WS) for SBFS based on accumulation of 175 hours of leaf wetness duration (LWD) since date of application of first-cover fungicide spray; after 2nd-cover spray, fungicides were applied every 14 days until harvest.
[w] Cyd-X Insecticide (0.4 ml ai/ha). Certis USA.
[x] Timing of 2nd-cover fungicide spray determined by a warning system (WS) for SBFS based on accumulation of 192 hours of relative humidity duration (RHD) $\geq$ 97 % since date of application of first-cover fungicide spray; after 2nd cover, fungicides were applied every 14 days until harvest.
[y] Rimon 0.83 EC Insecticide (31.6 ml ai/ ha). Chemtura USA Corporation.
[z] Calypso 4 Flowable Insecticide (20.4 ml ai/ ha). Bayer Cropscience.

Table 3. Number of insecticide and fungicide sprays by treatment during 2006, 2007, and 2008

	Treatment					
2006	**1**	**2**	**3**	**4**	**5**	**6**
Insecticide	9	4	13	7	15	9
Fungicide	10	10	7	6	6	6
Total number of sprays[w]	19	14	20	13	21	15
Total number of spray trips[x]	10	12	15	9	16	10
2007[y]						
Redfree						
Insecticide	8	3	12	9	-	-
Fungicide	8	7	4	4	-	-
Total number of sprays	16	10	16	13	-	-
Total number of spray trips	8	8	13	10	-	-
Liberty[z]						
Goldrush						
Insecticide	11	3	16	9	-	-
Fungicide	11	10	6	6	-	-
Total number of sprays	22	13	22	15	-	-
Total number of spray trips	11	11	19	12	-	-
2008[y]						
Redfree						
Insecticide	9	4	13	8	-	-
Fungicide	10	9	4	4	-	-
Total number of sprays	19	13	17	12	-	-
Total number of spray trips	10	11	14	8	-	-
Liberty						
Insecticide	10	4	17	8	-	-
Fungicide	12	11	6	6	-	-
Total number of sprays	22	15	23	14	-	-
Total number of spray trips	12	13	18	10	-	-
Goldrush						
Insecticide	11	4	19	8	-	-
Fungicide	13	12	7	7	-	-
Total number of sprays	24	16	26	15	-	-
Total number of spray trips	13	14	20	11	-	-

[w] Does not include dormant oil, bactericide, or miticide sprays applied to all treatments.
[x] Combines insecticide and fungicide sprays which were applied at the same time as a tank mix.
[y] During 2007 and 2008, treatment number was reduced to four.
[z] In 2007, no fruit from cv. Liberty were harvested.

Table 4. Summary of fruit yield means by treatment and cultivar[z] 2006, 2007, and 2008

Treatment	Weight (kg)		Number		Grade (cm diam.)			
2006	Marketable	Cull	Marketable	Cull	< 5.0	5.0-6.3	6.3-8.1	> 8.1
1	2.5 c[z]	0.7 c	21.3 b	5.7 b	1.3 b	22.5 a	3.1 b	0.5 ab
2	4.1 a	0.8 bc	32.7 a	6.6 b	1.9 b	25.3 a	6.3 a	0.4 ab
3	3.2 abc	0.9 bc	31.9 ab	9.3 ab	10.4 a	18.5 a	3.3 b	0.1 b
4	3.0 abc	1.3 ab	26.0 ab	11.3 a	2.1 b	23.9 a	4.3 ab	0.3 ab
5	2.8 bc	1.4 a	24.1 ab	12.3 a	4.2 ab	19.0 a	3.1 b	0.9 a
6	3.9 ab	0.9 bc	32.3 ab	8.0 ab	4.7 ab	22.9 a	4.9 ab	0.5 ab
2007								
Redfree								
1	5.5 a[z]	0.8 a	40.6 a	5.4 a	-	-	-	-
2	5.5 a	1.2 a	46.8 a	10.0 a	-	-	-	-
3	3.6 a	1.7 a	25.8 a	13.8 a	-	-	-	-
4	4.4 a	2.0 a	30.2 a	15.2 a	-	-	-	-
Goldrush								
1	8.1 a	2.7 a	56.2 a	19.8 a	-	-	-	-
2	6.9 a	1.8 a	49.4 a	13.6 a	-	-	-	-
3	4.5 a	2.1 a	32.8 a	16.2 a	-	-	-	-
4	6.4 a	1.7 a	45.4 a	11.0 a	-	-	-	-
2008								
Redfree								
1	9.3 a[z]	0.1 a	72.0 a	0.8 a	0.5 a	21.2 a	45.1 a	4.5 b
2	7.8 a	0.1 a	63.3 a	1.3 a	1.1 a	26.9 a	30.9 b	4.5 b
3	8.8 a	0.1 a	69.1 a	1.4 a	1.1 a	22.6 a	42.7 ab	3.5 b
4	9.4 a	0.1 a	69.6 a	1.3 a	0.3 a	16.7 a	41.4 ab	9.7 a
Liberty								
1	10.1 a	0.5 b	74.0 a	4.0 b	0.9 a	34.1 a	35.8 a	3.1 b
2	9.2 a	0.5 b	73.0 a	4.1 b	1.1 a	34.7 a	33.7 a	3.6 b
3	9.7 a	0.9 a	79.1 a	7.0 a	0.5 a	24.7 a	35.7 a	9.8 a
4	9.9 a	0.6 ab	74.7 a	5.1 ab	1.3 a	26.5 a	39.3 a	7.5 a
Goldrush								
1	19.3 a	0.1 a	113.2 a	1.2 a	1.3 a	29.4 a	47.0 a	35.5 a
2	14.1 b	0.2 a	99.1 a	1.7 a	2.7 a	36.6 a	38.8 a	19.0 b
3	17.1 ab	0.1 a	113.0 a	1.2 a	2.8 a	41.4 a	42.8 a	26.0 ab
4	18.4 a	0.3 a	125.1 a	2.1 a	1.5 a	39.3 a	53.5 a	30.8 a

[y] Means followed by the same letters are not statistically different (p=0.05).
[z] In 2007, no fruit were harvested from cv. Liberty.

Table 5. Summary of mean disease and pest damage by cultivar and treatment 2006, 2007, and 2008

Treatment	**Disease/Pest Incidence (%)**		
2006	Codling moth	SBFS	Plum curculio
1	0.7 ab[z]	0.7 b	-
2	0.7 ab	1.3 b	-
3	1.0 ab	1.7 b	-
4	6.0 a	12.7 ab	-
5	0.3 b	6.0 a	-
6	2.0 ab	4.3 ab	-
2007[y]			
Redfree			
1	1.3 a	0.0 a	1.3 a
2	0.0 a	0.0 a	0.4 a
3	0.5 a	0.0 a	27.8 a
4	0.0 a	0.0 a	16.2 a
Liberty[z]			
Goldrush			
1	2.6 a	13.4 a	1.6 a
2	1.0 a	6.4 a	2.9 a
3	0.0 a	9.8 a	11.8 a
4	0.4 a	3.6 a	11.0 a
2008			
Redfree			
1	0.1 a	0.0 a	0.0 a
2	0.0 a	0.0 a	0.0 a
3	0.2 a	0.0 a	0.0 a
4	0.0 a	0.0 a	0.0 a
Liberty			
1	0.0 a	0.4 b	0.2 a
2	0.0 a	0.8 b	0.0 b
3	0.0 a	1.7 a	0.1 ab
4	0.0 a	0.9 b	0.1 ab
Goldrush			
1	0.0 a	0.1 b	0.0 a
2	0.0 a	0.0 b	0.0 a
3	0.0 a	0.4 ab	0.0 a
4	0.0 a	0.9 a	0.0 a

[x] Means followed by the same letters are not statistically different (p=0.05).

[y] In 2007, no statistical differences among treatments were observed.

[z] In 2007, no fruit were harvested from cv. Liberty.

Table 6. Theoretical total Field EIQ of differing pest management strategies for three apple cultivars using Kovach et al's.1992 & 1999 EIQ[x] Field Use Rating[y] system for pesticides.

	Total Field EIQ[z] Treatment			
Cultivar/year	**1**	**2**	**3**	**4**
2007				
Redfree	136	113	77	78
Liberty	179	133	91	92
Goldrush	179	133	91	92
2008				
Redfree	120	84	36	31
Liberty	149	97	50	45
Goldrush	164	112	57	51

[x] EIQ=Environmental Impact Quotient

[y] EIQ Field Use Rating = EIQ X % active ingredient X rate per hectare X applications

[z] Total Field EIQ is the sum of the EIQ Field Use Ratings for (Appendix: Tables 4 and 5) all pesticides used.

Table 7. Estimated annual cost[x] and revenue[y] ($) per hectare by cultivar for varying orchard sizes in 2008.

Cultivar	Orchard size (ha)	Treatment 1	2	3	4
			Cost		
Redfree	**0.4**	336	420	635	463
	2	284	300	451	270
	4	281	291	431	252
	8.1	277	284	420	240
	16.2	275	280	413	233
Liberty					
	0.4	404	481	798	541
	2	343	351	584	324
	4	338	341	562	304
	8.1	334	334	549	291
	16.2	332	329	541	283
Goldrush					
	0.4	438	515	885	588
	2	372	380	652	352
	4	367	370	629	331
	8.1	363	362	614	317
	16.2	360	357	605	308
			Revenue[z]		
Redfree	**0.4**	9031	8947	8731	8903
	2	9082	9066	8916	9097
	4	9086	9076	8935	9115
	8.1	9089	9082	8947	9126
	16.2	9091	9087	8953	9133
Liberty					
	0.4	9932	9856	9538	9796
	2	9994	9985	9752	10013
	4	9998	9995	9774	10033
	8.1	10002	10003	9787	10045
	16.2	10005	10008	9795	10053
Goldrush					
	0.4	17916	17839	17469	17766
	2	17982	17974	17702	18002
	4	17987	17984	17725	18023
	8.1	17991	17992	17740	18037
	16.2	17994	17997	17749	18046

[x] Treatment costs include pesticides, machinery, labor, monitoring equipment, depreciation, and scouting labor.
[y] Revenue is determined by subtracting costs from gross revenue.
[z] All apples assumed sold for a fresh market/farm gate price of $3.31 per kilogram. Culls not considered in these calculations.

Table 8. Mean percent weed coverage of bare ground and mulch treatments during 2007 and 2008

						%			
Year	**Month**	**Treatment**	**Total[t]**	**DS[u]**	**EC[v]**	**PO[w]**	**TO[x]**	**CA[y]**	**TR[z]**
	May	**Bare ground**	13	10	0	0	2	0	0
		Mulch	6	0	0	0	3	3	0
	June	**Bare ground**	14	6	0	5	2	0	1
		Mulch	14	9	0	0	1	2	1
2007	**July**	**Bare ground**	64*	10	5*	48**	0	0	0
		Mulch	50*	27	18*	0**	1	0	1
	Aug.	**Bare ground**	56*	10	3*	42**	1	0	0
		Mulch	34*	20	12*	0**	0	0	1
	Sept.	**Bare ground**	66	28	9*	20**	3	0	1
		Mulch	56	28	20*	0**	3	2	1
	May	**Bare ground**	9	0	0	0	3	0	3
		Mulch	2	0	0	0	0	1	0
	June	**Bare ground**	70**	7	33**	2	3	0	10
		Mulch	7**	1	0**	0	2	0	1
2008	**July**	**Bare ground**	27**	4	4	8*	2	0	2
		Mulch	0**	0	0	0*	0	0	0
	Aug.	**Bare ground**	47**	18*	8	13**	0*	0	5
		Mulch	27**	7*	10	0**	1*	0	2
	Sept.	**Bare ground**	92**	34	13	35**	0	0	6
		Mulch	55**	30	11	0**	2	1	3

[t] Total weeds includes those in the table and other species appearing in very small amounts.
[u] Large crabgrass (*Digitaria sanguinalis*)
[v] Barnyard grass (*Echinochloa crus-galli*)
[w] Common purslane (*Portulaca oleracea*)
[x] Dandelion (*Taraxacum officinalis*)
[y] Canada thistle (*Cirsium arvense*)
[z] White clover (Trifolium repens)
* Difference in means significant at p=0.05.
** Difference in means significant at p=0.001.

Table 9. Mean tree growth (cm).

	Bare ground	Mulch
2007[z]		
Trunk diameter	3.0	3.1
Tree height	194.4	198.8
Limb spread	154.7	146.4
2008[z]		
Trunk diameter	3.6	3.7
Tree height	199.5	200.8
Limb spread	135.2	135.1

[z] No statistically significant differences (p=0.05) were observed between treatments either year.

Table 10. Comparison of spray number, cost, and EIQ[w] for 2007 and 2008 treatments.

Treatment	Field EIQ	Cost[x]	Number of sprays[y]
2007			
Redfree			
1	136	243	16
2	113	277	10
3	77	396	16
4	78	332	13
Liberty[z]			
Goldrush			
1	179	327	22
2	133	350	13
3	91	354	22
4	92	381	15
2008			
Redfree			
1	120	275	19
2	84	280	13
3	36	413	17
4	31	233	12
Liberty			
1	149	332	22
2	97	329	15
3	50	541	23
4	45	283	14
Goldrush			
1	164	360	24
2	112	357	16
3	57	605	26
4	51	308	15

[w] Field Environmental Impact Quotient.
[x] Cost from a 16.2 ha orchard size.
[y] Both insecticide and fungicide sprays included.
[z] No Liberty apples were harvested in 2007.

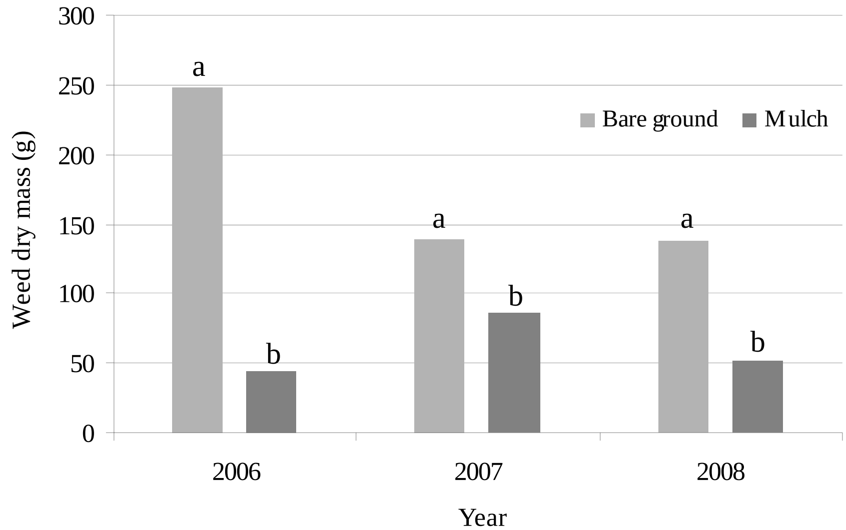
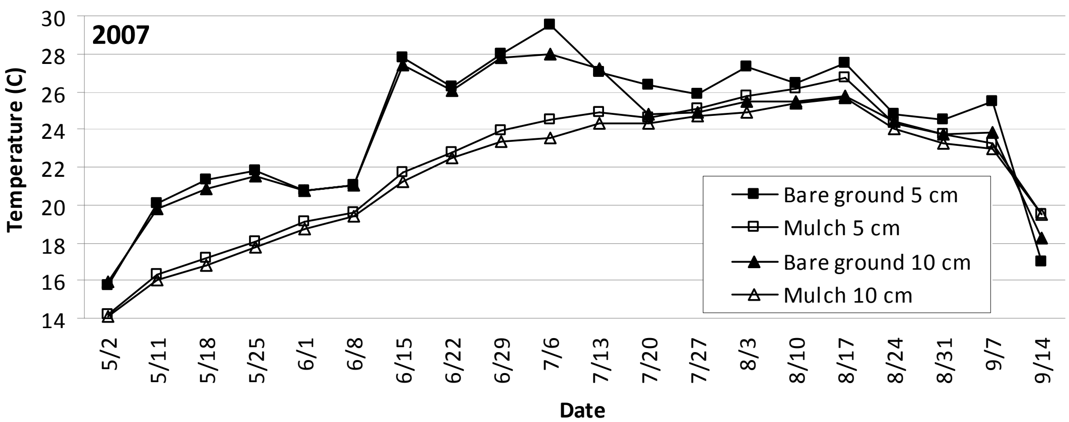


Figure 1. Mean weed biomass (g/m^2 dry weight) over three years in bare-ground and mulched plots (n=5).



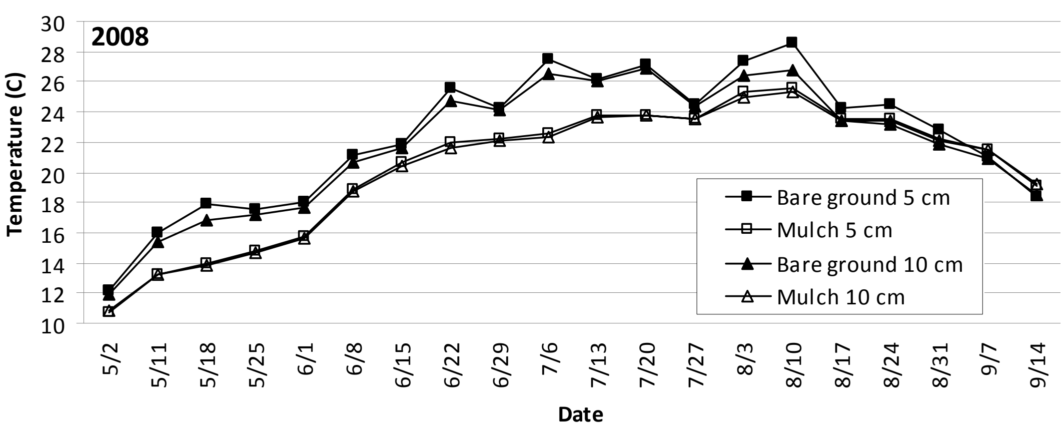


Figure 2. Average weekly soil temperature beneath bare-ground and mulched plots at 5 and 10 cm depths in 2007 and 2008.

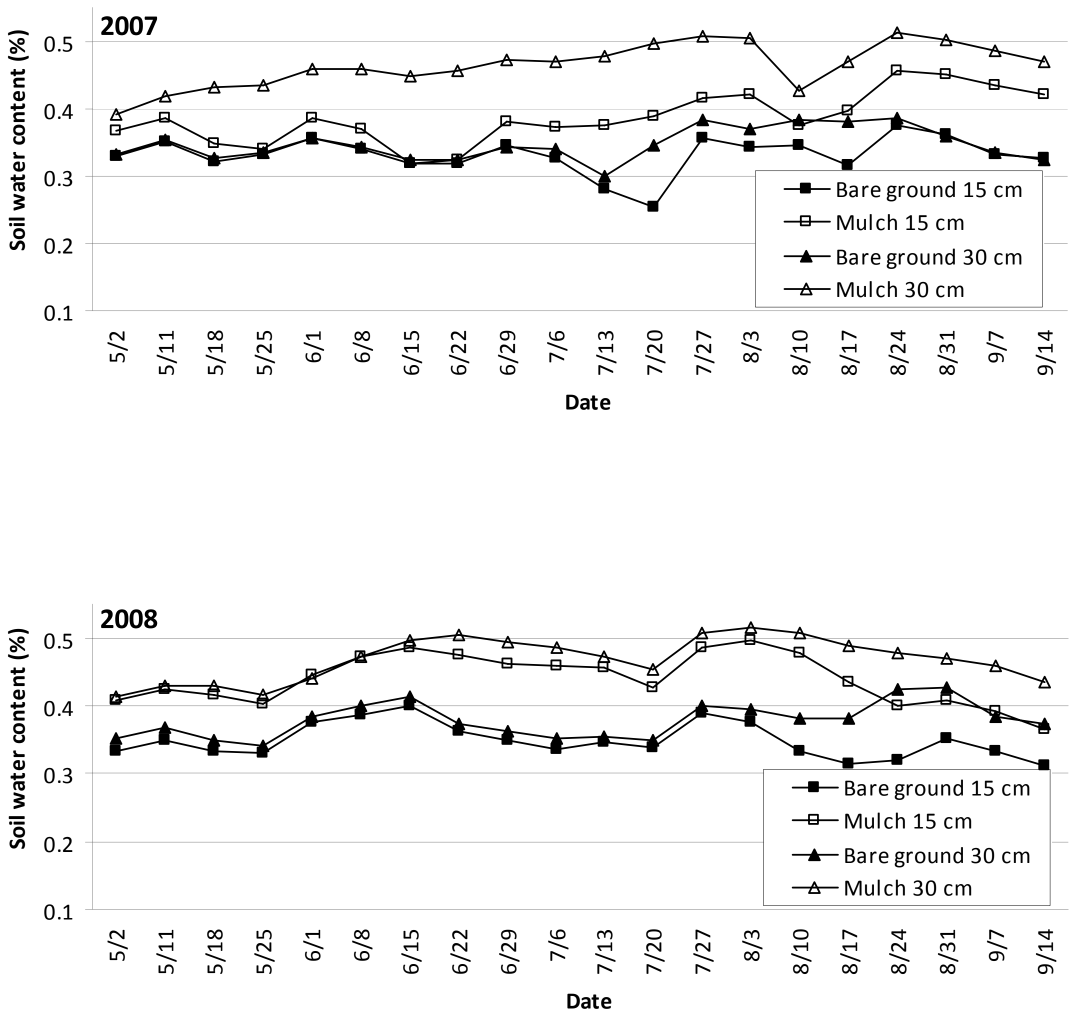


Figure 3. Average weekly soil volumetric water (VWC) content beneath bare-ground and mulched plots at 15 and 30 cm depths in 2007 and 2008.

CHAPTER 4. GENERAL CONCLUSIONS

The goal of this research was to help Midwest growers produce apples in more sustainable ways. Objectives toward this goal were to 1) evaluate new methods of integrated disease, insect, and weed management, and 2) clarify phenology of sooty blotch and flyspeck fungi.

In this study, sooty blotch and flyspeck, codling moth, and other pests were managed effectively by new integrated pest management (IPM) strategies in a fully dwarfed, scab-resistant orchard. The new IPM treatments were comparable to calendar-based and current IPM strategies in terms of yield and incidence of damage due to diseases and insects. In 2007-2008, Treatment 4 (New IPM B) resulted in less labor, fuel, and pesticide costs. This new IPM strategy may have other benefits including lowering environmental, applicator, and consumer risks associated with the use of pesticides. An attempt to quantify these benefits was made using the Field Environmental Impact Quotient (FEIQ) (1). New IPM treatments had the lowest FEIQ ratings, showing that these treatments may be preferable for reducing environmental, applicator and consumer risks. This was due to lower toxicity of pesticide active ingredients and the use of warning systems and scouting which reduced pesticide applications in IPM treatments. The additional benefits quantified by the FEIQ ratings are often overlooked but are arguably as valuable to society as yield and quality in the production of apples (2). The sustainability and safety of conventional farming methods have been questioned for not taking into account these environmental, safety, and social issues (2), and the new IPM techniques explored in this study could ultimately help growers to confront these key concerns.

The weed IPM trial provided evidence that mulch can supplement or replace reliance on chemical herbicides. Composted hardwood mulch coupled with herbicide spot treatments decreased the need for chemical herbicides in mulched compared to bare-ground plots, and mulch reduced weed coverage and biomass. Organic matter and carbon were enhanced in layers near the soil surface, and these benefits could increase in subsequent years of this study as mulch decays. Soil temperature and moisture extremes were also reduced during much of the spring and summer in soil under mulch. It is reasonable to hypothesize that hardwood bark mulch could enhance water use efficiency and fruit size, and protect tree health, during dry growing seasons; however, additional sites and years of field trials would be needed to test these ideas. These horticultural benefits would probably be needed to make mulching sustainable in view of substantial transportation and application costs associated with mulch.

The sooty blotch and flyspeck (SBFS) fungal complex is made up of many recently discovered species whose ecology is poorly understood. Since these fungi vary regionally in prevalence, incidence, and severity, it is useful from a management perspective to understand their behavior. In the present study, these fungi were shown to appear in a characteristic sequence during the growing season in Iowa orchards. Two putative species, sterile mycelia RS1 and RS2, appeared first and were most abundant in the majority of orchards surveyed; therefore, these species may be particularly important in determining fungicide timing according to warning systems that base timing of the 2nd-cover fungicide spray on the timing of initial appearance of SBFS colonies on apple during the growing season. Also, RS1 and RS2 appear only in the Midwest; this can help to explain why warning systems developed for other regions of the country have experienced failures when applied to some Midwest orchards.

It was also shown that colonies of one species, *Dissoconium aciculare*, appeared primarily during refrigerated (4° C) storage, revealing that SBFS development can occur in conditions not normally considered conducive to SBFS development. To my knowledge, this was the first research to characterize phenological development of SBFS taxa.

This research determined that incidence and prevalence of SBFS fungi are related. The number of visible colonies of a particular species per apple was directly proportional to the number of orchards where that species was observed. Species RS1 and RS2 appeared at all locations where SBFS was detected and with more visible colonies per apple than any other species. This was the first research to demonstrate that SBFS prevalence and incidence are related, and is important because it shows that the species which appear first are also the most common in Iowa.

The new IPM tactics explored in this study, along with an increased understanding of the phenology of SBFS fungi, may benefit growers attempting to increase sustainability, profitability, and affordability in apple production in the Midwest.

LITERATURE CITED

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2. Reganold, J.P., Glover, J. D., Andrews, P. K., and Hinman, H. R. 2001. Sustainability of three apple production systems. Nature 410:926-930.

APPENDIX

Table 1. Summary of thresholds determining fungicide and insecticide sprays

	2006		2007		2008	
Variable	**Date**	**Treatment**	**Date**	**Treatment**	**Date**	**Treatment**
Biofix[w]	25-May	2	10-May	2,4	26-May	2,4
120 DD[x]	-	-	17-May	4	5-Jun	4
250 DD	6-Jun	2	24-May	2	9-Jun	2
1250 DD	12-Jul	2	11-Jul	2	28-Jul	2
1st Cover	25-May	1-6	30-May	1-4	5-Jun	1-4
175 Hours LWD[y]	28-Jul	3-6	30-Jul	3	22-Jul	3
192 Hours RH≥97%[z]	-	-	3-Aug	4	2-Aug	4

[w] First sustained capture of five adult male codling moths per trap per week

[x] Degree days (base= 10° C; max=26.6° C)

[y] Leaf wetness duration determined by summing of wet hours reading at ≥ 6 occurring in groups ≥ 4.

[z] Relative humidity duration determined by summing hours at ≥ 97% occurring in groups ≥ 4.

Table 2. Summary of pesticide spray applications 2006

Application schedule	Fungicide	Insecticide
Calendar-based (Treatment 1)		
Half-inch green	captan[a] + myclobutanil[b]	permethrin[c]
Tight cluster	captan + myclobutanil	
Pink	captan + myclobutanil	chlorpyrifos[d]
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover & every 14 days	captan + thiophanate-methyl[e]	phosmet[f]
Conventional IPM (Treatment 2)		
Half-inch green		permethrin
Tight cluster	captan + myclobutanil	
Pink	captan + myclobutanil	chlorpyrifos
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover & every 14 days	captan + thiophanate-methyl	
1250 DD after biofix		phosmet
250 DD after biofix		phosmet
New IPM (Treatment 3)		
Half-inch green		permethrin
Pink	captan + myclobutanil	chlorpyrifos
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover	captan + thiophanate-methyl	
2nd Cover (175 h LWD) & every 14 days	captan + thiophanate-methyl	
1st Cover & every 7 days		virus[g]
New IPM (Treatment 4)		
Half-inch green - 1st cover	---------*Same as Treatment 3*---------	
2nd Cover (175 h LWD) & every 175 h LWD	captan + thiophanate-methyl	
1st Cover & every 14 days		virus
New IPM (Treatment 5)		
Half-inch green - 1st cover	---------*Same as Treatment 3*---------	
2nd Cover (175 h LWD) & every 175 h LWD	captan + thiophanate-methyl	
1st Cover & every 7 days		virus
1st Cover & every 14 days		spinosad[h]
New IPM (Treatment 6)		
Half-inch green - 1st cover	---------*Same as Treatment 3*---------	
2nd Cover (175 h LWD) & every 175 h LWD	captan + kresoxim-methyl[i]	
1st Cover & every 14 days		virus + spinosad

[a] Captan Pro 50 WP Fungicide (378.2 g active ingredient(ai)/ha). Drexel.
[b] Nova 40 W Fungicide (19.3 g ai/ha). Dow Agrosciences.
[c] Pounce 25 WP Insecticide (64.4 g ai/ha. FMC.
[d] Lorsban 50 WP (161.1 g ai/ha). Dow Agrosciences.
[e] Topsin M 70 WDG Fungicide (72.48 g ai/ha). Cerexagri-Nisso.
[f] Imidan 70 W Insecticide (360.9 g ai/ha). Gowen.
[g] Cyd-X Insecticide (0.4 ml ai/ha). Certis USA.
[h] SpinTor 2 SC (11.5 ml ai/ha). Dow Agrosciences.
[i] Sovran (20.95 g ai/ ha). BASF.

Table 3. Summary of pesticide spray applications 2007 & 2008

Application schedule	Fungicide	Insecticide
Calendar-based (Treatment 1)		
Half-inch green	captan[a] + myclobutanil[b]	permethrin[c]
Tight cluster	captan + myclobutanil	
Pink	captan + myclobutanil	permethrin
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover & every 14 days	captan + thiophanate-methyl[d]	phosmet[e]
Conventional IPM (Treatment 2)		
Half-inch green		permethrin
Tight cluster	captan + myclobutanil	
Pink	captan + myclobutanil	permethrin
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover & every 14 days	captan + thiophanate-methyl	
1250 DD after biofix		phosmet
250 DD after biofix		phosmet
New IPM (Treatment 3)		
Half-inch green		permethrin
Pink	captan + myclobutanil	permethrin
Bloom	captan + myclobutanil	
Petal Fall	captan + myclobutanil	permethrin
1st Cover	captan + thiophanate-methyl	
2nd Cover (175 h LWD) & every 14 days	captan + thiophanate-methyl	
1st Cover & every 7 days		granulovirus[f]
New IPM (Treatment 4)		
Half-inch green - 1st Cover	------------*Same as Treatment 3*------------	
2nd Cover (192 h 97 %RH) & every 14 days	captan + myclobutanil	
120 DD after biofix		novaluron[g]
16-18 days after Rimon		thiacloprid[h]
16-18 days after Calypso		granulvirus
7 days after Cyd-X		granulovirus
If CM trap captures >8 per trap per week		thiacloprid
If trap captures increase		granulovirus

[a] Captan Pro 50 WP Fungicide (378.2 g active ingredient(ai)/ha). Drexel.
[b] Nova 40 W Fungicide (19.3 g ai/ha). Dow Agrosciences.
[c] Pounce 25 WP Insecticide (64.4 g ai/ha. FMC.
[d] Topsin M 70 WDG Fungicide (72.48 g ai/ha). Cerexagri-Nisso.
[e] Imidan 70 W Insecticide (360.9 g ai/ha). Gowen.
[f] Cyd-X Insecticide ((0.4 ml ai/ha). Certis USA.
[g] Rimon 0.83 EC Insecticide (31.6 ml ai/ ha). Chemtura USA Corporation.
[h] Calypso 4 Flowable Insecticide (20.4 ml ai/ha). Bayer Cropscience.

Table 4. 2007 theoretical field environmental impact quotient (EIQ) of differing pest management strategies for three apple cultivars using Kovach et al.1992 & 1999 Field EIQ rating system.

Redfree

					Treatment 1		Treatment 2		Treatment 3		Treatment 4	
Trade Name	**Active Ingredient (ai)**	**EIQ**	**Fraction ai**	**Dose/acre**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**
Calypso	thiacloprid	31.3	0.4	0.04	0	0.0	0	0.0	0	0.0	1	0.5
Captan	captan	15.8	0.5	0.69	6	32.0	6	32.0	3	16.0	3	16.0
Cyd-X	*C. pomonella* virus	6.7	0.0	0.06	0	0.0	0	0.0	9	0.0	4	0.0
Imidan	phosmet	23.9	0.7	0.46	5	38.5	2	15.4	0	0.0	0	0.0
Nova	myclobutanil	33.0	0.4	0.04	3	1.7	3	1.7	3	1.7	3	1.7
Rimon	novaluron	14.3	0.1	0.29	0	0.0	0	0.0	0	0.0	2	0.8
Topsin	thiophanate-methyl	22.4	0.5	0.14	5	7.2	5	7.2	2	2.9	2	2.9
Polyram	metiram	40.0	0.8	0.69	2	44.2	2	44.2	2	44.2	2	44.2
Asana	esfenvalerate	39.6	0.1	0.23	1	0.8	1	0.8	1	0.8	1	0.8
Endosulfan	endosulfan	42.1	0.5	0.46	1	9.7	1	9.7	1	9.7	1	9.7
Intrepid	methoxyfenozide	33.4	0.2	0.23	1	1.7	1	1.7	1	1.7	1	1.7
Total Field EIQ						**135.8**		**112.7**		**77.0**		**78.3**

Liberty & Goldrush

					Treatment 1		Treatment 2		Treatment 3		Treatment 4	
Trade Name	**Active Ingredient (ai)**	**EIQ**	**Fraction ai**	**Dose/acre**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**
Calypso	thiacloprid	31.3	0.4	0.04	0	0.0	0	0.0	0	0.0	1	0.5
Captan	captan	15.8	0.5	0.69	9	48.0	9	48.0	5	26.7	5	26.7
Cyd-X	*C. pomonella* virus	6.7	0.0	0.06	0	0.0	0	0.0	13	0.0	4	0.0
Imidan	phosmet	23.9	0.7	0.46	8	61.6	2	15.4	0	0.0	0	0.0
Nova	myclobutanil	33.0	0.4	0.04	3	1.7	3	1.7	3	1.7	3	1.7
Rimon	novaluron	14.3	0.1	0.29	0	0.0	0	0.0	0	0.0	2	0.8
Topsin	thiophanate-methyl	22.4	0.5	0.14	8	11.6	8	11.6	4	5.8	4	5.8
Polyram	metiram	40.0	0.8	0.69	2	44.2	2	44.2	2	44.2	2	44.2
Asana	esfenvalerate	39.6	0.1	0.23	1	0.8	1	0.8	1	0.8	1	0.8
Endosulfan	endosulfan	42.1	0.5	0.46	1	9.7	1	9.7	1	9.7	1	9.7
Intrepid	methoxyfenozide	33.4	0.2	0.23	1	1.7	1	1.7	1	1.7	1	1.7
Total Field EIQ						**179.2**		**133.0**		**90.5**		**91.8**

Table 5. 2008 theoretical field environmental impact quotient (EIQ) of differing pest management strategies for three apple cultivars using Kovach et al.1992 & 1999 Field EIQ rating system.

Redfree

					Treatment 1		**2**		**3**		**4**	
Trade Name	**Active Ingredient (ai)**	**EIQ**	**Fraction ai**	**Dose/acre**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**
Calypso	thiacloprid	31.3	0.4	0.04	0	0.0	0	0.0	0	0.0	2	1.1
Captan	captan	15.8	0.5	0.69	10	53.3	9	48.0	4	21.3	3	16.0
Cyd-X	*C. pomonella* virus	6.7	0.0	0.06	0	0.0	0	0.0	11	0.0	3	0.0
Imidan	phosmet	23.9	0.7	0.46	6	46.2	2	15.4	0	0.0	0	0.0
Nova	myclobutanil	33.0	0.4	0.04	3	1.7	2	1.1	1	0.6	1	0.6
Rimon	novaluron	14.3	0.1	0.29	0	0.0	0	0.0	0	0.0	1	0.4
Topsin	thiophanate-methyl	22.4	0.5	0.14	6	8.7	6	8.7	3	4.3	2	2.9
Sovran	kresoxim-methyl	11.7	0.5	0.04	1	0.3	1	0.3	0	0.0	0	0.0
Pounce	permethrin	88.7	0.3	0.23	2	10.2	2	10.2	2	10.2	2	10.2
Total Field EIQ						**120.3**		**83.7**		**36.5**		**31.1**

Liberty

					Treatment 1		**2**		**3**		**4**	
Trade Name	**Active Ingredient (ai)**	**EIQ**	**Fraction ai**	**Dose/acre**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**
Calypso	thiacloprid	31.3	0.4	0.04	0	0.0	0	0.0	0	0.0	2	1.1
Captan	captan	15.8	0.5	0.69	12	64.0	11	58.6	6	32.0	5	26.7
Cyd-X	*C. pomonella* virus	6.7	0.0	0.06	0	0.0	0	0.0	15	0.0	3	0.0
Imidan	phosmet	23.9	0.7	0.46	8	61.6	2	15.4	0	0.0	0	0.0
Nova	myclobutanil	33.0	0.4	0.04	3	1.7	2	1.1	1	0.6	1	0.6
Rimon	novaluron	14.3	0.1	0.29	0	0.0	0	0.0	0	0.0	1	0.4
Topsin	thiophanate-methyl	22.4	0.5	0.14	8	11.6	8	11.6	5	7.2	4	5.8
Sovran	kresoxim-methyl	11.7	0.5	0.04	1	0.3	1	0.3	0	0.0	0	0.0
Pounce	permethrin	88.7	0.3	0.23	2	10.2	2	10.2	2	10.2	2	10.2
Total Field EIQ						**149.3**		**97.2**		**50.0**		**44.7**

Goldrush

					Treatment 1		**2**		**3**		**4**	
Trade Name	**Active Ingredient (ai)**	**EIQ**	**Fraction ai**	**Dose/acre**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**	**Apps.**	**Field EIQ**
Calypso	thiacloprid	31.3	0.4	0.04	0	0.0	0	0.0	0	0.0	2	1.1
Captan	captan	15.8	0.5	0.69	13	69.3	12	64.0	7	37.3	6	32.0
Cyd-X	*C. pomonella* virus	6.7	0.0	0.06	0	0.0	0	0.0	17	0.0	3	0.0
Imidan	phosmet	23.9	0.7	0.46	9	69.3	3	23.1	0	0.0	0	0.0
Nova	myclobutanil	33.0	0.4	0.04	3	1.7	2	1.1	1	0.6	1	0.6
Rimon	novaluron	14.3	0.1	0.29	0	0.0	0	0.0	0	0.0	1	0.4
Topsin	thiophanate-methyl	22.4	0.5	0.14	9	13.0	9	13.0	6	8.7	5	7.2
Sovran	kresoxim-methyl	11.7	0.5	0.04	1	0.3	1	0.3	0	0.0	0	0.0
Pounce	permethrin	88.7	0.3	0.23	2	10.2	2	10.2	2	10.2	2	10.2
Total Field EIQ						**163.8**		**111.7**		**56.8**		**51.5**

Table 6. Summary of weed management actions, active ingredient glyphosate, and area treated for each treatment for three years.

	2006		2007		2008	
Action	**Mulched**	**Bare ground**	**Mulched**	**Bare ground**	**Mulched**	**Bare ground**
Mulch application	28-Jun	-	-	-	25-Apr	-
Initial spray[u]	24-Apr[v]	24-Apr[v]	2-May[w]	2-May[w]	23-Apr[x]	23-Apr[x]
Glyphosate used (ml/ai)	10.1	10.1	20.2	20.2	20.2	20.2
Area treated (m^2)	83.7	83.7	83.7	83.7	83.7	83.7
Second spray[y]	21-Aug	21-Aug	5-Jun	5-Jun	28-May	28-May
Glyphosate used (ml/ai)	10.1	10.1	7.7	20.2	7.0	2.3
Area treated (m^2)	83.7	83.7	33.5	83.7	30.1	10.0
Third spray	-	-	18-Jul	18-Jul	9-Jun	9-Jun
Glyphosate used (ml/ai)	-	-	20.2	20.2	0.0	20.2
Area treated (m^2)	-	-	83.7	83.7	0.0	83.7
Fourth spray	-	-	-	-	14-Jul	14-Jul
Glyphosate used (ml/ai)	-	-	-	-	20.2	20.2
Area treated (m^2)	-	-	-	-	83.7	83.7
Total glyphosate used (ml/ai)	**20.2**	**20.2**	**48.1**	**60.6**	**47.4**	**62.9**
Total area treated (m^2)	**167.4**	**167.4**	**200.9**	**251.1**	**197.5**	**261.1**
Initial mowing[z]	1-Sep	1-Sep	7-Aug	7-Aug	15-Aug	15-Aug
Second mowing	-	-	30-Aug	30-Aug	-	-

[u] Spray applications triggered by weeds reaching a 12.5 centimeter threshold (applicator boom height).
[v] Roundup Ultramax (1.2 l ai/ha). Monsanto
[w] Roundup Weathermax (2.3 l ai/ha). Monsanto.
[x] Gly-star Plus (2.3 l ai/ha). Cropsmart.
[y] All subsequent sprays consisted of glyphosate generics (2.31 l ai/ha).
[z] Mowing triggered by weeds reaching an 45 centimeter threshold (bottom of tree canopy).

Table 7. Estimated means and corresponding p-values of the differences in means of soil nutrients compared between bare ground and mulch treatments each year.

		Nutrient (ppm)							(%)			
Year	**Treatment**	**P**	**K**	**Ca**	**Mn**	**Mg**	**NH4**	**NO3**	**C**	**N**	**OM**	**pH**
0-15 cm												
2006	**Bare ground**	108.50*	-	3268	55.8	357	1.85	17.7*	1.4	0.16	2.6	7.44
	Mulch	124.60*	-	3125	57.0	368	1.97	24.7*	1.5	0.16	2.7	7.39
2007	**Bare ground**	11.84	120*	2893	61.0	393	9.00**	5.0	1.5	0.14	2.7	7.52
	Mulch	13.35	183*	3077	64.8	437	3.10**	4.0	1.7	0.15	3.1	7.73
2008	**Bare ground**	13.95	98**	2518	57.8	376	1.39	7.7	1.4*	0.14*	2.5*	7.58
	Mulch	24.01	224**	2793	55.6	382	0.80	4.4	1.9*	0.17*	3.5*	8.02
15-30 cm												
2006	**Bare ground**	99.30	-	3476	43.6	366	1.40	16.3**	1.4	0.13	2.5	7.41
	Mulch	101.55	-	3064	44.8	350	1.38	9.5**	1.4	0.14	2.6	7.33
2007	**Bare ground**	14.05	90*	3222	52.5	366	3.80*	4.3	1.4	0.11	2.6	7.57
	Mulch	19.80	110*	3075	49.8	427	1.90*	3.7	1.5	0.12	2.7	7.49
2008	**Bare ground**	15.40	59	3109	41.6	374	1.51	3.3	1.3	0.11	2.4	7.71
	Mulch	19.60	73	2656	48.2	404	0.94	2.1	1.4	0.12	2.5	7.65

* Difference in means significant at p=0.05.

** Difference in means significant at p=0.001.

Table 8. Estimated means and corresponding p-values of the differences in means of leaf nutrients compared between bare ground and mulch treatments each year.

Year	Treatment	Nutrient (ppm)							(%)
		P	**K**	**Zn**	**Fe**	**Mn**	**Ca**	**Mg**	**N**
2007	**Bare ground**	2021	12831**	12.8	81	27	11937	2942*	2.025
	Mulch	1953	8021**	12.8	85	31	13343	4189*	2.027
2008	**Bare ground**	1849*	5992**	110.0	87	27	12880	4250	2.650
	Mulch	2172*	10282**	100.0	93	29	12204	3341	2.617

* Difference in means significant at p=0.05.
** Difference in means significant at p=0.001.

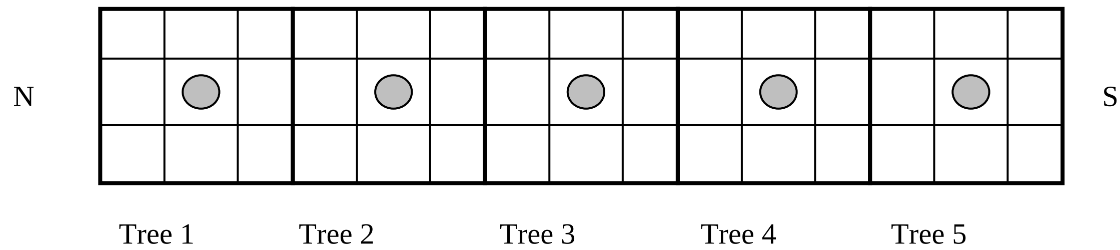

Figure 1. Bare ground and mulch soil sampling grid. This grid represents a five tree subplot, with grey circles corresponding to each tree. The eight spaces around each tree were assigned numbers from a random number table each year. The space with the highest number each year was the area used for soil extraction. Soil cores were 30 cm in length. The first 15 cm of each of five samples were combined and submitted as one sample. The last 15 cm were dealt with in the same fashion. Soil samples were submitted to the Iowa State University Soil and Plant Analysis Laboratory.

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