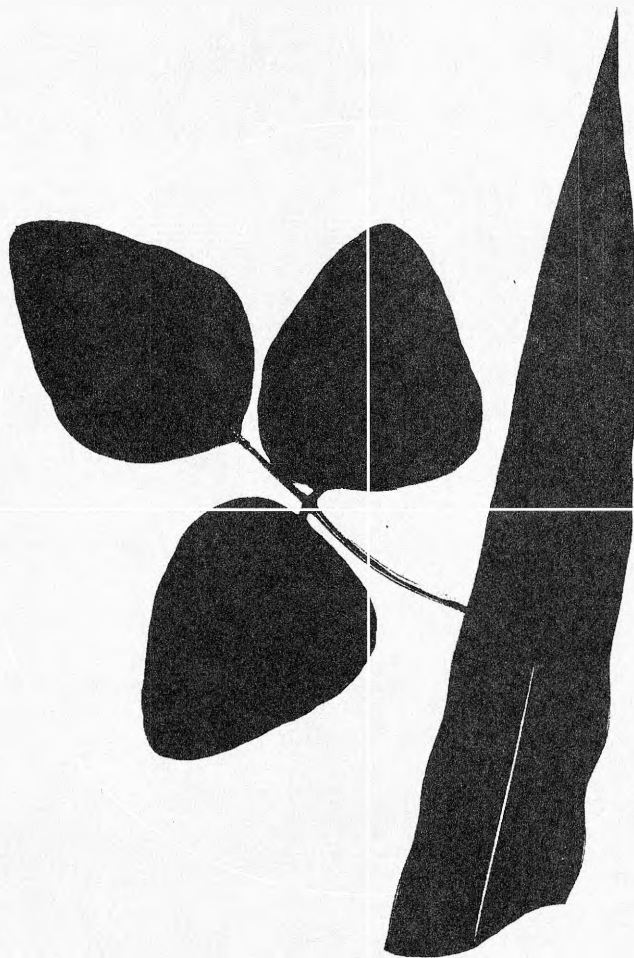


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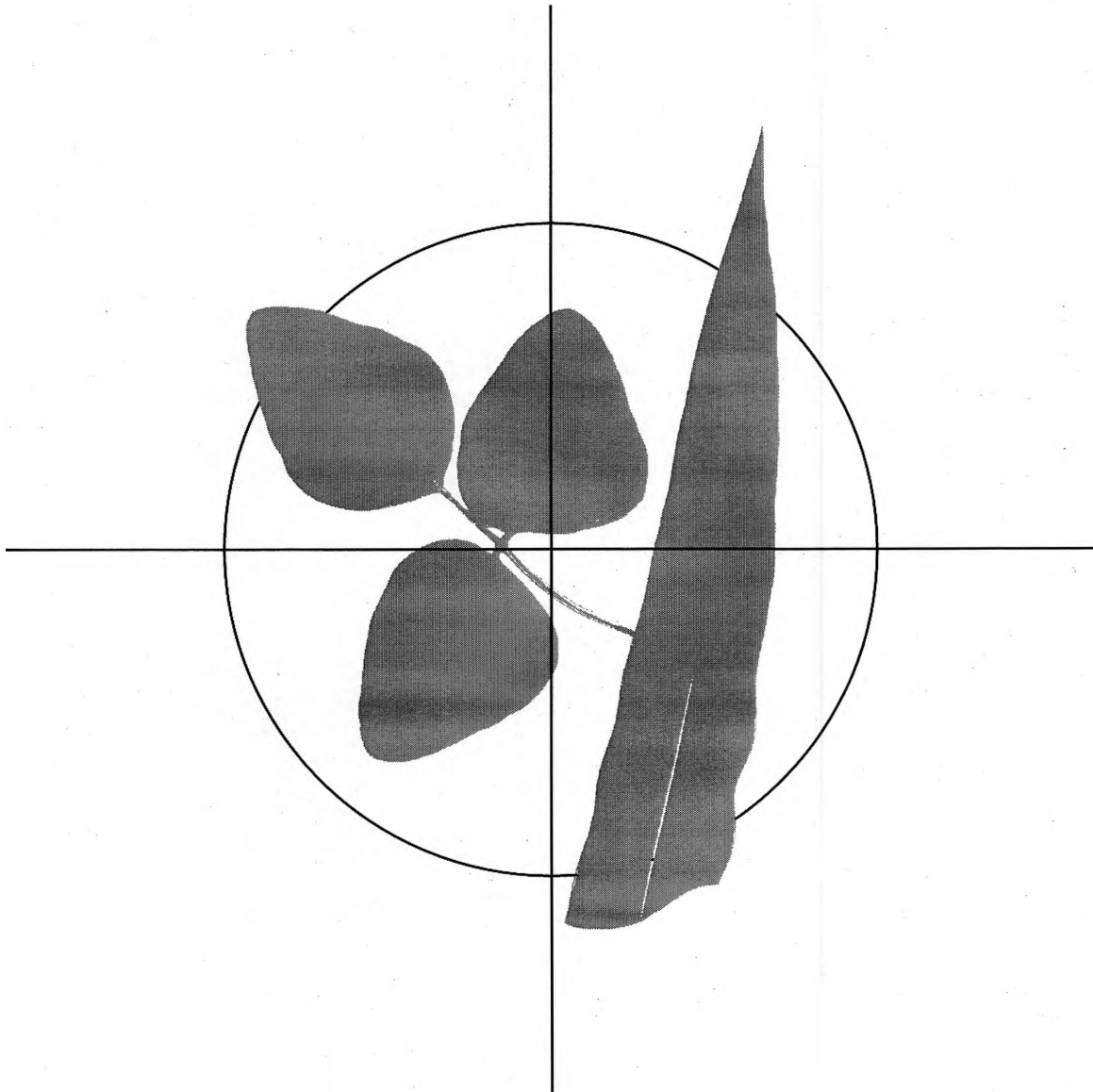
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Illinois Crop Protection Technology Conference Program

Wednesday Morning, January 9

All sessions in Illini Rooms A, B, and C

(Requested: 1.0 CCA credit in Professional Development)

8:30 AM	Welcome and Opening Remarks, <i>Mike Gray</i>
8:40 AM	Preventing Poly Tanks from Cracking Like an Egg, <i>Fred Whitford</i>
9:30–9:45 AM	Break, South Lounge

Symposium: High-Production Soybean Management

(Requested: 1.0 CCA credit in Crop Management and 1.0 CCA credit in Integrated Pest Management)

With more corn and less soybean acreage in 2007 and perhaps the near future, high-yielding soybean fields are important to help meet demand. Will new genetics, different production practices, and pest and disease management tools help soybean producers meet the demand? This symposium will focus on managing the soybean crop, pests, and diseases to achieve high-yielding and high-quality soybean.

9:45 AM	Soybean Management for Maximum Yields AND Profits, <i>Seth Naeve</i>
10:10 AM	Managing Soybean Cyst Nematode for Maximum Soybean Productivity, <i>Greg Tylka</i>
10:35 AM	Foliar Fungicides and Fungicide Seed Treatments: Getting that Return on Investment, <i>Anne Dorrance</i>
11:00 AM	Managing Insects in High-Production Soybeans: Forethought or Afterthought? <i>Kevin Steffey</i>
11:15 AM	Future Soybean Oil and Meal Traits, <i>Dennis Byron</i>
11:35-12:00	Questions and Answers
12:00 NOON–1:00 PM	Lunch, on your own

Symposium: Managing Nutrients and Water Quality—A Balancing Act

(Requested: 1.5 CCA credits in Soil and Water Management and 0.5 CCA credit in Nutrient Management)

Nutrients: It's the best of times, it's the worst of times. This Charles Dickens analogy is quite fitting. We face great opportunities in the

fertilizer sector given the increased corn acres and higher commodity prices. We also face serious challenges with the government hypoxia report calling for significant reductions in nitrate losses from the Upper Midwest, pointing a finger at the practice of fall-applied nitrogen. The speakers will discuss the issues, the latest research regarding nutrient losses, and what you can do to balance crop production and water quality objectives. Can we take the best and worst and make it all good?

1:00 PM	Developing Nutrient Standards for Illinois: Connecting Regulators with Researchers, <i>George Czapar</i>
1:20 PM	Gulf Hypoxia: The Saga Continues, <i>Dennis McKenna</i>
1:40 PM	Considerations for Managing Nitrogen When Switching from Corn/Soybean to Corn/Corn Rotations, <i>T. Scott Murrell</i>
2:05 PM	Hypoxia and the Upper Mississippi River Basin: How Can We Reduce Nutrient Losses from Agriculture? <i>Mark David</i>
2:35 PM	Questions and Answers
2:55–3:15 PM	Break, South Lounge

Symposium: Pest Resistance and Resistance Management: IPM vs. IRM

(Requested: 2.0 CCA credits in Integrated Pest Management)

The rapid increase in the use of transgenic plants has greatly affected how producers manage a broad spectrum of pests. Is the traditional view of IPM relevant in the current agricultural landscape of corn and soybean production? What are the current perspectives on refuge compliance and its relationship to resistance management? Will refuges be required in the future as we "integrate" multiple transgenes in corn and soybean plants? These and other questions will serve as the focus for this symposium and our panel discussion.

3:15 PM	Mechanisms of Fungicide Resistance and a Case Study of Fungicide Resistance in Potato Production, <i>Neil Gudmestad</i>
3:35 PM	Glyphosate-Resistant Weeds: Yes It Can Happen, Even When You Think You Know How to Kill Weeds, <i>Bill Johnson</i>
3:55 PM	Insecticide Resistance in Western Corn Rootworm: What Can We Learn from Previous Mistakes? <i>Blair Siegfried</i>
4:15 PM	Refuge Compliance and Future Requirements—Panel Discussion <i>Mike Gray, Moderator</i>

IRM Refuge Compliance, *Scott Baucum*

Increasing Corn Acres and Prophylactic use of Bt Hybrids: Implications for IPM and IRM,

David Onstad

5:15–6:30 PM

IFCA-Sponsored Mixer
South Lounge

This mixer is sponsored by the Illinois Fertilizer and Chemical Association. It is intended for everyone to meet with speakers, sponsors, and committee members in an informal atmosphere.

Thursday Morning, January 10

All sessions in Illini Rooms A, B, and C

Symposium: IPM in the Crosshairs

(Requested: 2.0 CCA credits in Integrated Pest Management)

The demands for higher yields of corn and soybeans and the availability of extremely effective pest-control technologies have placed significant pressure on integrated pest management (IPM) practices. In fact, some people are beginning to question the relevance of some IPM principles in the context of modern agriculture. Has IPM run its course? This symposium will shed some light on the effects of modern pest management practices on agricultural ecology and the potential role of IPM in the future.

8:00 AM **Managing the Consequences of Long-Term**

Weed Control,

Aaron Hager

8:20 AM

Fungicides on Disease-Free Corn:

The Case from 2007,

Emerson Nafziger

8:40 AM

Fungicides: Do They Adversely Affect Beneficial Insect Pathogens in Multiple Cropping Systems?

David Ragsdale

9:00 AM

How to Lose Money Despite High Crop Prices or Misuses, Misapplications, and Mistakes with Insect Thresholds,

Leon Higley

9:30 AM

Questions and Answers

9:50–10:10 AM

Break, South Lounge

Symposium: High-Production Corn Management

(Requested: 1.0 CCA credit in Crop Management and 1.0 CCA credit in Integrated Pest Management)

Corn market prices were at or near an all-time high in 2007. The cost of producing high-yielding corn is also on the rise, with a nearly bewildering array of inputs and their associated costs. Will the escalating demand for ethanol and the continuing demand for

food change the way we manage the most widely grown crop in North America? This symposium will focus on managing the corn crop and its associated pests to achieve higher yields while preserving environmental integrity.

10:10 AM

Tillage and Fertility Placement Aspects of Root Zone Optimization for Corn,

Tony Vyn

10:30 AM

Agronomics for Corn: Have We Exhausted the Easy Options?

Roger Elmore

10:50 AM

Corn Nematode Management,

Terry Niblack

11:10 AM

Foliar Fungicides in Corn Production: A Look at Local and Regional Data,

Carl Bradley

11:30 AM

The Seven Wonders of the Corn Yield World, *Fred Below*

11:55 AM

Questions and Answers

12:15 PM

Adjourn

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Mike Gray

Sandy Osterbur

Kevin Steffey

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University of Illinois

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Growmark, Inc.

Duane Frederking

Pioneer Hi-Bred International, Inc.

Mike Hellmer

Pioneer Hi-Bred International, Inc.

Gerald Kirbach

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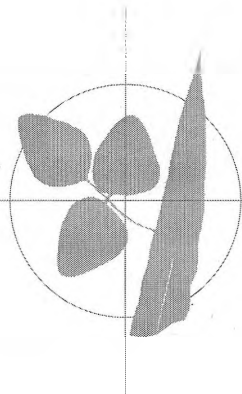
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Preventing Poly Tanks from Cracking Like an Egg

Fred Whitford

Copyrighted Extracts. Draft Only—Do Not Copy. Will be published in 2008 as a Purdue Pesticide Programs Publication. Check www.btny.purdue/ppp for Poly Tanks on Farms and Businesses: Preventing Catastrophic Failures.

Tanks constructed from plastic are commonly used on farms and by commercial pesticide and fertilizer application businesses. These plastic tanks help to more efficiently manage the storage and transportation of water and a host of other liquids such as pesticide and fertilizer products. Plastic tanks—called polyethylene or “poly” tanks—are quite popular.

While the attributes of poly tanks are many, their use has a potentially serious drawback—at some point in time, *they will fail*. No product is designed to last forever. Poly tank useful life depends on a number of factors, including the quality and amount of poly material used to manufacture the tank, the materials stored within them, and the tanks used. The challenge is to replace the tank before it ruptures; the hard part is knowing when to do this or assessing the risk of failure. Trying to get one more year out of an “old” tank can be a serious economic and environmental mistake when its structural integrity is pushed beyond its design capability.

No one likes spending money replacing a tank that *might* still have a “few” years left in it. Realistically, there have been many instances where a poly tank that needed replacing was still being used when—“for no apparent reason”—the side walls gave way, spilling the tank’s contents onto land and into water. Not only is the value of the spilled material written off as a complete loss, but the cost of cleaning up the spill can exceed the actual value of the product by thousands of dollars. In some cases, regulatory costs for restoring the environment (e.g., replacing fish) can be added to the total bill of an accidental release. Replacing used tanks should be viewed as equivalent to changing a vehicle’s tires, oil, filters,

and hoses; each has a limited operational life. Failing to do routine inspections and maintenance can result in expensive repairs, downtime, and aggravation.

Tank Material Construction

Poly tanks are built with highly durable and chemical-resistant resins formulated for today’s pesticides and fertilizers. Poly tanks generally are manufactured by using a process known as rotational molding. A powdered polymer compound with ultraviolet (UV) protection is poured into a two-piece mold. The mold is clamped shut and heated in a hot oven. Once completed, the mold is moved into a cooling chamber where the temperature is slowly decreased. The completed tank is then removed from the mold.

Poly tanks are molded as a single piece. A visible external seam—known as the parting line—gives the impression that two pieces are joined together at that line. The parting line is an external cosmetic artifact left over from the manufacturing process where the two halves of the mold were connected.

SPECIFIC GRAVITY

A measure of a poly tank’s ability to hold materials is based on its specific gravity rating. The specific gravity of a substance is a comparison of the chemistry (weight) of that substance to that of water. Higher specific gravity ratings mean the tank has greater ability to withstand hydrostatic stresses that can be caused by a stored liquid. Manufacturers have designed tanks with specific gravities ranging from 1.0 to 1.9 or more.

So, what do these specific ratings mean? Understanding how specific gravity is used in the evaluation of a poly tank begins with knowing that water weighs 8.334 pounds per gallon.

Water is assigned a specific gravity of 1.0, and all other specific gravities are relative to the weight of water. For instance, a poly tank with a specific gravity of 1.0 means it is designed to hold the weight of water and any other liquids weighing 8.334 pounds or less per gallon.

A poly tank rated at a 1.5 specific gravity is designed to handle the weight of a liquid product that is 1.5 times the weight of water (1.5×8.334). This means that a 1.5 specific gravity tank is built to withstand the internal forces of liquids weighing up to 12.5 pounds per gallon, while a 1.9 specific gravity tank can store products weighing up to 15.8 pounds per gallon.

In general, the weight of liquid fertilizers ranges from 10 to 12 pounds per gallon. Specifically, 10-34-0 liquid fertilizer weighs 11.67 pounds per gallon, while 28-0-0 liquid fertilizer weighs 10.7 pounds per gallon. Most pesticides weigh slightly below or just above the weight of a gallon of water. Thus, at a minimum, fertilizers should be stored in poly tanks with at least a 1.5 specific gravity rating. For safety reasons, a higher specific gravity tank is preferred for bulk pesticide storage, because their accidental release into the environment has significantly more negative consequences compared to those of fertilizers.

Tank Design: Vertical Storage and Horizontal Transport

Poly tanks are divided into two distinct use designs: vertical tanks (also called stationary, upright, or “hockey puck” tanks) and horizontal tanks (side-to-side, transport, application, or leg tanks). There are significant design differences between vertical tanks and horizontal tanks that dictate how they can and, more importantly, cannot be used. Using a tank outside of its design specifications will not only void the manufacturer’s warranty, but it will increase the odds of tank deterioration, tank failure, costly cleanups, and lost inventory.

Vertical tanks are flat-bottomed, cylindrical tanks designed and manufactured specifically for stationary placement on reasonably smooth, leveled surfaces. As the tank fills, the pressure of the liquid forces the wall to flex outwardly. As the tank is emptied, the walls revert back to their original shape. The pressure of the liquid is determined by the liquid’s specific gravity and the fluid depth. To strengthen the tank, a manufacturer thickens the plastic where the side walls contact the tank bottom, where pressure exerted on the wall is the greatest.

Horizontal tanks are designed for placement on trucks, trailers, and field sprayers. They can also be used as stationary

tanks. Pressure points on horizontal tanks are much different than those found on vertical tanks—liquid moves forward when the truck stops and backward as it accelerates, creating a surging effect that exerts the pressure on the front and back walls of the poly tank. Horizontal tanks also differ from vertical tanks in that they come with tie-down features that are more substantial in nature than vertical tanks. These tie-downs include pipe hoops and metal bands that are capable of holding the tank in place if the trailer or truck suddenly stops. In addition, the steel tubing and metal straps are used to support the sides when the tank is full.

Six Questions to Ask When Purchasing a Poly Tank

Often the decision to purchase one tank over another is predicated on cost. You may think you are getting a great deal on a less expensive tank, because you generally assume there can be little or no difference between two seemingly identical tanks. But without information such as its specific gravity rating and tank warranties, the less expensive tank may not actually be a better deal. Comparing tanks with similar specifications is the only way to accurately price tanks. Consider the following six questions when purchasing a poly tank.

Question 1. What size poly tank do I need to purchase?

Question 2. How will I use the poly tank?

Question 3. What specific gravity should I select?

Question 4. What level of service do I expect?

Question 5. How much does the poly tank really cost?

Question 6. How does the cost of the poly tank compare with other materials used to manufacture tanks?

Tank Longevity: How Long Can I Expect the Tank to Last?

Most farmers and business owners expect to use their storage, transport, and application tanks well beyond the 3 to 5 year manufacturer’s warranty. This obviously brings up the question: “How old is too old for a tank?” or “How long will a tank last?” No one can predict how long any given tank will last. There is not, nor has there ever been, a set rule that says a tank needs to be taken out of service at a certain age. It’s an impossible question to answer with any confidence or accuracy! All tank products fail at some time or another.

TABLE 1 • Factors that shorten and extend the life of a poly tank.

Contributing factor	Shortens life of tank	Extends life of tank
tank specific gravity rating	lower specific gravity rating	higher specific gravity rating
filling/refilling	frequent	infrequent
exposure to sunlight	constant exposure	covered and sheltered
operation	transportation	stationary
liquid type	reacts with tank	nonreactive (e.g., water)

Factors That Influence Longevity

A number of factors influence how long a tank remains serviceable. The factors shown in Table 1 all contribute to answering the question of how long a tank will last. However, the exact number of useable years varies highly from location to location. The only true way to assess the deterioration and damage of a tank is to do routine inspections and testing in the fall and spring. The surest way to avoid tank failures is to replace the poly tank when the warranty expires. Others will base their decision to replace a tank on the findings from an inspection and testing of the tank.

Fall and Spring Tank Inspections

Whether it's an 8-year-old application tank or one that you've used for 20 years, the only way to know whether a tank is structurally sound for use is to perform an inspection in the fall at the end of the season and in the spring prior to first fill for spring planting. Inspections at the end of the application season provide ample time to purchase a new tank if the old one is found defective or deemed unreliable. The inspection in the spring prior to filling provides reassurance that the tanks can safely store or transport the anticipated fertilizers and/or pesticides that will be placed into them.

It can be difficult to visually separate a good tank from a bad tank. Two simple inspection techniques—marking with a water-soluble pen and the “baseball bat test”—can pinpoint weakened walls and stressed areas around the fittings.

MARKING THE TANK WITH A WATER-SOLUBLE BLACK MARKER

The water-soluble marker can be used during inspections to highlight cracks and scratches on and in the tank. More importantly, this inspection technique can be used to pinpoint internal lines known as “crazing” within the resin. Crazing can be caused by physical damage or be the starting signs of UV damage. UV crazing is hard-to-see damage formed in

areas where the tank receives maximum sunlight exposure or stress. These lines may be made more visible to the eye with the marker coloring. Crazing or excessive surface oxidation is one of the first signs of deterioration. Tanks with crazing should be checked often, and consideration should be given to putting the tank to other uses (e.g., water tank).

Rub the marker over a 6- by 6-inch section around the sides of the tank exposed to sun, on its top, and around any fitting. Quickly rub off the ink with a dry cloth or paper towel. What is left behind is the ink that has penetrated into the surface of the tank.

In many cases, rubbing the ink off reveals no obvious signs of crazing or cracking. These tanks are in all likelihood good for another season of use. If the ink reveals evidence of cracking where the lines go in both directions, this represents classic UV radiation damage. An indication of advanced deterioration to the plastic is when a checkered appearance, or “dry rot,” look is seen on the tank's walls. Tanks showing this type of cracking have lost much of their plasticity, and they should be replaced or removed from service for chemical storage or transportation.

The first signs of UV damage on a tank—where the lines are parallel to each other but not connected—are also an indication of the beginnings of deterioration. These cracks will need to be watched more closely during the upcoming years. The only exception is that tanks with parallel lines in the plastic around the tank fittings should be immediately replaced or used for water.

HITTING AN EMPTY TANK WITH A BASEBALL BAT

Empty tanks showing UV cracking can be further evaluated by striking the affected area with a baseball bat. (It seems that most people are afraid to hit their tank with a bat for fear that they might break it!) This test reveals the symptoms of UV breakdown in the plastic. If the hit breaks the tank, it should not be in service. It may seem too aggressive a test,

but it is a better option than a tank breaking that is filled with product.

A good tank has flexibility to bend outward as the tank is filled and inward as the tank is emptied. Tanks that are brittle (excessive and advanced cracking) lose their ability to flex or rebound. To test the brittleness of the tank, take a baseball bat, and, with a solid swing, hit the empty tank where signs of cracking have been discovered by the water-soluble pen inspection. Hit the tank on the top and along the sides that receive most of the sunlight. Check the tank for signs of breaking after hitting it with a bat. Using this method, it is impossible to crack a tank that still retains resiliency—and, thus, strength—in its resin. Obviously, if the tank cracks or breaks open after being hit by a bat, the tank will have to be replaced.

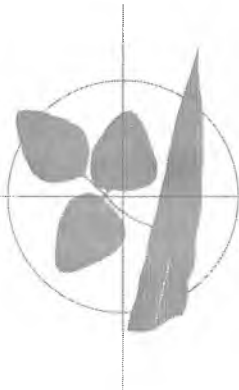
Conclusions

High-density polyethylene tanks have been successfully used for years by growers and commercial pesticide application businesses. Polyethylene tanks offer many advantages for

the producer and business owner. Lower cost compared with other tanks (such as stainless steel and fiberglass), ease of movement when empty, and rust resistance are just three of the advantages. Polyethylene tanks are low maintenance and are a relatively reliable means of storing and transporting liquids.

While the benefits of poly tank ownership are proven and well established, the risk of tank failure is real. Like any piece of equipment, poly tanks need to be maintained and inspected so that the benefits of use outweigh the risk of tank failures and subsequent product releases.

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Managing Soybean Cyst Nematode for Maximum Soybean Productivity

Gregory L. Tylka

The soybean cyst nematode (SCN), *Heterodera glycines*, has plagued midwestern soybean production for several decades. It continues to be a serious, yield-limiting pest of soybeans throughout the Midwest, causing yield losses directly as well as indirectly by intensifying other serious soybean diseases.

SCN is widely distributed throughout the most soybean-producing states in the Midwest. It was found in 74% of Iowa fields and 82% of Illinois fields in a random survey in the mid-1990s (Workneh et al. 1999). The nematode has excellent long-term survival, and its population densities build up each year that susceptible soybeans are grown, regardless of the rainfall and temperature that occur during the growing season. Up to 40% yield loss can occur without the appearance of any aboveground symptoms (Wang et al. 2003).

The SCN life cycle begins when the juvenile worm hatches from the egg (Figure 1). This juvenile cannot develop further until it enters a soybean root and successfully establishes and maintains a feeding site composed of living, but drastically altered, soybean root cells. With adequate nutrition, the hatched SCN juvenile passes through two additional juvenile stages while feeding inside the root before becoming an adult. As SCN females develop, the juvenile stages swell, eventually becoming round or lemon shaped.

The fully formed SCN female is as large as the period at the end of this sentence. The female's size causes it to rupture through and be exposed on the surface of the root. Development of SCN males is very similar to that of females until just before adulthood. At that time, the swollen male juveniles revert back into a worm shape, stop feeding, and exit the root to migrate through the soil. Adult males in the soil are attracted to adult females on the root surface by compounds produced by the SCN female, and mating occurs on the root surface.

After mating, the SCN females begin to produce eggs. The SCN female first produces approximately 50 eggs outside the body in a gelatinous material to form an egg mass. Once the egg-mass eggs are deposited, additional eggs begin to be retained inside the SCN female body cavity. There will be up to 200 or more eggs formed within the SCN female body cavity. Eventually, the SCN female dies, and her body wall turns tough and leathery to form a protective covering of the eggs called the cyst.

For all practical purposes, SCN can never be eliminated from a field once it is present. However, there are things that can be done to manage the nematode in order to maximize soybean yields and minimize reproduction of the nema-

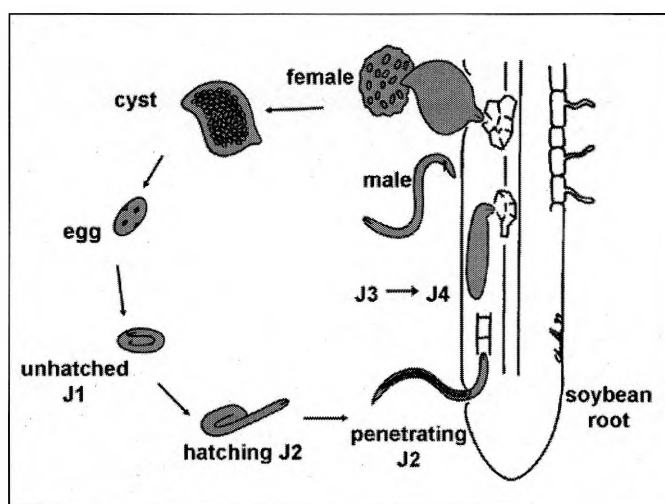


FIGURE 1 • Diagram of the life cycle of the soybean cyst nematode. J1 = first-stage juvenile, J2 = second-stage juvenile, J3 = third-stage juvenile, J4 = fourth-stage juvenile. Not all of the life stages illustrated are drawn to the same scale.

tode. Effective management of SCN involves an integrated approach of scouting for early detection of infestations, followed by proper use of resistant soybean varieties in rotation with nonhost crops in infested fields. Also, a few soil-applied nematicides are available for management of the nematode. The economics of fieldwide application of such chemicals need to be considered before utilizing this management strategy.

SCN-Resistant Soybean Varieties

SCN-resistant soybean varieties are not immune; they can allow up to 10% SCN reproduction. But allowing only 10% reproduction means the varieties are providing 90% control. So, SCN-resistant varieties not only produce greater yields than susceptible varieties in SCN-infested fields, but they also prevent large increases in SCN population densities. The suppression of SCN reproduction afforded by SCN-resistant varieties allows for profitable, long-term production of soybeans in SCN-infested fields.

The Iowa State University (ISU) SCN-Resistant Soybean Variety Trial Program annually evaluates the yield and SCN control provided by a large number of SCN-resistant soybean varieties available to Iowa growers in field experiments conducted at various locations throughout the state. Varieties are grown in replicated plots at each experimental location. Soil samples are collected from each four-row plot (ten soil cores from the center two rows of each plot) at the time of planting and analyzed to verify the presence of SCN in every plot. At harvest time, another soil sample is collected from each four-row plot, and SCN population densities are determined to assess how well the SCN population reproduced on the soybean variety grown in each plot. Commonly grown, SCN-susceptible varieties are included in each experiment.

The average yield of the numerous SCN-resistant soybean varieties in the Melrose and Churdan, Iowa, locations of the ISU SCN-Resistant Variety Trial Program compared to the four SCN-susceptible varieties included in each trial in 2006 are shown in Table 1. Also presented in the table are average end-of-season SCN population densities in plots planted with the SCN-resistant and SCN-susceptible varieties at these locations in 2006.

At the Melrose location, SCN-resistant soybeans yielded, on average, 4 to 5 bushels per acre more than SCN-susceptible soybean varieties, and there was 6 to 13 times more SCN reproduction on the susceptible varieties than on the resistant varieties. At Churdan, SCN-resistant soybeans yielded, on average, 16 to 17 bushels per acre more than SCN-susceptible soybean varieties, and the susceptible varieties allowed 8 to 14 times more SCN reproduction than the resistant varieties. These data clearly illustrate that SCN-resistant soybean varieties pay dividends twice—in the form of increased yields and in control of SCN population densities.

At the time that these conference proceedings were compiled, final SCN egg population density data were not yet available for the 2007 ISU SCN-Resistant Soybean Variety Trial Program locations. However, the summary yield data from 2007 for the SCN-resistant soybean varieties and the susceptible varieties, shown in Table 2, again illustrate the increased yield of SCN-resistant soybean varieties relative to susceptible soybean varieties in SCN-infested fields. In most of these variety trial locations in 2007, the SCN-resistant varieties, as a group, produced greater yields than the widely grown, SCN-susceptible soybean varieties. The smallest positive yield difference between resistant and susceptible varieties in 2007 was 1.5 bushels per acre at the Council Bluffs location, in southwest Iowa, where the initial SCN population density was 515 eggs per 100 cc of soil. And the

TABLE 1 • Average yield and end-of-season SCN population densities of SCN-resistant and SCN-susceptible varieties at the Melrose and Churdan locations of the ISU SCN-Resistant Soybean Variety Trial Program in 2006.

Location and variety type	Yield (bu/A)		Final SCN population densities (eggs per 100 cc soil)	
	Resistant varieties	Susceptible varieties	Resistant varieties	Susceptible varieties
Churdan				
Roundup Ready®	55.7	40.5	2,460	19,594
Conventional	52.2	34.6	1,629	22,568
Melrose				
Roundup Ready®	52.1	46.8	1,762	11,444
Conventional	52.2	48.2	936	13,168

TABLE 2 • Average yield of SCN-resistant and SCN-susceptible varieties at several locations of the ISU SCN-Resistant Soybean Variety Trial Program in 2007.

Location	Initial SCN population density (eggs/100 cc)	Yield (bu/A)		Yield benefit (bu/A)
		Resistant varieties	Susceptible varieties	
Northern Iowa District				
Albert City	3,353	63.0	51.8	11.2
Manchester	301	58.9	60.2	1.3
Vincent	4,001	45.4	31.2	14.2
Central Iowa District				
Cambridge	3,156	59.3	55.1	4.2
Farnhamville	5,461	54.8	48.0	6.8
Urbana	5,369	59.5	52.6	6.9
Southern Iowa District				
Council Bluffs	515	67.4	65.9	1.5
Crawfordsville	2,329	57.2	59.8	-2.6
Melrose	5,242	60.9	50.8	10.1

greatest yield difference, 14.2 bushels per acre, occurred at the Vincent location, in north-central Iowa, where the initial SCN population density was 4,001 eggs per 100 cc of soil.

In two of the ISU SCN-Resistant Soybean Variety Trial Program locations in 2007, the SCN-susceptible varieties yielded more than the SCN-resistant varieties as a group (Table 2). This occurred at Manchester, in northeast Iowa, where the initial SCN population density was very low (301 eggs per 100 cc of soil) and in Crawfordsville in southeast Iowa, where there was an initial SCN population density of 2,329 eggs per 100 cc of soil. Complete yield and SCN population density data from the 2007 ISU SCN-Resistant Soybean Variety Trial Program experiments will be available online in early 2008 at www.isuscntrials.info.

SCN Populations That Can Reproduce on PI 88788 Resistance

Surveys have been conducted and are ongoing in several Midwest states to determine how well the SCN populations can reproduce on the various sources of SCN resistance. In 1991, Sikora and Noel reported that 34% (15 of 44) of surveyed SCN populations in Illinois had >10% reproduction on PI 88788. But 65% of 260 SCN populations from Illinois surveyed in 2005 had >10% reproduction on PI 88788 (T.L. Niblack, personal communication). Niblack et al. (2003) reported that nearly 60% of 183 SCN populations obtained through a random survey of Missouri in 1998 had >10% reproduction

on PI 88788, but Mitchum et al. (2007) reported that 78% of 45 samples collected from Missouri in 2005 had >10% reproduction on PI 88788.

Many Iowa SCN populations are able to reproduce greater than 10% on PI 88788, too. In fact, the SCN populations in about half of the ISU SCN-Resistant Soybean Variety Trial Program locations from 2005 to 2007 had >10% reproduction on PI 88788. And, although almost all of the SCN-resistant varieties evaluated in the ISU SCN-Resistant Soybean Variety Trial Program have SCN resistance genes from PI 88788, most of the resistant varieties usually yielded greater than the susceptible varieties at these locations.

Use of Nonhost Crops

There are many crops on which SCN is unable to feed. These are called nonhost crops. Corn, most small grains, and some legumes are nonhosts for SCN. The greatest decrease in SCN population densities may occur during the first year a nonhost crop is grown after a soybean crop. In general, growing corn for 1 year after a soybean crop in Iowa will reduce the SCN population density from as little as a few percent to as much as 50%. It is not known why there is so much variation in the effect of corn on SCN population densities from year to year. SCN population densities decline less in the second year of corn after a soybean crop, and even less in the third year of corn in Iowa.

Summary

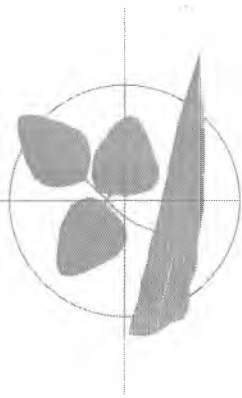
SCN is a very damaging, long-lived, and widespread pest of soybeans. Successful, long-term management of SCN requires growing SCN-resistant soybean varieties in rotation with the nonhost crop corn.

SCN-resistant soybean varieties are an effective and affordable tool to manage SCN, providing greater yields than susceptible varieties and preventing increases in SCN population densities. Almost all SCN-resistant soybean varieties available to Iowa and Illinois growers possess SCN-resistance genes from PI 88788 (Tylka 2006; Shier 2007), and it is no longer uncommon for SCN populations to have 10% or greater reproduction on PI 88788. But SCN-resistant varieties with PI 88788 as the source of resistance continue to yield better than susceptible soybean varieties and also continue to prevent increases in SCN population densities throughout the growing season. So, growing resistant varieties is still an effective way to manage SCN.

SCN-resistant varieties with different sources of resistance should be rotated whenever possible to reduce selection of SCN populations that can reproduce on SCN-resistant varieties. And growers who have managed SCN with resistant soybean varieties for several years should collect soil samples from fields and determine SCN population densities to assess whether nematode population densities are increasing.

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Foliar Fungicides and Fungicide Seed Treatments: Getting That Return on Investment

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Fungicide use on soybeans, both from seed treatment and foliar applications, has been increasing over the past five years. These added inputs can cost from \$4 to \$28 per acre, depending on the fungicide active ingredient and application costs. We evaluated several different compounds both in on-farm studies and research plot studies to determine what conditions favor the greatest return. This article is separated into two parts: Foliar Fungicides and Seed Treatment Fungicides.

Foliar Fungicides

The use of foliar fungicides is a routine practice in the southern U.S. (Tennessee, Arkansas, Georgia, Mississippi, Alabama, and Louisiana) to manage frogeye leaf spot, purple leaf stain, southern stem canker, and aerial blight. In the north-central U.S., none of these diseases are present at economic levels with one exception, frogeye leaf spot during the 2006 and 2007 production season in Ohio. The most common foliar diseases in Ohio are brown spot and downy mildew. Soybean rust has not been found (infected leaves with sporulating pustules) to impact the crop in Ohio.

We have taken three approaches to evaluate the impact of foliar fungicides on soybeans in Ohio:

1. the combination of fungicide and insecticides in on-farm trials
2. the impact of strobilurin and triazole fungicides on brown spot
3. the effects of brown spot on soybean yield

The primary foliar pathogen in Ohio is brown spot caused by *Septoria glycines*. This is believed to be a minor pathogen because it infects older leaves in the lower canopy and rarely

moves up into the midcanopy until R7–R8. The following is a brief summary of each of these studies.

EVALUATION OF THE COMBINATION OF FUNGICIDES AND INSECTICIDES IN ON-FARM TRIALS

For these trials, large fields (50 acres or more) were selected. Producers and county Extension educators applied treatments using their own equipment and harvested the plots. The study was treated in a randomized block design with three to five replications, depending on the size of the field. Data were collected 3 weeks after the last application on the incidence and severity of brown spot and other foliar diseases, if present, and aphids. During 2004 and 2005, the treatments were Quadris (6.4 fl oz/A), Warrior (3.2 fl oz/A), Quadris plus Warrior (6.4 and 3.2 fl oz/A, respectively), and a nontreated strip. During 2006, the treatments were Headline (6.0 fl oz/A), Folicur (4.0 fl oz/A), Headline plus Folicur (4.7 and 3.2 fl oz/A, respectively), and a nontreated control strip. During 2007, the treatments were Headline (6.0 fl oz/A), Domark (4.0 fl oz/A), and a nontreated strip.

There was no significant difference in the levels of brown spot at any of the locations during the 4 years of this study. During 2004, 2006, and 2007, aphids were not found in any of the locations, but, during 2005, high levels of aphids were identified in some of the locations. Frogeye leaf spot was present in three locations during 2006 and none in 2007.

These studies found no consistent advantage in the application of Quadris, Headline, or Domark (Tables 1–4). Across all studies, Quadris and Headline contributed to an increase in yield 50% of the time, with an average increase of 3.5 bushels per acre. Warrior provided excellent control of soybean aphids; however, timing of applications was better at the

recommended time (250 aphids per plant) compared to applications made at the R₃ growth stage with lower aphid populations.

In two fields, aphid populations were low at the R₃ growth stage, and the fields required a second application or did not get the huge benefit of the insecticide.

STROBILURIN AND TRIAZOLE CONTROL OF BROWN SPOT

During 2006, four soybean varieties were planted at the OARDC Northwestern and Western research stations. This study consisted of Headline, Folicur, Headline plus Folicur, Quadris applied at R₃ and R₅ growth stages, and two nontreated plots. The study was arranged in a split-plot design, where the varieties were replicated first, then, for each variety, the fungicide treatments were randomized.

In both locations of this study, fungicide treatments increased yields, albeit at 3.4 and 6.8 bushels at Northwestern and

TABLE 1 • Comparison of Quadris and Warrior to the nontreated control during 2004.

There were no aphids and very low levels of foliar-feeding insects. Only at the Hardin and Wood locations were the treatments significantly better than the control, and, in these situations, the increase over the nontreated controls was 5 and 3.5 bushels per acre.

2004 location	Quadris + Warrior, yield difference from nontreated (bu/A)
Henry/Beck	-2.0
Henry/Fritz	-0.6
Hardin/Shick	5.4*
Hancock/Wilson	4.1
Woods/Keys	3.1*
Fulton/Shininger	-4.1
Miami/Worthington	0.4
Miami/Hodge	2.2
Shelby/Joslin	3.9
Morrow/Weiler	-0.6
Wayne/OARDC	-1.1
Wooster/OARDC	1.9

* Denotes that yield was significantly different than that of the nontreated controls for that location ($P = 0.05$).

Western from one untreated plot and 1.5 and 4.3 from the second untreated plot at the same locations (Table 5).

EFFECTS OF BROWN SPOT ON YIELD

For the final study, we assessed disease severity levels of brown spot on four soybean varieties treated with Echo (chlorothalonil) at two locations. This study was arranged in a split-plot design, with the varieties replicated first and chlorothalonil treatments as the subplots. (Note: This is not a labeled use of chlorothalonil; this study was done to determine

TABLE 2 • Five of the locations with very low or no aphid pressure during 2005. For these fields, Warrior was significantly better than the nontreated controls in Hardin and Licking counties. Both locations had a high amount of feeding from grasshoppers and Japanese beetles.

2005 location	Yield difference from nontreated (bu/A)		
	Quadris	Warrior	Quadris + Warrior
Fayette	-0.2	4.6	2.2
Hancock	-0.6	0.5	5.5
Hardin	1.2	4.5	6.0
Licking	4.2	3.0	5.1
Morrow	2.2	4.4	4.8

TABLE 3 • Seven of the locations had very high aphid populations. For all but one location, treatments were significantly better than the controls. In these cases, Warrior alone was providing the protection.

2005 location	Yield difference from nontreated (bu/A)		
	Quadris	Warrior	Quadris + Warrior
Fulton	1.0	13.0	12.5
Henry/B	3.1	7.0	7.3
Henry/F	3.1	13.6	15.3
Ottawa	-1.5	8.0	8.1
Shelby/J	0.1	3.8	2.6
Wood/M	0.2	0.9	4.3
Wood/S	5.1	15.2	16.2

TABLE 4 • Difference from nontreated control during 2006 and 2007 in on-farm evaluations. Three locations during 2006 had 0.5% to 3.0% leaf area affected by *Cercospora sojina*, which causes frogeye leaf spot during 2006, but no fields were heavily impacted during 2007.

Location	2006			2007	
	Headline	Folicur	Headline + Folicur	Headline	Domark
Ross	8.6	3.6	6.8	3.6	2.5
Ross	—	—	—	1.3	-1.4
Wood	0.2	0.3	1.1	6.3	5.3
Fayette	4.3	1.4	9.8		
Hardin	4.8	-0.2	1.6	0.7	-0.6
Henry	0.3	1.2	1.7		
Shelby	3.7	3.0	2.2		
Overall	3.5	1.5	4.1	3.2	1.7

the effects of brown spot). Echo was applied, almost weekly, beginning at V1 (first fully expanded trifoliolate) until R6 (full seed). The total number of Echo applications in this study ranged from 0 to 10. Again, this is not a labeled use of chlorothalonil and is the type of study suited only for research farms.

In this study, disease severity was reduced with the weekly applications of Echo and yield was increased (Table 6). Final yields were 4 and 2.8 bushels per acre over the nontreated control at Western and Northwestern Agricultural research stations, respectively. From this first year, brown spot does contribute to yield loss, at least at low levels.

In these trials, fungicides, in the majority of cases, increased yield. Sometimes the results were difficult to measure. In other cases, the increased yield was substan-

tial but highly variable, as in Ross County during 2006.

We demonstrated that many of these fungicide applications reduce the incidence and severity of foliar diseases and we demonstrated efficacy on some of the minor foliar pathogens found in Ohio. However, the final question is, are these applications economically viable in today's volatile soybean price market?

Across all studies, on average, we gained 3 bushels per acre. For application to be economically viable, soybean price must be \$8 or higher and the gain must be consistently greater than 3 bushels per acre. Under Ohio conditions, this occurred only 20% to 50% of the time. The best economic use of fungicides was when frogeye leaf spot was prevalent at the R3 growth stage on highly susceptible soybean varieties.

Fungicide Seed Treatments

TABLE 5 • There was a significant difference among the fungicide treatments compared to one of the untreated plots—for the level of brown spot at the NWB location only, Headline, Folicur, Headline plus Folicur, Quadris, and Headline at R3 followed by Folicur at R5. Disease levels were much lower at the Western research station and were not significantly different.

Treatment	Percent leaf area affected @ R5		Yield, bu/A	
	Northwestern	Western	Northwestern	Western
Nontreated	19	11	46.2 c	61.9 d
Headline @ R3	18	7	49.6 a	66.0 a-c
Headline @ R5	25	14	48.9 a	65.4 a-d
Headline + Folicur @ R3	14	8	48.6 ab	65.3 a-d
Headline + Folicur @ R5	29	10	48.3 abc	68.7 a
Folicur @ R3	17	7	46.5 bc	66.1 ab
Folicur @ R5	27	11	47.8 abc	65.1 a-d
Nontreated	26	15	48.1 abc	64.3 b-d
Quadris @ R3	16	12	49.5 a	62.0 cd
Headline @ R3 + Folicur @ R5	17	13	46.5 bc	65.7 a-d
Means	21.2	10.6	48	65

Means followed by the same letter are not significantly different ($P = 0.05$).

TABLE 6 • Echo reduced the level and severity of brown spot at both locations and increased yield by 4 and 2.8 bushels per acre at the Western and Northwestern research stations, respectively. Brown spot is a minor foliar disease of soybean in Ohio.

Number of sprays	Percent leaf area affected								
	10	9	8	7	6	5	4	3	2
Western Station	0.08	0.42	0.0	0.83	0.83	12.6	5.75	9.58	10.08
Northwestern Station	5.8	5.4	5.4	5.4	7.5	9.6	18.3	18.8	26.7
Yield difference from nontreated, bu/A									
Western Station	5.6	4.6	4.5	3.2	9.8	0.5	2.2	1.8	3.1
Northwestern Station	2	3.8	4.1	3.7	1.9	1.8	3.7	0.9	0.3

Many production fields along the Great Lakes and rivers have higher clay contents. Areas of the Midwest that were once covered with swampland are now highly productive fields. However, these same fields are prone to several soil-borne pathogens including *Phytophthora sojae*, *Pythium*, and *Fusarium*.

Several years ago, we demonstrated that to manage *P. sojae*, a high rate of mefenoxam or metalaxyl (ApronXL and AllegianceFL) was required for efficacy. Despite the higher rates of seed treatment, some producers were still experiencing stand loss without excessive flooding. In addition, establishment of corn in some fields was becoming an annual problem even with the use of seed treatments. We have begun a series of studies that evaluate which seed and seedling pathogens are predominant in Ohio and which seed treatment fungicides are most effective against these corn and soybean pathogens.

Seeds and seedlings with symptoms of early-season damping-off were collected from 42 locations throughout the state from problem fields. From these samples, 11 species and two distinct morphological groups of *Pythium* were identified, of which six species were moderately to highly pathogenic

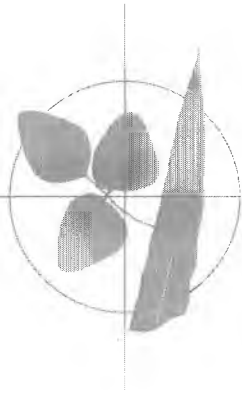
on corn seeds and nine species were highly pathogenic on soybean seeds.

Our most important finding in this study was that mefenoxam, azoxystrobin, trifloxystrobin, or captan, when used individually, may not inhibit all pathogenic species of *Pythium* found in Ohio soils. Thus, reliance on only one active ingredient may have contributed to some of the stand establishment problems.

These studies were all from problem fields. Our next priority is to determine how widespread these problems are in the state and then to develop some recommendations on which fungicide combinations will be able to control the majority of Ohio's *Pythium* populations.

Acknowledgments

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Managing Insects in High-Production Soybeans: Forethought or Afterthought?

Kevin L. Steffey

Crop production practices, technologies, and expectations have changed significantly during the past 10 years, reshaping agriculture as we used to know it. These changes are particularly obvious in the Midwest, where most of the arable land is devoted to production of corn and soybeans.

The demand for corn is at an all-time high, so more acres are being dedicated to its production. In large part, the increase in acreage of corn will occur at the expense of acreage dedicated to soybean production. Consequently, soybean producers will expect higher yields per acre, counting on improved soybean genetics, different production practices, and new pest management technologies and practices to help them meet their expectations. Companies that supply seed and agricultural chemicals to soybean producers anticipated the producers' expectations and have developed products that offer solutions for yield-limiting factors such as insects and plant diseases.

Where does insect management fit into the expectations for higher yields of soybeans? Do our expectations for higher yields include regular, possibly annual, expenditures for insect control? What will befall the ecology of soybean fields if regular use of insecticides becomes routine?

These questions cannot be addressed with simple responses, and many related questions remain to be asked and answered. So, the objective of this paper is to frame the discussion regarding the future of insect management in soybeans. Ultimately, all of the opportunities and challenges will be sorted out in the fields.

Soybean Insect Management, 1960s Through 1990s

Before 2000, soybean producers in the Midwest had very few recurring concerns about insect management. From the 1960s through the 1990s, insect and mite pests of soybeans caused widespread economic losses infrequently, so average annual expenditures for insect management for the vast majority of producers were very low to nil. Only relatively uncommon outbreaks of insect or mite pests (e.g., the outbreak of twospotted spider mites in 1988) required conspicuous use of insecticides. Most insect pests of soybean during this time period were classified as either subeconomic or occasional,¹ so most producers were content to rely on occasional scouting trips and knowledge of economic thresholds for making informed insect management decisions.

Scouting and economic thresholds were outgrowths of the emphasis on integrated pest management (IPM) in the 1970s and 1980s and became the foundation of insect management programs. Soybean producers in particular understood the concept that an insecticide was unnecessary unless densities of insects were large enough to cause economic loss (Pedigo and Rice 2006a).

¹ The average population density of a subeconomic pest does not reach the economic injury level (roughly, cost of control = value of loss). The average population density of an occasional pest exceeds the economic injury level occasionally, sporadically, and usually unpredictably.

Insecticide use to prevent insect injury to soybeans was virtually unheard of because insect pests threatened soybean yields so infrequently. Because soybean plants have an exceptional ability to tolerate and compensate for insect injury, entomology researchers were able to determine simple economic thresholds based on percentage defoliation caused by insects. These percentage defoliation thresholds² were associated with most of the “major” soybean insect pests at the time (e.g., bean leaf beetle, Japanese beetle, grasshoppers, green cloverworm), and they served us remarkably well as insect management guidelines. Making insect management decisions was simple and relatively easy—semi-regular scouting trips, a sweep net, a drop cloth, the ability to count, the ability to estimate percentage defoliation, an array of effective insecticides (carbamates, organophosphates, pyrethroids), and an applicator, if needed, were all the “tools” necessary to deal with occasional insect problems. IPM principles for soybean insect management were relatively easy to accept during the 1960s through the 1990s.

Soybean Insect Management, 2000 Through 2007

During the 1990s, leaders in soybean production strove to narrow the gap between attainable yields and yields usually harvested by producers. Breaking through the soybean yield barrier and improving oil and protein content became objectives for soybean producers who had higher expectations for soybean production. Expectations for higher soybean yields were addressed with improved genetics, biotechnology, and improved production practices. Concomitant with the emphasis on higher yields of soybeans were some significant events that have changed soybean producers’ attitudes about pest management:

- ✿ 2000—elevated concerns about bean leaf beetles transmitting bean pod mottle virus
- ✿ 2000—discovery of the soybean aphid in North America
- ✿ 2003 to 2005—registration of seed-applied neonicotinoid insecticides (Cruiser, Gaucho) for control of soybean insects

² Roughly 30% defoliation before bloom and 20% defoliation from bloom to pod fill.

- ✿ 2004—Asian soybean rust confirmed in the United States, followed by numerous registrations of fungicides for use in soybeans

These events have focused considerable attention on pest management in soybeans and have resulted in promotion of practices that may or may not be necessary for obtaining higher soybean yields. Promotions of “progressive approaches,” “innovative products,” and “plant health” encourage soybean producers to spend money on fungicides and insecticides to maximize yields. Consequently, insect management has become a forethought (suggesting a preventive approach) rather than an afterthought (suggesting a therapeutic approach)—quite a change from the attitude in previous decades. Although there is nothing inherently wrong with prevention of a known insect problem, widespread “prevention” of an insect problem that does not exist and may not develop is not cost effective and may have unintended consequences.

Many soybean producers use relatively simple economic metrics when considering the use of a pest control product (i.e., the economic return is equal to or greater than the economic investment). Promotions of “plant health” products almost always indicate yield gains that will more than offset the cost of the products, especially considering the recent, significant increase in the value of soybeans. A soybean producer needs to gain only 1 bushel (or less) per acre of \$10 soybeans to offset the cost of a typical insecticide application. If the goal is maximization of soybean yield, applying pesticides will probably help producers achieve the goal, at least for the short term. Planting soybean seed treated with fungicides and insecticides and application of tank mixes of pesticides (e.g., fungicide + insecticide, herbicide + insecticide) in some fields for a few years probably will bolster soybean yields. The “instinct to capitalize on the opportunity for financial reward” (a quotation from a friend) currently is very strong.

In keeping with simple economic metrics, however, it is necessary to call attention to the fact that the cost of producing soybeans also is increasing. In a recent report, Schnitkey and Lattz (2007) revealed that non-land costs for producing soybeans are projected to increase in 2008, averaging around \$220 per acre. With land costs included, producing soybeans on many farms in Illinois will cost \$400 to \$450 per acre. Given these costs, break-even revenues will be above \$8 per bushel for soybeans in 2008. Consequently, spending money on pesticides for presumed yield benefits represents an economic risk.

Soybean Insect Management, 2008 and Beyond: Opportunities and Challenges

At least for the short term, it is likely that reliance on inputs for pest management will prevail over the decision-making requirements associated with IPM, which is information intensive. Short-term cost/benefit ratios are relatively easy to calculate; the costs associated with misuse or overuse of pesticides are not easy to calculate. Ecological disruptions (e.g., pest resistance, pest resurgence, pest replacement) are the unintended consequences of over-reliance on pesticides for pest control, and there are always costs associated with unintended consequences. Ecological backlash in agriculture, which has been thoroughly documented in the scientific literature and experienced repeatedly in the real world, ultimately diminishes the effectiveness of management tactics (Pedigo and Rice 2006b).

For decades, the soybean ecosystem was not challenged annually with widespread use of insecticides and fungicides. As pesticide use in soybeans intensifies, it is important to realize that ecological balance will be tested. The opportunities implied by marketing claims for pest control inputs all have potential challenges:

- ✿ Control of insect pests with a neonicotinoid seed treatment represents a convenient and relatively cheap opportunity; dealing with insect populations that develop resistance to neonicotinoids is a potential challenge (Nauen and Denholm 2005).
- ✿ Control of weeds with glyphosate is a convenient and cost-effective opportunity; dealing with the fungicidal effects of some formulations of Roundup and their impact on arthropod communities is a potential challenge (Morjan et al. 2002).
- ✿ Control of insects with insecticides applied to soybean foliage is an opportunity in response to a real insect threat; dealing with arthropod populations that develop resistance to repeated use of these insecticides is a potential challenge (Yang et al. 2002).
- ✿ Control of fungal organisms with a fungicide is an opportunity in response to a real soybean disease threat; dealing with the ecological disruption caused by killing insect-pathogenic fungi with fungicides is a potential challenge (Ragsdale and Koch 2008, in these proceedings).

The potential challenges enumerated in the preceding list have not occurred in soybean fields in Illinois yet, at least as far as we know. However, a quotation from Todd et al. (1994) bears

repeating: "... because of the use of IPM tactics, insecticide use on soybean has remained low relative to other row crops, thus reducing the potential for resistance development." In striving toward maximum soybean yield, we need to reflect on this remark made several years ago when insecticide use in soybeans was limited.

In addition to having expectations for higher soybean yields, soybean producers also have greater expectations for insect management guidelines. During the past couple of years, members of the Illinois Soybean Association have asked whether the percentage defoliation thresholds are still reliable for modern soybean varieties grown for high yields with modern production practices.

I conveyed this question to a group of field crop Extension entomologists in the north-central states at a meeting in St. Louis in November 2007. Planting dates have changed, row spacing has changed, plant populations have fluctuated, and the timing of soybean canopy closure has changed since the percentage defoliation thresholds were widely recommended in the 1970s and early 1980s (e.g., Kogan and Kuhlman 1982). Most of us agreed that the percentage defoliation thresholds are not very practical any more. Rather, experts have indicated that treatment decisions should be based on leaf area indices or light interception (Hammond et al. 2000). Unfortunately, there currently are no practical guidelines that support this preferred method of decision making for defoliators of soybeans. So, we continue to use the percentage defoliation thresholds as a contingency.

Producers also wonder why we continue to recommend regular scouting in drilled soybeans or soybeans planted in 15-inch rows after mid-July. And what are the effects of multiple insect species feeding on soybeans, even though the density of each species is below the economic threshold? This question has been asked scientifically (e.g., Hutchins et al. 1988), although not resolved for insect pests causing dissimilar types of injury. These questions and concerns present opportunities for research associated with modern soybean production and insect management strategies, but they are challenges for soybean producers.

Additional glimpses into the future of soybean insect management suggest that host plant resistance will play a significant role. Soybean varieties with putative resistance to soybean aphids are already in development in soybean breeding programs at several land-grant universities, and resistant varieties will be commercialized relatively soon. Assuming that soybean resistance to soybean aphids holds up under field conditions, "conventional" host plant resistance holds real promise for managing soybean aphids. It is also pos-

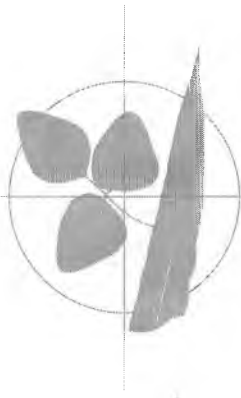
sible that Bt soybean varieties will be commercialized in the not-too-distant future. However, the Bt soybean lines that have been tested in the United States (MacRae et al. 2005) are resistant to Lepidoptera, a group of insects that, for the most part, has not threatened soybean production in the Midwest for many years.

The previous sentence raises the final point I will make in this paper. Although our primary insect and mite pests of soybeans in the Midwest have been bean leaf beetles, Japanese beetles, soybean aphids, and twospotted spider mites over the past 7 years, a shift in pest species can be induced by significant use of pesticides. Many soybean producers observed large numbers of whiteflies in soybean fields in the Midwest in 2007. More often than not, large whitefly populations in the Midwest have not been identified to species, so their threat to soybeans is difficult to assess (Johnson and Nuessly 1994). The species of whiteflies sampled from a couple of locations in Illinois were identified as greenhouse whiteflies, *Trialeurodes vaporariorum* (Steffey 2007), a species that does not seem to cause economic damage to soybeans. However, some entomologists suspected another species, the more dreaded sweetpotato (or silverleaf) whitefly, *Bemisia tabaci*, which is resistant to many insecticides and has caused economic losses to soybeans in the southeastern United States (Johnson and Nuessly 1994). An experienced entomologist also believed he observed bandedwinged whiteflies, *Trialeurodes abutiloneus* (Kevin Black, personal communication).

Observations of whiteflies in soybean fields in 2007 may have been circumstantial and not related to any of our pest management practices—but we do not know this for certain. The possibility for the occurrence of new pests or the resurgence of old pests in soybeans is just over the horizon if we disregard ecological principles.

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Future Soybean Oil and Meal Traits

Dennis Byron

The soybean provides one of the best sources of protein and oil for human and animal nutrition. It is an industry standard for protein and oil. However, it is not perfect for all applications.

Input from the food industry indicated a need for soybean oil trait enhancements that lower the saturated fat content in soybean oil and reduce or eliminate the need for hydrogenation, which results in the production of trans fatty acids. Some components of the food industry also requested improvements in flavor stability to provide more consistency and longer shelf life.

Input from the feed industry suggested that, while soybean meal is a superior source of protein for animal feed, reducing indigestible phosphorous, increasing metabolizable energy, and changing the amino acid balance could help improve animal efficiencies and reduce environmental impacts.

Low-Linolenic Soybeans

Research on altered linolenic acid content of soybean oil began at Iowa State University in 1968. The research team, led by Walt Fehr and Earl Hammond, identified three genes that individually reduce linolenic acid. The genes are designated as *fan1*, *fan2*, and *fan3*. Different combinations of the three individual genes result in linolenic acid contents that range from 3% to 1%. All three genes are required to reach 1%.

To develop commercial varieties, lines with reduced linolenic content are crossed with the best conventional varieties, and high-yielding "Low Lin" commercial varieties are ultimately selected and released after several years of testing.

These soybean oils with reduced linolenic fatty acid have better flavor stability over nonhydrogenated vegetable oils and

rival the flavor stability of lightly hydrogenated oil. Shelf life of products with low lin oil exceed that of nonhydrogenated oil. Best of all, the low linolenic trait reduces or eliminates the need for hydrogenation, which creates trans fat, and it is best suited for commercial frying purposes.

In 2007, approximately 1.5 million acres of low linolenic soybeans were grown and will produce more than 700 million pounds of oil. More than 2 million acres are expected in 2008, including significant acres in Illinois.

Numerous low lin varieties are available from multiple companies. Care must be taken in variety selection to make certain the varieties are adapted to local environments and pest pressures. Premiums for growing low linolenic varieties vary but generally are around \$.60 per bushel.

Increased Oleic Soybeans

The next step in enhanced functionality will be soybean oil with improved oxidative stability and superior flavor stability. Several research programs are developing soybeans with increased levels of oleic fatty acid along with reduced linolenic. Soybeans with higher levels of oleic resist oxidative breakdown even under high heat applications. Fried products and other food products that undergo high heat during processing will benefit from this oil. In addition, products made from this oil have even greater shelf life than products with only low linolenic oils.

Iowa State University will be releasing soybean varieties with mid-oleic content in 2009. These varieties are non-GMO and will have oleic acid levels exceeding 50%, compared to that of current varieties, which typically have oleic levels in the mid-20% range. In addition, the varieties will also have linolenic levels at 1%.

Pioneer is using gene transfer technology to increase the oleic content to approximately 80%. Documents for regulatory approval have been submitted to USDA and FDA. Approvals are expected in 2008, with introductory release of high-oleic varieties projected for 2009. Pioneer high-oleic varieties are expected to have linolenic levels near 3%. Monsanto is also developing soybeans with increased oleic levels. Premiums for increased oleic varieties have not yet been set.

Low Saturated-Fat Soybeans

In the United States, all food products must be labeled for their total content of saturated fatty acids because of their impact on cardiovascular health. The American Heart Association recommends that the intake of saturated fat be limited to 7% to 10% (or less) of the total calories consumed each day.

Even though soybean oil is not high in saturated fats, it is still significantly higher than canola oil, with about 7% saturates. There is significant research under way to develop varieties with reduced saturates, especially reduced palmitic fatty acid, considered by many scientists to be the fatty acid most detrimental to human health. The saturated fatty acids in conventional soybean oil consist of about 12% palmitate, about 4% stearate, and about 1% of other saturated fatty acids. Low-saturate soybean oil is possible due to two major genes (*fap1* and *fap3*) that have been developed to reduce the palmitate content to about 4%.

The first low-saturate cultivar that was grown commercially in 1996 was developed jointly by Iowa State University and Pioneer Hi-Bred International, Inc. The low-saturate oil from the crop was sold for the first time in fall 1997. It was sold in grocery stores in the midwestern United States and was distributed to schools nationally through the U.S. Department of Agriculture's National School Lunch Program and School Breakfast Program as a means of lowering the saturated fat content of the meals. With only 1 gram of saturated fat per tablespoon (14 grams), the oil matches the saturated fat content of canola oil and reduces by half the saturated fat found in traditional soybeans. Demand for this oil was limited, and the varieties are no longer available.

The goal of most of the research organizations developing modified soybean oil is to achieve perhaps the ultimate soybean oil, which includes a maximum of 3% linolenic fatty acid, oleic acid above 60%, and total saturates less than 7%. This might be the almost perfect "commodity" vegetable oil for optimizing human health while producing food products with exceptional flavor characteristics and superior shelf life. Soybean varieties with the fatty acid combination are expected to be available near 2010.

Omega-3 Soybeans

Another issue concerning cardiovascular health is increasing the omega-3 fatty acids in soybeans. People must get two types of polyunsaturated fats, known as alpha-linolenic acid (an omega-3 fatty acid) and linolenic acid (an omega-6 fatty acid), from the foods they consume because neither is synthesized in the body. Studies suggest that omega-3 fatty acids have anti-inflammatory properties and cardio-protective benefits.

Soybean oil is one of the few nonfish sources of omega-3s, and it's also rich in omega-6 fatty acids. Health professionals and nutrition experts emphasize the importance of looking at the omega-6 to omega-3 ratio, because Americans tend to overconsume omega-6 fatty acids. Soybean oil features an omega-6 to omega-3 ratio of 1 to 7.5, which is well below the suggested ratio of 1 to 10 that's cited in the new Dietary Reference Intakes.

Monsanto is developing soybean varieties with increased omega-3 fatty acid. The goal of this project is to create an affordable, land-based, renewable source of omega-3s that makes it easier than current alternatives to create great-tasting food products rich in this nutrient. Monsanto expects to have varieties available around 2012.

Soybean Meal Traits

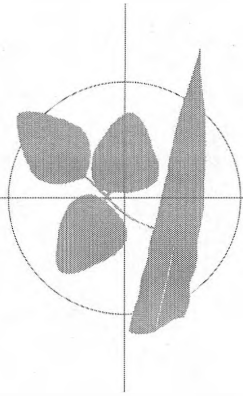
While the soybean is valued for its high-quality protein, about 25% is composed of various carbohydrates. Most of these are not nutritionally available to poultry and livestock as sources of calories, and some even exhibit negative nutritional qualities in nonruminants. Research on soybean varieties with reduced "negative" oligosaccharides and increased metabolizable energy is under way. These soybeans are lower in indigestible carbohydrates and higher in digestible sucrose, resulting in higher usable energy and more efficient livestock production.

Other meal traits that are under development include a soybean variety with reduced phytate-phosphorus. Much of the phosphorus found in grain and protein meals is bound in phytate compounds. This phosphorus is not nutritionally available for livestock and poultry to digest and thus contributes to the phosphorus of animal waste, an especially serious problem in concentrated livestock feeding operations. To overcome this problem, feed providers add inorganic phosphorus to rations, and excessive phosphorus is excreted in the manure. Experimental reduced phytate soybeans have resulted in improved phosphorus uptake by animals and reduced phosphorus in waste. Additional livestock feeding

trials are under way. Low phytate and low oligosaccharide soybeans may be available around 2010.

Additionally, scientists are working on improving the amino acid composition of soybean protein. Soybeans are inherently low in sulfur-containing amino acids, so research is under way to increase methionine and cysteine to make soybean meal more effective for livestock and poultry. This research uses gene transfer technology and is in the early stages of development. Consequently, soybeans with improved amino acid profiles will not be available until after 2012.

Many improved soybean oil and meal traits are under development. Demand for enhanced traits will be determined by the value they provide to end users and the ability of all components of the value chain to share in this value. It is likely that multiple oil and meal traits will be required to provide enough value for sustainable utilization of these traits.



Developing Nutrient Standards for Illinois: Connecting Regulators with Researchers

George F. Czapar

In 2000, the United States Environmental Protection Agency (USEPA) published ambient water-quality criteria recommendations for rivers and streams and directed states to set water-quality standards “to protect the physical, biological, and chemical integrity of their waters.” The recommended criteria were developed for 14 different ecoregions in the United States, and reference conditions were proposed for total phosphorus, total nitrogen, chlorophyll a, and turbidity.

The USEPA reference conditions for Ecoregion 6, which includes approximately the northern two-thirds of Illinois, and Ecoregion 9, which includes the southern one-third of Illinois, are shown in Table 1.

Because the reference conditions were based on the 25th percentile for all nutrient data, they did not account for local site conditions that may have significant impacts on water quality. Most waters in Illinois would exceed the proposed nutrient criteria, including some high-quality streams that support a rich diversity of aquatic species but may have elevated nutrient concentrations during high-flow events in the spring.

As a result, developing water-quality standards for nutrients is a challenge facing Illinois and many other states. The USEPA did allow for individual states to adopt other scientifically defensible criteria or adjust them to better reflect state-specific conditions. In Illinois, a collaborative research program was organized to help provide the basis for standard development. This research is funded by the State of Illinois through the Illinois Council on Food and Agricultural Research (C-FAR).

TABLE 1 • Ambient water quality criteria recommendations (US EPA 2000).

Nutrient parameters	Reference conditions, Ecoregion 6	Reference conditions, Ecoregion 9
Total phosphorus ($\mu\text{g/L}$)	76.25	36.56
Total nitrogen (mg/L)	2.18	0.69
Chlorophyll a ($\mu\text{g/L}$)	2.7	0.93
Turbidity (FTU)	6.36	5.7

As part of its research focus, C-FAR established the Strategic Research Initiative (SRI) in water quality. This program encourages collaboration among the state universities and other research entities throughout Illinois and brings together scientists to work together for a common purpose. The goals of the Water Quality SRI are (1) to help develop the scientific basis for nutrient standards in the surface waters of Illinois, and (2) to assist in the appropriate development and implementation of Total Maximum Daily Loads (TMDLs).

This initiative required close collaboration with regulatory agencies in Illinois. As part of the SRI, an advisory team from the Illinois Environmental Protection Agency (IEPA) and the Illinois Department of Agriculture identified information gaps and prioritized the most important research needs. A request for proposals was developed from this priority list. The projects that were funded included those from the University of Illinois, Illinois State University, Southern Illinois University, the Illinois State Water Survey, and the Illinois Natural History Survey.

The SRI is organized into four research teams, each with a slightly different focus. Project components include a detailed

analysis of existing IEPA data, intensive sampling at fixed locations, statewide temporal sampling at 140 sites, investigating the effects of sediment on phosphorus dynamics in streams, and improving the methodology for collecting and analyzing algal samples. Laboratory experiments to isolate the effects of phosphorus on algal growth were also conducted.

Because standards need to consider all sources of nutrients, they directly affect both rural and urban residents. The SRI collaborated with two water reclamation districts to collect information on effects of sewage treatment plants on water quality. The shared goal of the Illinois plan is the development of practical and effective nutrient standards based on identified causes and thresholds of water-body use impairment due to nutrient enrichment.

On October 23, 2007, Water Quality SRI researchers participated in a Nutrient Standards Forum that was held at the University of Illinois at Springfield. Each research team presented key findings and summarized their work. Information about the meeting and copies of all presentations are available on the C-FAR Web site at www.ilcfar.org/research/waterqualityforum.html.

The C-FAR strategic research initiative has provided valuable insight in the development of nutrient standards. It has also raised additional questions and identified other factors that may have greater impacts on biotic integrity than nutrient concentration alone. Factors such as physical habitat, sediment, light availability, temperature, and hydrology are

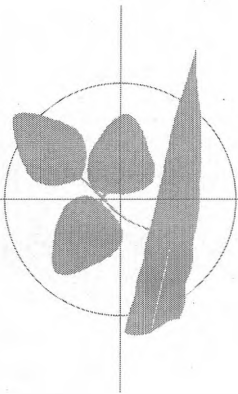
part of a complex relationship affecting biotic responses in rivers and streams.

Cause and effect relationships can be difficult to establish because Illinois lacks a wide range of nutrient conditions, and nutrients are almost never the primary limiting factor to algal production. The challenge remains for regulators to adopt practical and effective nutrient standards, but developing partnerships with the research community is an important first step.

Primary funding for this research was provided by the State of Illinois through the Illinois Council on Food and Agricultural Research. Additional funding was provided by the governor of Illinois and the Illinois Environmental Protection Agency through Section 319 of the Clean Water Act. Collaborators include the Illinois Environmental Protection Agency, Illinois Department of Agriculture, Metropolitan Water Reclamation District of Greater Chicago, Bloomington-Normal Water Reclamation District, Oak Ridge National Laboratory, and The Nature Conservancy.

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Gulf Hypoxia: The Saga Continues

Dennis McKenna

The hypoxic zone is an area in the northern Gulf of Mexico where dissolved oxygen concentrations in the shallow ocean are less than 2 mg/L, the level necessary to sustain most aquatic life. In response to the low oxygen levels, mobile organisms, such as fish and shrimp, leave the hypoxic zone; the others die at varying rates. Although these responses have been observed in the Gulf, an economic analysis based on past data did not detect a direct relationship between hypoxia and Gulf fisheries (CENR 2000).

The occurrence of hypoxic conditions depends on stratification of the water column—warm, less-dense freshwater above cold, denser saltwater—and consumption of oxygen during the decomposition of organic materials. The organic matter in the lower part of the water column is a result of algal growth and death in the surface waters. The growth of the algae is controlled by the presence of nutrients. In most

saltwater systems, nitrogen is commonly the nutrient that limits algal growth. However, in the northern Gulf of Mexico, phosphorus is an important limiting nutrient during the spring and summer of the year in the lower salinity, near-shore regions. In freshwater systems, phosphorus is the nutrient that most often controls algal growth.

The size of the hypoxic zone varies considerably from year to year, depending on the timing and extent of water-column stratification during the spring and summer, weather conditions, temperature, and amount of precipitation in the Mississippi River drainage basin. In 1999, the hypoxic zone was almost 20,000 km², the greatest extent since measurements began in 1985. In the summer of 2000, it was about 4,400 km², the smallest area since the drought year of 1988. Hypoxia in bottom waters covered an average of 8,000 to 9,000 km² in 1985–1992 but increased to 16,000 to 20,000 km² in 1993–1999. The 5-year running average of the hypoxic zone for 2003–2007 was about 15,000 km² (Figure 1).

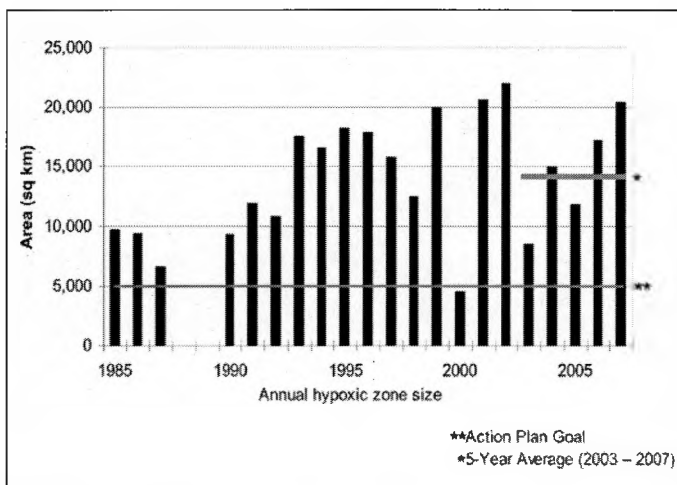


FIGURE 1 • Size of hypoxic zone in northern Gulf of Mexico, 1985–2007.

2001 Action Plan

The Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (P.L. 105-383) required that the president, in conjunction with the chief executive officers of the states, submit a plan to reduce, mitigate, and control hypoxia in the northern Gulf of Mexico. The law also required that the plan include the social and economic costs and benefits of the measures for reducing hypoxia.

In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force submitted to Congress the Action Plan for Reducing, Controlling, and Mitigating Hypoxia in the Northern Gulf of Mexico (Task Force 2001). The task force is composed of federal agencies and ten state agencies, including the Illinois Department of Agriculture. The task

force has met seven times since 1997 to develop the action plan, which proposed ten short-term actions to achieve long-term coastal, basin, and quality of life goals, as follows: “States, Tribes, and Federal agencies within the Mississippi and Atchafalaya River Basin will

- ✿ expand the existing monitoring efforts within the Basin,
- ✿ develop strategies for nutrient reduction,
- ✿ identify point source dischargers with significant discharges of nutrients and undertake steps to reduce those loadings,
- ✿ increase assistance to landowners for voluntary actions to restore, enhance, or create wetlands and vegetative or forested buffers along rivers and streams within priority watersheds, and
- ✿ increase assistance to agricultural producers, other landowners, and businesses for the voluntary implementation of best management practices (BMPs), which are effective in addressing loss of nitrogen to waterbodies.”

Although it was recognized that implementation of the action plan would require a significant level of commitment from the federal agencies and state governments, the first and most important action item to develop an integrated federal budget proposal was never completed. Consequently, there has been limited progress in achieving the other actions.

Reassessment of the Hypoxia Action Plan

The 2001 action plan also included an action item to assess the nutrient reductions achieved and the response of the hypoxic zone, water quality throughout the Basin, and economic and social effects. The reassessment (www.epa.gov/msbasin/taskforce/reassess2005.htm) included a series of actions to develop the information necessary for the task force to review the 2001 action plan and make revisions as necessary. These actions included reassessment of the primary causes of Gulf hypoxia and management approaches to address these causes. To capture recent advances in scientific understanding of hypoxia, the causes, and potential solutions, the task force sponsored four scientific symposia, including

- ✿ Upper Basin Science Symposium, September 26–28, 2005, Ames, Iowa, which evaluated the effectiveness and cost effectiveness of the various management practices currently available to agriculture to reduce nutrient losses (proceedings available at www.umrshnc.org)
- ✿ Gulf Hypoxia Science Symposium, April 25–27, 2006, New Orleans, Louisiana

- ✿ Lower Basin Science Symposium, June 1–2, 2006, New Orleans, Louisiana
- ✿ Sources, Fate and Transport Symposium, November 7–9, 2006, Minneapolis, Minnesota

The task force recognized the need to have an updated, independent assessment of the causes of Gulf hypoxia and recommendations as to whether the most recent body of scientific evidence supported revisions to the assessment that formed the basis of the 2001 action plan. After review of several options, the task force agreed that an expert panel be chartered through EPA’s Science Advisory Board (SAB) to review available scientific information and provide a report that synthesizes the current state of knowledge of the causes of Gulf hypoxia.

The task force selected the SAB because of the opportunities for public access, timeliness, and cost. All SAB panel meetings and deliberations are open to the public in accordance with the Federal Advisory Committee Act and EPA administrative policies for advisory committee management. The EPA Science Advisory Board Hypoxia Advisory Panel (www.epa.gov/sab/panels/hypoxia_adv_panel.html) was charged with evaluating the scientific basis for, and recommending revisions to, the goals proposed in the action plan, and the scientific basis for the efficacy of recommended management.

The specific charges to the panel included the following:

1. Characterization of Hypoxia—The development, persistence and areal extent of hypoxia is thought to result from interactions in physical, chemical, and biological oceanographic processes along the northern Gulf continental shelf; and changes in the Mississippi River Basin that affect nutrient loads and freshwater flow.

- A. Address the state-of-the-science and the importance of various processes in the formation of hypoxia in the Gulf of Mexico. These issues include
 - i. increased volume or funneling of freshwater discharges from the Mississippi River;
 - ii. changes in hydrologic or geomorphic processes in the Gulf of Mexico and the Mississippi River Basin;
 - iii. increased nutrient loads due to coastal wetlands losses, upwelling, or increased loadings from the Mississippi River Basin;
 - iv. increased stratification, and seasonal changes in magnitude and spatial distribution of stratification and nutrient concentrations in the Gulf;
 - v. temporal and spatial changes in nutrient limitation or co-limitation, for nitrogen or phosphorus, as significant factors in the development of the hypoxic zone; and

- vi. the implications of reduction of phosphorus or nitrogen without concomitant reduction of the other.
- B. Comment on the state of the science for characterizing the onset, volume extent, and duration of the hypoxic zone.

2. Characterization of Nutrient Fate, Transport, and Sources—Nutrient loads, concentrations, speciation, seasonality, and biogeochemical recycling processes have been suggested as important causal factors in the development and persistence of hypoxia in the Gulf. The Integrated Assessment (CENR 2000) presented information on the geographic locations of nutrient loads to the Gulf and the human and natural activities that contribute nutrient loadings.

- A. Given the available literature and information (especially since 2000), data and models on the loads, fate and transport, and effects of nutrients, evaluate the importance of various processes in nutrient delivery and effects. These may include
- i. the pertinent temporal (annual and seasonal) characteristics of nutrient loads/fluxes throughout the Mississippi River Basin and, ultimately, to the Gulf of Mexico;
 - ii. the ability to determine an accurate mass balance of the nutrient loads throughout the basin; and
 - iii. nutrient transport processes (fate/transport, sources/sinks, transformations, etc.) through the basin, the deltaic zone, and into the Gulf.
- B. Given the available literature and information (especially since 2000) on nutrient sources and delivery within and from the basin, evaluate capabilities to
- i. predict nutrient delivery to the Gulf, using currently available scientific tools and models; and
 - ii. route nutrients from their various sources and account for the transport processes throughout the basin and deltaic zone, using currently available scientific tools and models.

3. Scientific Basis for Goals and Management Options—The task force has stated goals of reducing the 5-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5,000 km² by the year 2015, improving water quality within the basin and protecting the communities and economic conditions within the basin. Additionally, nutrient loads from various sources in the Mississippi River Basin have been suggested as the major driver for the formation, extent, and duration of the Gulf hypoxic zone.

- A. Are these goals supported by present scientific knowledge and understanding of the hypoxic zone, nutrient loads, fate and transport, sources, and control options?
- i. Based on the current state-of-the-science, should the reduction goal for the size of the hypoxia zone be revised?
 - ii. Based on the current state-of-the-science, can the areal extent of Gulf hypoxia be reduced while also protecting water quality and social welfare in the basin?
- B. Based on the current state-of-the-science, what level of reduction in causal agents (nutrients/discharge) will be needed to achieve the current reduction goal for the size of the hypoxic zone?
- C. Given the available literature and information (especially since 2000) on technologies and practices to reduce nutrient loss from agriculture, runoff from other nonpoint sources, and point source discharges, discuss options (and combinations of options) for reducing nutrient flux in terms of cost, feasibility, and any other social welfare considerations. These options may include
- i. the most effective agricultural practices, considering maintenance of soil sustainability and avoiding unintended negative environmental consequences;
 - ii. the most effective actions for other nonpoint sources; and
 - iii. the most effective technologies for industrial and municipal point sources.

Findings of the Hypoxia Advisory Panel

The following is excerpted from the Science Advisory Board Hypoxia Panel Advisory Draft Report (www.epa.gov/sab/panels/hypoxia_adv_panel.htm):

- ✿ Recent science has affirmed that contemporary changes in the hypoxic area in the northern Gulf of Mexico are primarily related to nutrient loads from the basin.
- ✿ The 5,000 km² target remains a reasonable endpoint for continued use in an adaptive management context; however, it may no longer be possible to achieve this goal by 2015.
- ✿ To reduce the size of the hypoxic zone and improve water quality in the basin, the SAB panel recommends a strategy targeting at least a 45% reduction in total nitrogen flux and at least a 45% reduction in total phosphorus flux.

- ✿ Phosphorus limitation is now occurring because of excessive N loadings over the past 50 years, which have dramatically altered nitrogen to phosphorus ratios.
- ✿ One physical factor that has changed substantially over the past century is river hydrology due to the diversion of a large amount of freshwater from the Mississippi River through the Atchafalaya River to the Atchafalaya Bay and maintenance of this diversion by the U.S. Army Corps of Engineers. The major injection of freshwater into Atchafalaya Bay, some 200 kilometers to the west of the Mississippi River delta, has profoundly modified the spatial distribution of freshwater inputs, nutrient loadings, and stratification on the Louisiana–Texas continental shelf.
- ✿ The latest USGS estimates show that total N flux averaged 1.24 million metric tons/yr from 2001–2005 (65% of the flux is nitrate), and the total P flux averaged 154,000 metric tons/yr. This change represents a 21% decline in total N flux and a 12% increase in total P flux when compared with the averages from the 1980–1996 time period.
- ✿ The spring (April–June) flux of nutrients appears to be an important determinant of hypoxia, for that is when the river is disproportionately enriched with both N (especially nitrate) and P. Spring total N flux has declined since the 1980s; whereas total P flux shows a 9.5% increase (when average total P flux for 2001–2005 is compared with the 1980–1996 average).
- ✿ USGS data also show that during the past 5 years, the Upper Mississippi and Ohio–Tennessee sub-basins contributed 80% of total N flux and 64% of total P flux, although these sub-basins represent only 32% of the entire Mississippi/Atchafalaya River Basin (MARB) area.
- ✿ Ballpark estimates of point source discharge show that point sources represented 22% of total N flux and 34% of total P flux during the past five years.
- ✿ Net anthropogenic N inputs (NANI) for the MARB have declined in the past decade because of increased crop yields, reduced livestock populations, and little change in N fertilizer inputs.
- ✿ From 1999–2005, NANI calculations show 54% of non-point N inputs in the MARB were from fertilizer, 37% from fixation, and 9% from atmospheric deposition.
- ✿ Changes in benthic and fish communities in the Gulf of Mexico with the change in frequency of hypoxia are cause for concern and suggest that the Gulf has undergone a regime shift.
- ✿ The Gulf of Mexico ecosystem is more sensitive to inputs of nutrients than in the past, with nutrient inputs inducing a larger response in hypoxia.
- ✿ Certain aspects of the nation's current agricultural and energy policies are at odds with the goals of hypoxia reduction and improving water quality.
- ✿ The SAB panel's calculations suggest that tighter limits on N and P in effluent (3 mg N/L and 0.3 mg P/L) from sewage treatment plants could realize an estimated 11% reduction in annual average total N flux and a 21% reduction in total annual average P flux to the Gulf.
- ✿ Restructuring subsidies and conservation programs represents an important tool for reducing nutrient runoff from agricultural production.

The 2008 Action Plan

In November 2007, the task force released a draft of the 2008 action plan for public comment. One significant change from the 2001 plan was to propose that nutrient reduction strategies to meet the goals of the action plan be developed at a state level rather than for the large sub-basin or national scale. The Task Force recognized that no single approach to nutrient reduction would be effective in every state within the Mississippi River Basin because the soils, hydrology, land use, and cropping practices as well as the legal, legislative, and administrative framework vary considerably across the 31 states in the basin. These strategies will provide a road map for each state, a more detailed basis for budget development, and a vehicle for coordination with other states in the basin. Once the strategies have been adopted and new funding is provided, federal and state agencies can accelerate efforts to reduce nutrient impacts on local waters and the Gulf.

The task force (www.epa.gov/msbasin/taskforce/pdf/2008draft_actionplan.pdf) also proposed amending the coastal goal to read as follows: "Subject to the availability of additional resources, we strive to reduce or make significant progress towards reducing the 5-year running average [areal] extent of the Gulf of Mexico hypoxic zone to less than 5,000 square kilometers by the year 2015 through implementation of specific, practical, and cost effective voluntary actions by all States, Tribes, and address all categories of sources and removals within the Mississippi/Atchafalaya River Basin to reduce the annual discharge of nitrogen and phosphorus into the Gulf."

The modification of the goal was prompted by the difficulty of meeting the 2015 goal. As the Science Advisory Board concluded, "The 5,000 km² target remains a reasonable end-

point for continued use in an adaptive management context; however, it may no longer be possible to achieve this goal by 2015 ... It is even more important to proceed in a directionally correct fashion to manage factors affecting hypoxia than to wait for greater precision in setting the goal for the size of the zone. Much can be learned by implementing management plans, documenting practices, and measuring their effects with appropriate monitoring programs” (SAB 2007).

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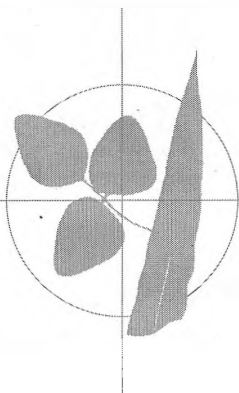
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Considerations for Managing Nitrogen When Switching from Corn–Soybean to Corn–Corn Rotations

T.S. Murrell



There are many questions producers and their advisers are asking as more corn is being incorporated into crop rotations. In this article, we focus on a few key questions related to switching from corn–soybean (CS) to corn–corn (CC) rotations.

How Much Do I Need to Change My Nitrogen (N) Rate?

The following factors will need to be considered when deciding how much N to apply to corn in CC versus CS systems:

Soybean N credit. Many recommendation algorithms have a soybean N credit that reduces the N rate. Most states use a constant, which ranges across states from 30 to 45 lb N/A (Figure 1). Other states use a credit of 0.5 to 1 lb N/bu of soybean yield, with some caveats for yield level. When soybean is omitted from the rotation, this credit is sacrificed.

Soil nitrate level. Soybeans are good scavengers of soil nitrate. When soybeans are omitted and the switch is made to CC, residual soil nitrate levels may increase, although levels are very dependent on the weather. Drier years typically produce higher levels of residual nitrate. Given such variability, it is usually a good practice to test for residual soil nitrate before deciding how much N to apply.

Attainable yield. University research has shown that there is a potential for CC systems to yield, on average, less than CS systems when managed in the same way. This possibility reinforces the need to keep accurate yield records on fields. If, over time, yields have in fact decreased, N rates will need to be adjusted downward in recommendation systems using yield goal as a factor.

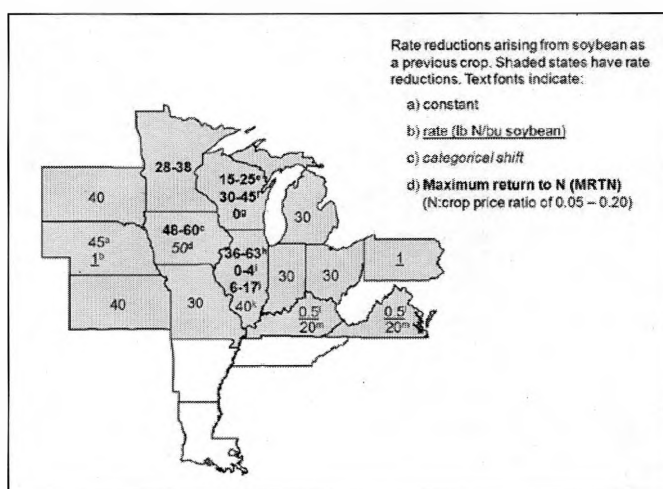


FIGURE 1 • Data taken from state Extension publications and the online regional MRTN database.

State specific notes:

Nebraska

- ^a Constant used when soybean yield is equal to or greater than 30 bu/A.
- ^b Rate used when soybean yield is less than 30 bu/A.

Iowa

- ^c Range in MRTN from online database.
- ^d Categorical shift in ranges given in pub. PM1714 (Blackmer et al. 1997).

Wisconsin

- ^e High/very high yield potential soils.
- ^f Medium/low yield potential soils.
- ^g Sands/loamy sands.

Illinois

- ^h Northern Illinois
- ⁱ Central Illinois
- ^j Southern Illinois
- ^k Constant given in *Illinois Agronomy Handbook* (Hoeft and Nafziger 2002).

Kentucky and Virginia

- ^l Rate when previous soybean crop yield is known.
- ^m Constant used when previous soybean crop yield is unknown.

TABLE 3 • Average nutrient removal rates calculated from published coefficients in the north central United States (Murrell 2005).

	Removal coefficients				
	N	P ₂ O ₅	K ₂ O	Mg	S
	(lb/bu)				
Corn	0.90	0.38	0.27	0.09	0.08
Soybean	3.8	0.84	1.3	0.21	0.18

band near the seed at planting often results in early-season growth responses that can translate to end-of-season yield increases. Several factors affect response to starter fertilizer. Soil conditions that increase the probability of response include

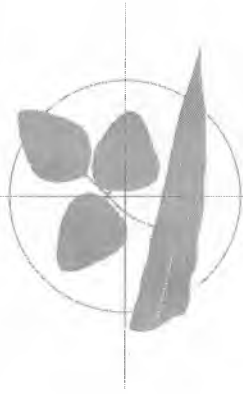
- ✿ cool, moist soil conditions at planting
- ✿ longer-season hybrids planted later in the spring
- ✿ root growth restrictions, such as soil compaction, soil acidity, and soil salinity

In a 4-year Minnesota study, starter fertilizer produced equally beneficial responses (8 bu/A average) for CC and CS under a variety of tillage systems: no-till, zone till, strip till, and conventional tillage (Vetch and Randall 2002). The

need for starter fertilizer for corn, regardless of rotation, may arise from the rapid influx of nutrients by corn roots early in the season and the positive effect of N and P on root proliferation.

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Hypoxia and the Upper Mississippi River Basin: How Can We Reduce Nutrient Losses from Agriculture?

Mark B. David

The recent USEPA Science Advisory Board (SAB) Hypoxia Panel report reaffirmed the importance of nitrogen (N) transported down the Mississippi River as a major factor determining the size of the hypoxic zone that forms each summer in the Gulf of Mexico. The SAB report also concluded that phosphorus (P) was an additional important factor that was not previously recognized. Therefore, the SAB panel recommended that the transport of both nutrients would need to be reduced by 45% (from 1980 to 1996 loads) to meet the goal of reducing the hypoxic zone to 5,000 km² (~2000 mi²). Recently (since 2001) the size of the hypoxic zone has been 16,500 km² (~6400 mi²). This reduction in nutrients would benefit both the Gulf as well as local water quality conditions in the Mississippi River Basin (MRB). Finally, the panel concluded that the greatest emphasis needed to be placed on the spring (April, May, and June) load of N to the Gulf.

Most of the nitrate load to the Gulf comes from the upper Mississippi and Ohio-Tennessee River sub-basins, as well as more than half of the total P load. A major source area documented by the SAB panel for nitrate was the upper Mississippi River between Clinton, Iowa, and Grafton, Illinois, which includes the Illinois River. The tile-drained, corn and soybean landscape of Iowa, Illinois, Indiana, and Ohio was highlighted as the critical source area of nitrate to the Gulf, as well as nearly all of the spring load. Sewage effluent and other point sources were found to be a relatively small portion (14%) of the spring nitrate load. For P, these same sub-basins were important sources, although other areas of the basin also contributed P, and sewage effluent (and other point sources) was about 34% of the annual P load and 27% of the spring load.

In terms of nutrient balances, the SAB report found that, in the upper Mississippi sub-basin, the N balance had declined

quite a bit recently, due to the combination of greater yields, declining manure inputs, and steady fertilizer use. These changes may be leading to a depletion of soil organic matter (and soil organic N) in corn and soybean rotations, because N leaching losses have remained high.

For P, the nutrient balance is now negative, with more P removed in grain in the upper Mississippi sub-basin than applied as fertilizer plus manure. Again, however, P losses to streams and rivers have not declined.

Finally, given current nutrient inputs and outputs in the upper Mississippi River sub-basin, the loss of N and P from fields to streams is not thought to be due to overapplication of fertilizers, but rather leakiness in the corn and soybean production system now in place. This means that even when current best management practices are followed, losses of N and P may be too great—and additional measures will need to be implemented.

Given this background, producers in the tile-drained corn and soybean landscape of the Midwest will likely receive new pressure to reduce losses of both N and P (and non-tiled land for P), as will sewage treatment plants for P. What could we do within corn and soybean agriculture to reduce nutrient losses? Who will pay for these changes? When will they need to be implemented?

I can't really address the latter two questions, which are quite important and certainly influence the first question. I can, however, lay out what the SAB panel concluded were options for reducing N and P losses from agricultural fields, with a focus on the tile-drained landscape.

One conclusion was clear from the SAB report—the idea that there is a “one size fits all” land use or conservation practice that would be cost effective everywhere—was clearly not true or appropriate. An overall conclusion was that there needed

to be site-specific and regional conservation practices with targeting of conservation practices and measures with a broad range of alternative practices and land uses such as crop, animal, fertilizer, and drainage management measures.

Another important conclusion was that practices that might be effective in tile-drained landscapes can be very different from those appropriate for non-tiled lands.

In the following paragraphs, I will highlight what practices might be effective. They might not be desirable from a view of current production methods and income sources, but perhaps they will lead to new production methods that maintain yields *and* reduce nutrient losses. These new production systems will likely increase costs, and who pays those costs will need to be worked out.

The SAB panel concluded that the greatest reduction in both nitrate and P loss from tile-drained fields, and P loss from other fields, would result from alternative and more complex cropping systems that might include perennials. However, it was recognized that current constraints in our agricultural production systems would likely not allow for these changes at this time. If a market for new cellulosic biomass crops such as switchgrass or *Miscanthus* were to develop, that could change. Biomass crops that need little fertilization and maintain plant cover throughout the year would clearly minimize N and P losses.

Given that there won't be a change to cellulosic biomass energy crops soon, the following recommendations were made for reduced spring nitrate loss in tile-drained regions:

- ✿ reduce or discontinue fall N application for corn
- ✿ improve N fertilizer management techniques
- ✿ use cover crops
- ✿ establish wetlands
- ✿ implement drainage management techniques

For P loss, recommendations included

- ✿ riparian buffer strips
- ✿ improved P fertilizer and manure management
- ✿ cover crops

Some complications were pointed out, including that controlled drainage could reduce nitrate losses but might increase surface runoff and, therefore, particulate loss of P. It was recognized that cover crops increase costs and risk to the cash crop, and that wetlands and buffer strips can remove land from production and cannot be placed at the edge of every field. However, the recommended practices are what we have available to reduce nutrient loss from fields in our current production systems.

For reducing spring nitrate losses, one of the lowest-cost techniques would be to discontinue fall N application. Most years, this will likely reduce losses and would not include construction or installation costs. However, even if fall N application were completely stopped, it would not lead to a 45% reduction in spring N loads to the Gulf; other practices would have to be implemented with higher costs.

For P, incorporation of P fertilizer into the soil is one lower-cost practice that could reduce losses. Again, however, this one practice will not lead to 45% reductions.

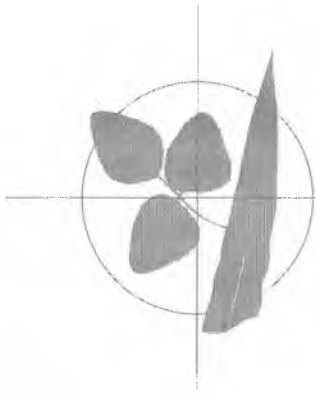
To meet 45% reduction goals for both N and P, many of the recommended practices would need to be incorporated into most fields in areas where losses are highest (targeted implementation). These practices have a range of costs, many of which are substantial, but they would need to be implemented to reduce N and P losses to the level necessary to reduce the hypoxic zone. Unfortunately, there is no simple and inexpensive solution that could be easily applied.

In conclusion, the corn and soybean crop production system now in place in the Midwest leads to losses of N and P that cause hypoxia in the Gulf of Mexico, even if all current recommendations and best management practices are followed. There are cropping systems and on- and off-field practices that could greatly reduce N and P losses, but they have costs and can increase risk. There is no single, overall solution at no or very low cost.

If we want profitable production systems and reduced N and P losses, then new cropping systems combined with a revised conservation and subsidy payment system would be necessary to allow for the full range of practices described in this article to be implemented.

Mechanisms of Fungicide Resistance and a Case Study of Fungicide Resistance in Potato Production

Neil C. Gudmestad



The development of resistance to fungicides in plant pathogenic fungi has become an increasingly more important problem worldwide. There are a number of reasons for this. First, nearly all modern fungicides have a single site mode of action, providing an opportunity for a pathogen to develop resistance with only a single mutation. Second, fungicide use has risen dramatically in the past 10 years, thereby increasing the selection pressure placed on many pathogen populations. This paper will attempt to summarize the mechanisms and factors that lead to the development of fungicide resistance and provide examples on the successful and unsuccessful attempts to prevent fungicide resistance from developing.

Factors Affecting Fungicide Resistance Development

Numerous factors interact and affect the development of fungicide resistance. These factors include population dynamics of the pathogen involved, mode of action of the fungicide, the level of control provided by the fungicide, frequency of fungicide use, persistence of the fungicide, and the reproduction of the fungus. Each of these factors will be discussed in some detail.

POPULATION DYNAMICS

Polycyclic pathogens, such as foliar disease-causing fungi, are more likely to develop resistance to fungicides than monocyclic pathogens. The reasons are quite obvious. A fungicide-resistant “mutant” is likely present in any fungal pathogen population at an initial frequency of 1 in 1–10 billion spores of the pathogen in a wild type population. Once this population is exposed to a fungicide with a single site mode of action, the proportion of the individuals that can

resist the fungicide survives and will increase in proportion to the sensitive population. It is only when the proportion of the resistant pathogens reaches between 1 in 1,100 and 1 in 10 that the presence of a resistant population is evident or detectable. This is why the development of fungicide resistance often appears to occur abruptly when, in reality, it has been building up over some length of time—albeit at undetectable levels.

MODE OF ACTION

The mode of action of many fungicides is to bind or inactivate a key enzyme that regulates life-sustaining processes in the fungal pathogen. This would be an example of a single site mode of action, as previously mentioned. All that is required for a fungus to resist the action of a single site fungicide is a change in a single gene or a mutation. In fungicides that have multiple sites of action, more than one life-sustaining process is affected, and the ability to resist the action of more than one of these becomes highly unlikely. This is why fungicides with multiple sites of action, such as mancozeb or chlorothalonil, have never successfully had a resistant pathogen population develop. Simply stated, too many gene changes or mutations would be required before a resistant isolate could withstand the activity of a fungicide with multiple sites of action.

There are exceptions to this general rule. Despite the fact that triazole (DMI) fungicides have a single site mode of action—specifically, they inhibit sterol biosynthesis—the development of resistance to this class of fungicide is a multi-step process involving multiple gene or mutation changes. No single gene in plant pathogenic fungi conveys full resistance to triazole fungicides. Rather, multiple mutations are required, each of which provides small decreases in fungicide sensitivity and loss in efficacy. For this reason, the development of resistance

to triazole fungicides develops slowly over time and can be effectively managed in many instances.

LEVEL OF CONTROL

It may seem counter-intuitive, but the selection of fungicide-resistant individuals in a population of a plant pathogen is more likely to build up rapidly when fungicide efficacy is high. Highly efficacious products place a greater degree of selection pressure on the pathogen. In other words, products that provide 95% disease control place more pressure on the pathogen than products that provide only 80% disease control.

FREQUENCY OF USE

The selection and buildup of fungicide-resistant individuals is greater the more times a fungicide or fungicide group is used. This is more likely to occur if sequential applications of the same chemistry are made in the absence of alternations with other modes of action. For example, if only two to four applications of a fungicide are made on a crop to control a foliar disease and only QoI (strobilurin) fungicides are used, the target pathogen is more likely to develop resistance to this class of fungicide than if QoI and triazole fungicides were alternated.

PERSISTENCE OF THE FUNGICIDE

The longer fungicide residues remain on or in the plant, the more exposures a polycyclic pathogen will have to the same chemistry and the greater the selection pressure.

REPRODUCTION OF THE FUNGAL PATHOGEN

Sexual reproduction in a fungus allows for increased variation of genetic material within the fungal population. Fungi that reproduce only asexually do not have as great an opportunity for genetic variability. Fungal plant pathogens that reproduce sexually, in general, have a greater likelihood of developing resistance to fungicides and for this trait to be genetically stable. However, many asexually reproducing plant pathogens produce multiple generations of spores per year and are also capable of becoming resistant to fungicides.

Case Study of Fungicide Resistance in Potatoes

Potato growers have been plagued by the development of fungicide resistance in a number of important pathogens. The dry rot and silver scurf pathogens, *Fusarium sambucinum* and *Helminthosporium solani*, respectively, developed

resistance to benzimidazoles (FRAC group 1) in the early 1990s. Two *Phytophthora*-caused diseases, late blight and pink rot, caused by *P. infestans* and *P. erythroseptica*, respectively, have developed resistance to mefenoxam (FRAC group 4). Among these pathogens, only the late blight pathogen is polycyclic, capable of producing multiple generations of spores during a growing season—hereby increasing exposure to fungicide chemistry. Furthermore, only *P. erythroseptica* has the ability to reproduce sexually. Therefore, it is obvious that, although we can make general statements about factors that affect the development of fungicide resistance, exceptions occur and valuable disease control chemistry can be lost. The development of resistance to fungicides among these disease-causing potato pathogens has been very problematic for the potato industry and has left serious voids in disease management options.

QoI fungicides (strobilurins; FRAC group 11) were introduced in the late-1990s in the United States. Azoxystrobin (Quadris®, Syngenta) was registered for use on potato in 1999. This fungicide provided excellent control of early blight, caused by *Alternaria solani*. Early blight disease pressure in the midwestern United States is usually high due the frequent formation of dew at night. The fungus that causes early blight survives in debris from the previous crop and requires alternating wet and dry periods for infection and subsequent production of secondary cycles of inoculum. Standard protectant fungicides such as mancozeb and chlorothalonil are frequently inadequate alone to provide full-season control of this foliar disease. Azoxystrobin initially provided excellent control of early blight and was so efficacious that many potato growers made four to six applications of the chemical per season, alternated with standard protectants.

A decrease in the level of disease control provided by azoxystrobin was first observed during the summer of 2000 in Nebraska and subsequently in North Dakota in 2001 (Pasche et al. 2004). It was also determined that the mechanism of QoI resistance in *A. solani* was the presence of the F129L mutation (Pasche et al. 2004, 2005). This mutation conveys a 10–15× loss in sensitivity to the QoI fungicides azoxystrobin and pyraclostrobin (Headline®, BASF) and effectively reduces the efficacy of these two fungicides, making them equivalent to mancozeb and chlorothalonil (Pasche and Gudmestad 2007). Because QoI fungicides represent a premium-priced option, we no longer recommend them for the control of early blight in the Midwest.

Interestingly, the effect of the F129L mutation is differential in its impact on other QoI fungicides, such as trifloxystrobin (Gem®, Bayer CropScience), famoxadone (Tanos®, DuPont), and fenamidone (Reason®, Bayer CropScience). The F129L mutation conveys only a 2–3× loss in sensitivity, which does

TABLE 1 • Number and percentage of F129L mutant isolates of *Alternaria solani* collected from across the United States from 2002 to 2006 (from Pasche and Gudmestad 2007).

State ¹	2002 ²		2003		2004		2005		2006		2002–2006	
	Total ³	% Mutant ⁴	Total	% Mutant	Total	% Mutant	Total	% Mutant	Total	% Mutant	Total	% Mutant
Nebraska	240	98.8	247	100.0	758	99.0	46	100.0	9	88.9	1300	99.3
Minnesota	—	—	—	—	767	96.7	136	91.9	309	92.2	1212	95.7
North Dakota	181	100.0	225	91.2	230	98.7	66	97.0	58	62.1	760	93.8
Wisconsin	—	—	—	—	—	—	258	96.1	138	89.1	396	93.7
Michigan	—	—	11	100.0	148	94.1	55	98.2	—	—	214	96.7
Texas	—	—	1	100.0	60	100.0	131	98.5	—	—	192	99.0
Colorado	—	—	9	100.0	—	—	20	100.0	78	91.0	107	93.5
Idaho	—	—	—	—	—	—	26	15.4	—	—	26	15.4
Wyoming	—	—	—	—	—	—	13	23.1	—	—	13	23.1
Oregon	—	—	—	—	—	—	—	—	10	60.0	10	60.0
Washington	—	—	—	—	—	—	8	12.5	—	—	8	12.5
Total	421	99.3	493	95.9	1963	98.4	759	91.4	602	87.9	4238	96.5

¹ State from which isolates were originally collected.

² Year isolate was collected.

³ Total number of isolates examined for a given time period.

⁴ Percentage of isolates determined to contain the F129L mutation for a given time period.

not appear to affect fungicide efficacy of these chemistries (Pasche et al. 2004, 2005). This is highly unusual because the only other mutation detected in nature that induces resistance to QoI fungicides, the G143A mutation, conveys resistance factors of several hundred or a thousand times lower sensitivity to all QoI fungicides and a complete loss of disease control. Unfortunately, the other QoI fungicides were never as efficacious in the control of early blight as azoxystrobin and pyraclostrobin. For this reason, there remains a need in the potato industry for fungicides that provide enhanced control of early blight in the midwestern United States.

We initially hypothesized that the development of resistance in *A. solani* to QoI fungicides was caused by the repeated exposure of the pathogen to this chemistry. Although we could find no evidence of growers abusing the chemical through sequential applications without alternations with other fungicides, potato producers did apply multiple applications each season, consistent with the label. Our investigations led us to believe that the development of resistance occurred in *A. solani* populations because potato growers used 10 to 12 applications over a 2-year period (Pasche et al. 2004). The

frequency of resistance to QoI in the early blight fungus in the Midwest is generally >95% (Table 1). However, we now know that our earlier conclusion was incorrect because QoI resistant populations exist in potato production areas where QoI fungicides have been used infrequently over the past 8 years (Pasche and Gudmestad 2007). In most of these instances, growers either did not apply a QoI fungicide to their crop or made only one or two applications per year since they first became available in 1999. For example, the frequency of resistance in Western potato production areas of Idaho, Washington, and Oregon varies from 12% to 60% of the population despite infrequent QoI fungicide use and low disease pressure (Table 1). This strongly suggests that the selection pressure QoI fungicides place on the *A. solani* population is so high that F129L mutant populations can develop readily. This is a hard lesson learned by the potato industry—one that should be considered thoughtfully in other agricultural commodities.

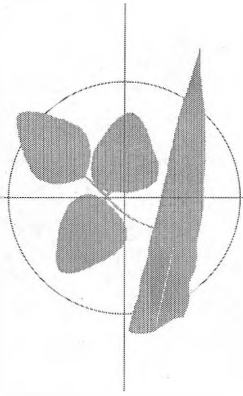
Summary

The development of fungicide resistance in a pathogen is a costly venture. Fungicide resistance means the loss of a valu-

able tool to manage diseases important to producers and it also means a loss of sales for basic manufacturers of agricultural chemicals. The management of fungicide resistance is difficult but not impossible to achieve. Agricultural producers need to be cognizant of indiscriminate use of specific fungicide chemistries, and they should not use a fungicide in isolation. It is important to use multiple methods to manage disease and not to rely on a single disease management tactic, such as a single fungicide chemistry. Finally, methods to monitor important fungal pathogens must be in place in order to detect fungicide-resistant populations before they become widespread. This requires coordination and the cooperation of agricultural producers, state agricultural professionals, and basic manufacturers.

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Glyphosate-Resistant Weeds: Yes It Can Happen, Even When You Think You Know How to Kill Weeds

Bill Johnson, Vince Davis, and Andy Westhoven

Development of herbicide-resistant weed populations results from overdependence on a specific herbicide mode of action. Target site-based triazine or ALS-inhibitor resistance in weeds is expressed at high levels in plants, which usually means that field use rates will have little or no effect on resistant plants while susceptible plants will be killed. Thus, it is usually fairly obvious when these types of resistant populations develop in a field; as a result, the use of specific products becomes obsolete in controlling the specific herbicide-resistant weed. However, glyphosate resistance is typically expressed at much lower levels and, in many instances, poor application techniques or low rates are considered the primary cause of poor weed control with glyphosate.

However, detailed greenhouse and field investigations by university researchers across the United States have shown that there are indeed a number of weeds that have evolved low levels of glyphosate resistance (GR), and we can no longer blame poor application techniques on all cases of poor weed control with glyphosate.

The purpose of this presentation is to showcase field history and weed control practices in Indiana production fields that lead to the development of glyphosate-resistant horseweed (aka marehail), giant ragweed, and glyphosate-tolerant common lambsquarters biotypes. We will also show that some weed biotypes that have evolved low levels of resistance show various degrees of injury by glyphosate but can recover and produce viable seed. In addition, we will review the economic implications of these weeds in the event that glyphosate and glyphosate + ALS-resistant biotypes are present in a specific field, or if multiple weed species develop resistance to glyphosate in a specific field. We will focus specifically on soybeans, because there more

herbicide options to manage these glyphosate-resistant species in corn than in soybeans.

Glyphosate-resistant horseweed has been documented in most midwestern states that grow soybeans and corn. The first documented case of glyphosate-resistant horseweed was in Delaware following 2 years of exclusive glyphosate use for preplant and in-crop weed control in glyphosate-resistant soybeans. In Indiana, glyphosate-resistant horseweed was first noticed in southeast Indiana, where continuous soybeans are grown more frequently than in other parts of the state.

On our main glyphosate-resistant horseweed research site, horseweed, which shows a sixfold level of resistance, was documented in 2003. The history of this field was a no-till corn-soybean rotation with conventional (nonglyphosate) herbicide programs used for postemergence weed control from 1996 to 1999. In 2000, GR soybeans were grown for the first time, and glyphosate was used for burndown and postemergence weed control. In 2001, glyphosate was used for the burndown treatment prior to no-till corn establishment, and conventional herbicides were used for postemergence weed control. No-till GR soybeans were then grown in both 2002 and 2003, with glyphosate used as the burndown and postemergence treatments in both years. Thus, there were a total of five glyphosate applications over a 3-year period prior to the evolution of GR horseweed at that site.

Horseweed is not considered to be highly competitive, but it can affect soybean establishment, yields, and harvest. Several options exist to manage glyphosate-resistant horseweed in soybeans. The additional cost to control horseweed prior to planting can be relatively low for 2,4-D (\$2/A) or moderately expensive with Gramoxone plus Sencor (\$13/A).

However, horseweed with multiple-resistance can evolve. Several counties in Indiana and Ohio have horseweed that is

resistant to both glyphosate and ALS-inhibiting herbicides such as FirstRate and Classic, which limits that option when growers wish to avoid the plant-back time restrictions with preplant applications of 2,4-D or use a tankmix partner with glyphosate after soybeans emerge. When multiple-resistant (glyphosate and ALS) horseweed exists, 2,4-D or Gramoxone are basically the only preplant herbicide options to control existing plants other than tillage; other in-crop postemergence soybean herbicides are not effective.

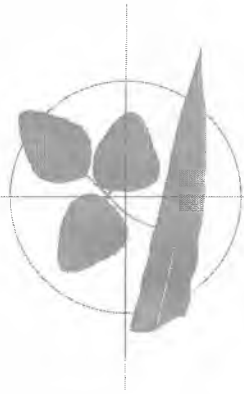
Giant ragweed is one of the most competitive weeds in the Midwest and is a challenge to control even in Roundup Ready crops. Glyphosate-resistant biotypes have been recently confirmed in Ohio and Indiana giant ragweed populations, and ALS-inhibitor resistance has been reported in several states.

In the first Indiana population that was documented to be glyphosate resistant, the field history included glyphosate-resistant soybeans the last 8 out of 9 years with at least one or two postemergence glyphosate applications. Giant ragweed is currently managed with burndown glyphosate applications plus one or two in-season glyphosate applications. With evolved glyphosate resistance, PPO- and ALS-inhibitor herbicides become the principal options. However, there is a strong likelihood that multiple resistance to glyphosate

plus ALS-inhibitor herbicides will evolve, leaving PPO-inhibiting herbicides as the primary remaining option, given that preemergence herbicide options often do not provide adequate control.

Although multiple herbicide resistance increases the challenge to manage specific weed species, the potential also exists for multiple glyphosate-resistant weed species in the same field. Glyphosate-resistant horseweed and giant ragweed have been confirmed in one field where a glyphosate-“tolerant” common lambsquarters is also being investigated. The history of this field included use of nontransgenic corn (i.e., no glyphosate use in corn) and glyphosate-resistant soybeans in a 1:1 rotation. The soybeans were grown without tillage and two to three glyphosate applications were made during the soybean growing seasons for weed control.

The soybean weed management program of this field will now require the grower to use a soil-applied residual herbicide for common lambsquarters control plus 2,4-D to control existing giant ragweed and horseweed, followed by higher rates of glyphosate postemergence to effectively protect yield. The presence of two glyphosate-resistant weeds and glyphosate-tolerant common lambsquarters resulted in weed control expenses that increased from \$18/A to \$37/A.



Insecticide Resistance in Western Corn Rootworms: What Can We Learn from Previous Mistakes?

Blair D. Siegfried, Lance J. Meinke, and Haichuan Wang

The western corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae), is arguably the single most important pest of field corn, *Zea mays* L., throughout most of the U.S. Corn Belt, both in terms of crop losses and the use of synthetic insecticides (Levine and Oloumi-Sadeghi 1991; Sappington et al. 2006). Managing corn rootworm populations to minimize risk of economic loss is extremely difficult, in part because of its nearly unlimited capacity to evolve resistance both to chemical insecticides (Metcalf 1986; Meinke et al. 1998; Siegfried et al. 2004; Parimi et al. 2006) and cultural control practices such as crop rotation (Levine et al. 2002). Recent management practices have relied extensively on neurotoxic and nonspecific synthetic insecticides that are directed against both larvae and adults. Corn rootworm management strategies that include prescriptive insecticide applications have not been widely adopted (Gray and Steffey 1995), placing increased pressure on the limited number of options available to growers.

Novel control techniques are being developed and marketed for corn rootworm management. The two most recent and significant developments involve transgenic corn hybrids expressing insecticidal genes from *Bacillus thuringiensis* (Bt) and seed treatments employing neonicotinoid insecticides. Both technologies have the potential to drastically reduce the environmental and human health risks associated with conventional rootworm management practices (e.g., soil insecticides). However, the remarkable history of western corn rootworm adaptation to the selective pressures imposed by recent pest management practices necessitates the proactive implementation of management strategies designed to sustain these novel management alternatives. Moreover, because of the invasive nature of this pest, proactive intervention for the purposes of mitigating invasions or minimizing the

spread of resistance outbreaks is critical to future management decisions.

Pesticide resistance management can be defined as the effort to delay or prevent adaptation in pest species to pesticides by preserving the genes that confer susceptibility in pest populations. Several theories have been advanced for managing insect resistance, but few experimental data on their comparative utility are available. In many instances, resistance management decisions rely on poorly validated assumptions of important parameters related to resistance inheritance and population genetic structure of pest species. Mathematical models provide a means to compare the durability of insecticides or transgenic toxins under different patterns of use (varying temporal vs. spatial patchworks, sequential use of toxins vs toxin mosaics, etc.) and to determine the optimal size and placement of “refuges” to minimize selection by the toxins in question. While resistance management strategies based on a set of models have an excellent chance of working provided the genetic assumptions are satisfied, efforts to develop management strategies based on incomplete or incorrect biological data are inherently risky.

In the case of the western corn rootworm, there are a number of striking examples of how this species has evolved resistance that can be tracked both temporally and spatially using diagnostic insecticide bioassays and a number of different biochemical and genetic markers. Information gained from study of these resistance outbreaks provides a unique opportunity to better understand population response to selection pressures, movement of resistance-conferring genes, and fitness costs of resistance, all of which ultimately will lead to improved resistance management recommendations for novel control strategies.

Examples of Resistance Evolution

CYCLODIENE RESISTANCE

Cyclodiene insecticides were commonly used as soil treatments for the control of both western and northern corn rootworms from the late 1940s to early 1960s. Benzene hexachloride (Muma et al. 1949), aldrin, chlordane (Ball and Hill 1953), and heptachlor (Ball and Roselle 1954) were the recommended active ingredients for control of root-feeding larvae during this period. Control failures with these compounds were first noted in Nebraska in 1959 (Roselle et al. 1959), and further evaluations in 1960 (Roselle et al. 1960) and 1961 (Roselle et al. 1961) revealed the magnitude and rapid development of the resistance. During 1961, western corn rootworm adults were collected from different fields in Nebraska, and susceptibility to aldrin and heptachlor was determined by topical application (Ball and Weekman 1962, 1963). Differences in susceptibility among field populations provided the first direct evidence of resistance evolution.

The development of cyclodiene resistance coincided with a rapid eastward range expansion. By 1980 the distribution of *D. v. virgifera* covered most of the U.S. Corn Belt, including areas where cyclodienes were not widely used as soil insecticides (Metcalf 1983). Resistance has persisted in populations for many years after the use of these compounds was discontinued (Siegfried and Mullin 1989), even in areas where the insecticides were not commonly used as soil insecticides. Parimi et al. (2006) reported the presence of high levels of resistance in both the laboratory-reared and field-collected adult western corn rootworms based on topical bioassays with the cyclodiene insecticide, aldrin. Aldrin resistance apparently has remained consistently high among field populations over the four decades since resistance was first reported. These high resistance levels have persisted in spite of reduced selective pressures since the cyclodiene insecticides were banned in 1972. However, considerable variation in resistance levels among populations has been detected.

A general decline in resistance among Nebraska populations and consistently higher levels of resistance in more eastern populations were noted (Figure 1) based on survival at a diagnostic concentration of the cyclodiene insecticide, aldrin. The

general trend for higher resistance levels among populations where selection pressures are believed to have been lowest is puzzling. The use of broadcast applications of cyclodiene insecticides was generally confined to the western Corn Belt where resistance was first identified, and the higher resistance levels in eastern North America seem counter to the geographic gradient in selection intensity.

The only population examined to exhibit what appears to be complete susceptibility to aldrin was a nondiapause laboratory strain that was established from field collections in 1968. This strain was derived from a field collection made in an area where resistance was reported to have been present at the time of collection (Metcalf 1983). Because up to four generations of the nondiapause strain can be reared in the laboratory in a single year, slight fitness disadvantages may have been manifested in the loss of resistance over a shorter period of time relative to field populations. It should also be noted that the nondiapause population has likely undergone a rather restrictive genetic bottleneck during selection for the nondiapause trait. Therefore, in selecting for a nondiapause trait, the genes conferring resistance may have been lost and the susceptibility observed in this strain, unrelated to possible fitness disadvantages.

In most other insect species studied, resistance involves a form of nerve insensitivity caused by a conserved point mutation (French-Constant et al. 2000) in the gene encoding the receptor for the inhibitory neurotransmitter, γ -aminobutyric acid (GABA). Significant progress has been made recently in two specific areas related to cyclodiene resistance in western corn rootworms: (1) identification of the same point mutation in the GABA receptor associated with cyclodiene resistance and (2) identification of significant variation in susceptibility to the cyclodiene insecticide aldrin among

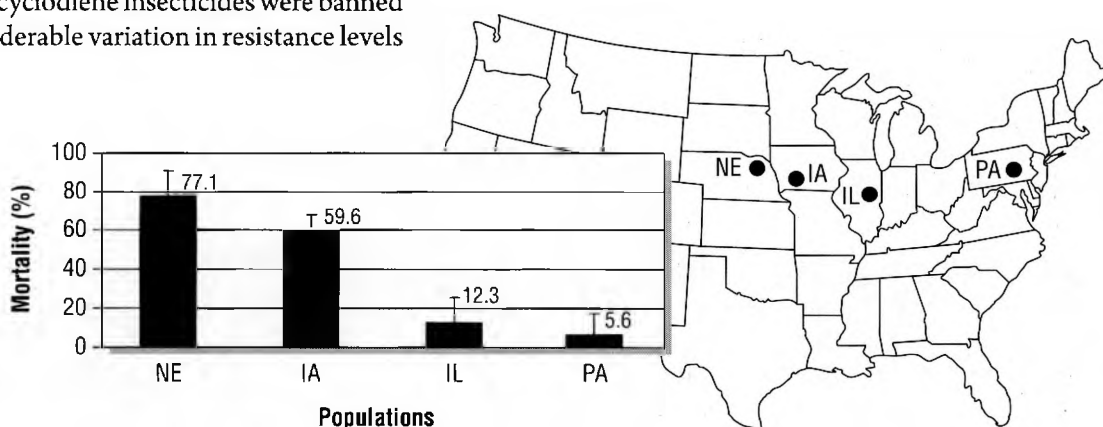


FIGURE 1 • Susceptibility of *D. v. virgifera* adults collected from Nebraska, Iowa, Illinois, and Pennsylvania to a diagnostic concentration of aldrin corresponding to the LC_{99} of the susceptible nondiapause strain.

western corn rootworm populations. Because of the rapid range expansion and persistence of cyclodiene resistance in *D. v. virgifera*, detectable variation in susceptibility and availability of molecular markers, cyclodiene resistance in this species represents a potentially important model for understanding the evolution and movement of target site-mediated resistance genes. The identification of molecular markers that are diagnostic for specific resistance genotypes should provide an important tool for clarifying the number of origins of resistance-associated mutations for determining the population genetic structure of invading populations and for refining decisions regarding resistance management and mitigation recommendations. Moreover, because cyclodiene resistance has persisted among rootworm populations for over 40 years, understanding the impact of resistance on reproductive fitness in the presence and absence of selective pressures will be particularly insightful.

ORGANOPHOSPHATE RESISTANCE

Organophosphate and carbamate insecticides were introduced following the failure of cyclodienes and successfully replaced these compounds as the predominant soil insecticides throughout the U.S. Corn Belt. Both organophosphates and carbamates are still used as soil insecticides and as foliar insecticides in adult management programs. Both soil insecticides and adult rootworm management were adopted as primary management tools where irrigated, continuous corn is planted over large acreages throughout the Platte River valley of central Nebraska. However, in some areas of Nebraska, aerially applied PennCap-M® (methyl parathion) was used almost exclusively (Meinke 1995) over relatively large areas and in consecutive years.

Control failures of aerially applied methyl-parathion were first reported in the early 1990s, and resistance to organophosphate and carbamate active ingredients was documented in rootworm adults from a number of Nebraska populations (Meinke et al. 1998). The distribution of resistant rootworms was initially restricted to areas of the state where adult management had been practiced in excess of ten years, while areas relying on soil insecticides and crop rotation apparently remained susceptible.

In 1996, a diagnostic bioassay was developed for quickly assessing the resistance status of field-collected rootworm populations. Based on the dose response curves of representative resistant and susceptible populations, a diagnostic concentration corresponding to the LC_{99} of a standard susceptible colony was determined. This concentration was used to assess the resistance by identifying the proportion of a given population that exceeds 1% survival at LC_{99} for a susceptible population. Based on sampling results over a

4-year period using the diagnostic concentration of methyl-parathion, resistance exhibited significant expansion both in distribution and in intensity (Figure 2). Initial sampling of rootworm susceptibility in 1996 indicated the presence of two distinct resistant areas based on the presence of susceptible populations that separate these two regions. However, by 1998, significantly increased levels of tolerance were observed in the areas of York and Hamilton counties, and areas previously identified as being susceptible had become highly resistant (Adams County, Figure 2). Although resistance appears to have grown both in intensity and in geographic range, there were still populations of rootworms that remain susceptible to methyl-parathion in proximity to resistant populations. Furthermore, in areas where aerially applied methyl-parathion no longer provides effective control of adult rootworms, growers are adopting other management practices, such as crop rotation and use of soil insecticides.

Importantly, the development and spread of methyl-parathion resistance provides an important tool in validating models of resistance evolution. This approach was recently used to validate a stochastic model of the evolution of resistance to adulticidal sprays of methyl-parathion in western corn rootworm populations in Nebraska (Caprio et al. 2006). When resistance was examined as a genetic phenomenon, the rate of increase of the resistance allele depended almost entirely on genetic factors (LC_{50} values), the characteristics of the pesticide (residual activity), and the variance associated with emergence of adults. When resistance was measured as failure of methyl-parathion to reduce populations below threshold levels (0.5 gravid females per plant), parameters

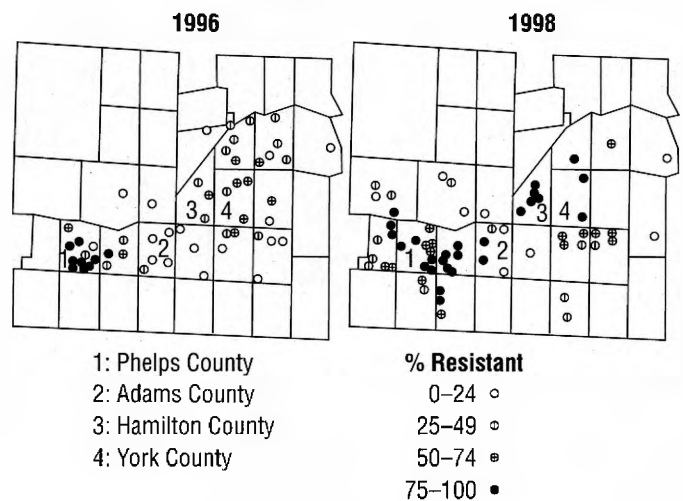


FIGURE 2 • Distribution of methyl-parathion-resistant western corn rootworms based on percentage of survival at diagnostic concentration after 4-hour exposure; N = 50-100.

that contributed to population growth rate (mortality and fecundity) were also important. These data suggest two important phases in resistance evolution in corn rootworms: (1) a genetic phase associated with negative growth rates and rapid changes in resistance allele frequencies and (2) a rebound phase associated with positive growth rates and near fixation of the resistance allele.

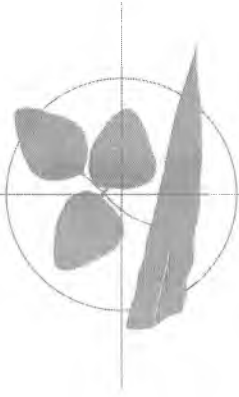
What Can We Learn?

For transgenic crops expressing the Bt toxin, current resistance management recommendations favor combining a high dose of insecticidal protein with a refuge of nontransgenic plants (Roush 1996; Andow and Hutchison 1998; ILSI 1998; Bates et al. 2005). Theoretically, the high dose kills all heterozygous individuals (i.e., resistance is functionally recessive) and constrains the frequency of resistance alleles to a low level (Roush and Daly 1990; Gould 1998; USEPA 1998). The purpose of a refuge is to supply susceptible, nonselected individuals to the general population. The use of a refuge strategy should increase the probability that rare, homozygous-resistant individuals will mate with homozygous-susceptible individuals. These matings will produce only heterozygous progeny that can be eliminated by the high-dose plants (Roush 1996). This strategy relies on several assumptions regarding the genetic architecture of resistance that are difficult to validate. Utilizing the information that is available from previous resistance events provides an important opportunity to limit the uncertainty that is inherent to some of these assumptions. Specifically, understanding the population response to selective pressures, fitness costs associated with resistance, and movement of resistance-conferring alleles are all important to the design and implementation of resistance management and mitigation strategies. Given the western corn rootworm's remarkable history of resistance evolution to both chemical and cultural control tactics, the implementation of sound resistance management programs is critical to its sustainable management.

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Insect Resistance Management (IRM) Requirements in Bt Crops

Scott Baucum

The Monsanto Commercial Trait Stewardship Team holds primary implementation responsibility for insect resistance management (IRM) education, monitoring for compliance, remediation, and enforcement related to the conditional registrations of Monsanto's insect-protected seed traits.

Monsanto meets these objectives with attention to the Monsanto pledge and the Biotechnology Industry Organization's "Excellence Through Stewardship" commitment.

IRM

Maintaining product conditional registrations for insect protection traits requires annual monitoring and reporting to EPA. Metrics include

- ✿ on-farm assessments where farmers and, in Monsanto's case, an independent third party sit down with the farmer to discuss corn and/or cotton seed planting for the current year and compare them to the planting options available to farmers under the end-user licensing agreement (EULA).
- ✿ phone-market research to determine the percentage of compliance.
- ✿ grower point of sale (GPOS) reporting to track each sale to named growers. Annual EPA reporting also includes details related to education efforts, complaint management, and enforcement actions such as dealer or grower license actions that remove product access from noncompliant parties. EPA requires continuing product registration on Monsanto's performance of these tasks and grower and dealer compliance. Monsanto, like other trait registrants, reports this information to the Ag Biotech Stewardship

Technical Committee (ABSTC) for compilation into one single report submitted to EPA the final week of January each year.

Monsanto reports the following information to ABSTC:

- ✿ total units of insect-protected seed sold and not returned, by county, by grower, and licensed by 7/31
- ✿ results from on-farm assessments
 - 250 Bollgard/Bollgard II cotton
 - 700 YieldGard Corn Borer
 - 200 YieldGard Corn Rootworm
 - 300 YieldGard Plus
- ✿ a list of stewardship education and training materials used to train growers and dealers
- ✿ results of annual grower phone survey
- ✿ details for refuge violations

Monsanto recently commissioned market research to determine what could be done to preserve IRM compliance. The results were clear. Self-discipline initiatives can be expected to yield little, if any, increase in compliance. On the other hand, farmers indicated that communicating consequences for noncompliance could improve compliance, provided that awareness of these consequences was broad and certain. The problem with a private company communicating "consequences" to customers is obvious. At Monsanto, we separate these responsibilities from the sales and marketing groups and involve independent third parties, when possible, to retain all possible integrity in our commitment to stewardship excellence.

Similar reasoning supports the necessity for industry standards across brands for stewardship integrity. Without industry standards and similar company commitment to those standards, stewardship can become a competitive disadvantage to those who “hold the line” versus those who manage issues with a “wink and a nod,” and it is in these critical seconds when a farmer will take his or her lead from those given charge to set the right example.

Likewise, working together, we can best determine the least disruptive path to achieve our mutually important goals. Our

farmers deserve the very best we can give them in regard to keeping any “regulation” as minimally invasive as possible while still accomplishing its intended protection.

Many people sacrifice now to save money in a 401(k) with an expectation of benefits later. People discipline themselves now to eat in moderation and to exercise with an expectation of greater health over a longer time period. It is important to follow this same sense of delayed gratification to preserve the benefits of these important technologies.



Increasing Corn Acres and Prophylactic Use of Bt Hybrids: Implications for IPM and IRM

Michael E. Gray and David W. Onstad

At a conference in Winnipeg, Manitoba (March 25–28, 2007), some members of the North Central Branch of the Entomological Society of America grappled with a controversial topic at a symposium titled “The Future of IPM in Corn and Soybean Production.”

Is it surprising that this question is being debated? Is it startling that the very question of IPM implementation, or the lack thereof, in the corn and soybean agroecosystem is being discussed among academics? Will those engaged in large-scale commercial production of corn and soybeans look back on the 2007 growing season as a year in which the principles of IPM were followed, or largely ignored? Is IPM relevant in 2008? Most of us engaged in commercial agriculture seem to have our own interpretation of what these three letters represent.

There are many formal definitions of IPM. A definition (Rabb 1972) used many times is as follows: “Pest management is the intelligent selection and use of pest-control actions that will ensure favorable economic, ecological, and sociological consequences.” Another definition is provided by Geier (1966):

- (1) determining how the life system of a pest needs to be modified to reduce its numbers to tolerable levels, that is, below the economic threshold;
- (2) applying biological knowledge and current technology to achieve the desired modification, that is, applied ecology;
- and (3) devising procedures for pest control suited to current technology and compatible with economic and environmental quality aspects, that is, economic and social acceptance.

Many participants who took part in the Winnipeg symposium agreed that a relatively easy case can be made that the use of Bt hybrids and herbicide-tolerant crops leads in most

instances to favorable economic returns. Additionally, the use of transgenic crops has led to reductions in pesticide use and presumably improved environmental consequences and human health and safety.

With regard to “sociological” consequences—the last component of Rabb’s IPM definition—those of us in the IPM community continue to struggle with how to adequately describe the changing sociological forces across the agricultural landscape and how to enhance IPM implementation. It seems certain that maximizing crop production inputs does not equate to IPM. Some of the sociological forces (Gray and Steffey 2007) that are shaping how IPM decisions are being made in the corn and soybean production systems include

- ✿ surging interest and investment in biofuels
- ✿ favorable commodity prices
- ✿ significant increase in continuous corn acres
- ✿ escalating demand for triple-stacked corn hybrids (even in areas where corn rootworms and European corn borers do not represent a persistent economic threat)
- ✿ use of insecticidal seed treatments (neonicotinoids: clothianidin and thiamethoxam) on every kernel of Bt seed
- ✿ increasing interest in the use of fungicides on corn, in many instances through a prophylactic approach
- ✿ concern about inadequate refuge deployment
- ✿ increasing reliance on a restricted spectrum of herbicides in corn and soybeans
- ✿ larger farms
- ✿ fewer farmers, more absentee landowners

- ✿ an increasingly trait-driven marketplace
- ✿ a paradigm shift from IPM to IRM (insect resistance management)

Against this backdrop of factors, the principles of integrated pest management in the corn and soybean agroecosystem are increasingly being ignored. Of particular concern is the lack of integration of pest management tactics and the over-reliance on single-tactic approaches without any scouting input. Some of the very costly and unpleasant outcomes associated with pesticide misuse are being forgotten. What are some examples of these unwanted consequences (Gray and Steffey 2007)?

- ✿ insecticide resistance
- ✿ secondary pest resurgence
- ✿ harmful effects against nontarget insects and other organisms
- ✿ potentially harmful pesticide residues on food products
- ✿ pesticide movement into our natural resources, such as ground and surface water

In a report released on July 5, 2007, titled *Adoption of Genetically Engineered Crops in the United States* (www.ers.usda.gov/Data/BiotechCrops), the USDA Economic Research Service revealed the significant escalation in use of Bt corn in Illinois and other states. In 2006, 19% of all planted corn in Illinois was characterized as a “stacked gene” variety. In 2007, the use of stacked corn hybrids in Illinois more than doubled and is estimated to be at 40% of planted corn acres. In 2006, 55% of corn planted in Illinois was estimated to be a genetically engineered hybrid (Bt only, herbicide-tolerant only, or stacked gene variety). In 2007, that percentage has increased to 74%. Therefore, roughly three-quarters of corn acreage in Illinois during the most recent growing season was planted to a genetically engineered corn hybrid. Adoption of this technology is occurring at a remarkable pace. What percentage of the corn produced in Illinois during 2008 will rely on a stacked gene hybrid?

Why is there any concern about the escalating use of Bt hybrids for insect control? Why is there any debate regarding whether the use of Bt hybrids should be considered within an IPM framework? After all, don't Bt hybrids fall into the host plant resistance category of pest management tactics?

The easy answer to the last question is “yes.” Our primary concern is that the “I” in IPM is largely being ignored. Where is the integration of management tactics? Even the cultural management approach of crop rotation for western corn rootworm control broke down after a few decades.

In recent years, there has been a proliferation of journal articles about the development of simulation models that seek to predict the longevity of transgenic crops based on a variety of biological, genetic, and ecological assumptions.

The remaining portion of this paper focuses on the predictions of one journal article published last year (Crowder et al. 2006). One has to be cautious in interpreting these models because they are built on many assumptions that may later be proven inaccurate. Nonetheless, they are helpful in assessing the potential for resistance development to Bt in a very complicated agricultural landscape.

In addition, through modeling analyses, we can begin to see where more biological and ecological research is required to improve our predictions of Bt longevity.

The Crowder et al. (2006) paper offers some interesting projections regarding the potential development of western corn rootworm resistance to transgenic corn. The landscape simulated with this model included 100% continuous corn and a nonvariant western corn rootworm population. Interestingly, the results of the simulation (assuming R, the allele for resistance to transgenic Bt corn, is recessive) did not vary that much with respect to toxin dose (high, medium, or low). Unlike Bt hybrids engineered for European corn borer control, transgenic hybrids that offer protection against corn rootworms are not high-dose events.

In the simulation model, the durability of transgenic corn (15 years or more) was not greatly affected by the type of management strategy selected (assuming R, the allele for resistance to transgenic Bt corn, is recessive): “(1) planting 80% transgenic corn to the continuous cornfield each season, (2) planting transgenic corn based on sampling and economic thresholds along with a 20% refuge, (3) planting 100% transgenic corn to the continuous cornfield each season, and (4) planting transgenic corn based on sampling and economic thresholds without refuges.”

Based on the results of this simulation model, if the western corn rootworm allele for resistance to transgenic corn is recessive, we can expect long-term durability of the Bt technology (15 years or more before the allele for resistance reaches 50% among the western corn rootworm population), regardless of the four management strategies employed. If the allele (R) for resistance to transgenic Bt corn among western corn rootworms is partially recessive and the toxin dose is characterized as medium, the durability of transgenic hybrids is quite short, only 5 to 6 years, regardless of the management strategy (1–4) described previously.

If low-dose transgenic Bt hybrids are used, and the allele (R) for resistance to transgenic Bt corn is partially recessive, then the longevity of these transgenic hybrids can be improved

to 9 to 10 years. If the allele (R) for resistance is dominant among western corn rootworms, it reaches 50% within the population very quickly (~5 years), even with refuges.

The authors (David W. Crowder, David W. Onstad, and Michael E. Gray) of the paper made the following concluding statements:

The use of economic thresholds slightly slowed the evolution of resistance to transgenic insecticidal crops. In areas with or without rotation-resistant western corn rootworm phenotypes, the use of sampling and economic thresholds generated similar returns compared with strategies of planting transgenic corn, *Zea mays* L., every season. Because transgenic crops are extremely effective, farmers may be inclined to plant transgenic crops every season rather than implementing costly and time-consuming sampling protocols.

Although the durability of transgenic Bt corn for western corn rootworms was not affected significantly (assuming the resistance allele is recessive) by the use of any of the management strategies used in this simulation model and described previously, the fact that many Bt hybrids that will be planted in 2008 will be “stacked” places a special emphasis on the deployment of 20% refuges as required by the U.S. Environmental Protection Agency. Maintaining the viability of the refuge to delay or prevent resistance to Bt by European corn borers is essential. The IRM strategy of using a high-dose event along with a refuge has worked exceptionally well for more than a decade in preventing the development of resistance by European corn borers. We are concerned that some producers will ignore the use of the refuge this spring. If this behavior begins to occur on a more regular basis, resistance will develop, and we risk the loss of a very valuable pest management tool.

The Crowder et al. (2006) paper has similar elements with the Foster et al. (1986) journal article about the use of soil insecticides in continuous corn production systems. The authors of the Foster et al. (1986) paper offered the following concluding statement: “The optimal strategy for managing corn rootworms in Iowa in our study was not to sample for adults and always to treat corn following corn with a soil insecticide at planting time.”

To date, resistance development has not occurred with the granular soil insecticides despite the fact that they have been commonly used for decades. However, it must be mentioned that producers have been unwittingly deploying “refuges” between corn rows due to the application of granular soil insecticides in a band or in-furrow at planting.

Because the four management strategies described by Crowder et al. (2006) seemed to have relatively little impact

on the speed at which resistance development to Bt corn occurred within the western corn rootworm population, some may argue against the need for a refuge. Because of the escalating use of stacked Bt hybrids, this would be a serious mistake. If Bt hybrids (nonstacked) are deployed only for corn rootworms, the value of sampling, thresholds, and use of refuges to delay the onset of resistance will continue to be debated among academics. The authors of the Crowder et al. (2006) article offered the following cautionary statement with regard to their simulation model:

The application of these results is limited by several assumptions in the model. First, we assumed that a very simple genetic system is responsible for evolution of the behavioral changes and rotation resistance. Second, we assumed that all farms are the same in a homogeneous region or that areawide pest management is occurring. Third, we did not include costs of sampling or uncertainty because of sampling error, unlike Nyrop et al. (1986). Changes in these assumptions could have produced other outcomes.

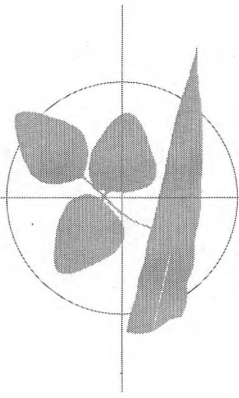
The results of this simulation model reinforce our concern about the lack of integration of pest management tactics in the current corn and soybean production system. As we begin to move in the direction of pyramiding genes with different modes of action in transgenic hybrids for insect resistance management purposes, several questions surface:

- ❖ Will integration of management tactics in the field be replaced with the insertion of a diverse array of genes with transgenic crops for insect control?
- ❖ Will the use of refuges for resistance management purposes be necessary over the long haul as we begin to utilize more transgenic crops with a different internal arsenal of genes effective against a wide array of insect pests?
- ❖ How long will the use of scouting, economic thresholds, and economic injury levels continue to be relevant in large-scale commercial cornfields for many insect pests?
- ❖ Will producers increasingly make their most important pest management decisions in the fall and winter months as they evaluate the transgenic seed opportunities before them?

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Managing the Consequences of Long-Term Weed Control

Aaron G. Hager

Plant species considered to be weeds have caused myriad maladies to befall human society since the beginning of recorded time, including hunger caused by losses in crop productivity and yield, dramatic reductions in the aesthetic value of countless landscapes, significant and sometimes permanent loss of ecological diversity, physical ailments of humans and livestock alike, and untold expenditures of financial resources aimed toward their control. Yet, despite man's best efforts to keep these undesirable plants in check, weeds continue to plague multiple aspects of daily life.

Those who are considered weed management practitioners of agronomic cropping systems know all too well how difficult it can be to remove weeds from the cropping landscape. History is replete with examples of how weeds have evolved and evaded many of the tools designed for their management. Previous papers in this conference's proceedings have illustrated some of these adaptations, including changes in the emergence characteristics of giant ragweed (once considered an early-emerging species) in response to long-term crop production practices; increased occurrence of weed species (such as hophornbeam copperleaf) not previously well characterized; and selection of herbicide-resistant biotypes of species sensitive to a particular herbicide (such as waterhemp with resistance to three herbicide modes of action).

Some of these adaptations could perhaps be described as being analogous to corn yield potential—many plant genes and environmental factors contribute to the observed response. Other adaptations in weeds are the result of our intense selection for traits that ensure survival of the species in the “artificial” environment of agronomic cropping systems. For example, waterhemp was once very sensitive to many ALS-inhibiting herbicides but now demonstrates high-level resistance via an altered herbicide target site selected by

repeated use of these herbicides. Some weeds have even adapted to the age-old practice of hand weeding; intense hand weeding of flooded rice fields has selected for a barnyardgrass biotype that closely mimics rice in appearance and thus escapes being hand weeded from the crop.

The examples previously described illustrate how weed species have adapted to changes in production practices. In some instances, weeds adapt in response to a single selection factor. Other times, the adaptation is due to multiple changes in production practices. Whether single or multiple factors are involved, it is important to remember that weeds will continue to adapt and challenge us.

The introduction and commercialization of glyphosate-resistant soybean varieties and corn hybrids has, in many ways, dramatically altered the weed management practices of farmers across much of the Midwest. Estimates place the adoption of herbicide-resistant soybean varieties and corn hybrids (principally glyphosate resistant) at approximately 90% and 37%, respectively, of the U.S. soybean and corn acreage, according to the USDA National Agricultural Statistics Service Report, June 2006.

Glyphosate-resistant crops offer many advantages to farmers, but as the previous examples illustrate, over-reliance on a single management option can lead to new weed management challenges.

Figure 1 illustrates the worldwide “history” of herbicide-resistant weeds. Until 2007, glyphosate-resistant weeds were the least represented herbicide-resistant biotypes among all major herbicide mode-of-action families. In 2007, the frequency of glyphosate-resistant weed biotypes surpassed the frequency of dinitroaniline-resistant weed biotypes.

A “philosophical” consideration sometimes discussed among academic weed scientists is the difference (real or perceived)

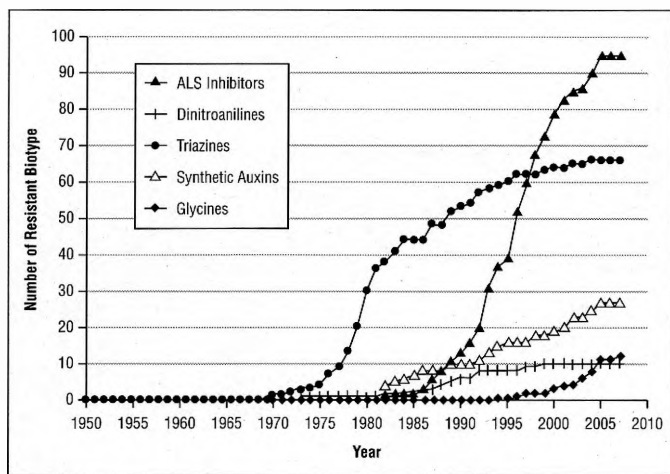


FIGURE 1 • The worldwide occurrence of herbicide-resistant weed biotypes, presented by herbicide family.

between what is accomplished through weed *management* compared with weed *control*. The weed science community has no “Webster’s of Weed Science Terminology” from which to seek definitive answers, so debate often becomes spirited, and conjectures abound among pontificators. The great writer and author Merriam Webster offers several possible ways to define the terms *control* and *management*. Careful scrutiny and (biased) selection of possible definitions provide the following:

☛ *control*: to reduce the incidence or severity of, especially to innocuous levels

☛ *manage*: to handle or direct with a degree of skill

The weed spectrum in many Illinois soybean fields today is such that a singular control strategy (e.g., a single postemergence herbicide application) may not always provide consistent control. Over the past decade, many practitioners have become very proficient at controlling weeds, but perhaps less proficient at managing weeds. Potentially serious repercussions are poised to plague Illinois soybean farmers in 2008 due to the widespread adoption of *weed control* in lieu of *weed management*. A specific consequence of widespread weed control is the selection of Illinois waterhemp biotypes resistant to glyphosate.

A pertinent question to consider is, how will Illinois soybean farmers manage a waterhemp population that may no longer be susceptible to glyphosate or diphenylether herbicides, the only postemergence soybean herbicide options that control waterhemp?

Weed scientists at the University of Illinois have conducted field, greenhouse, and laboratory research with an Illinois

waterhemp population that is not controlled at field-use rates of glyphosate-containing products. Although evidence to date suggests this *particular* population is in fact resistant to glyphosate, it is altogether likely that other populations of glyphosate-resistant waterhemp exist within Illinois. Indeed, anecdotal reports in 2007 suggested that glyphosate-resistant waterhemp may be present in several fields, ranging from counties in southeast Illinois to west-central Illinois. Observations suggested putative glyphosate-resistant waterhemp populations were more prevalent in soybeans than corn, but there is scant reason to believe these biotypes were not present in the 2007 Illinois corn crop.

The following recommendations are suggested for management of herbicide-resistant waterhemp in the 2008 soybean crop. Many of the 2007 soybean acres will be rotated to corn in 2008, so a relevant consideration is whether glyphosate-resistant waterhemp will be more *problematic* in 2008 or 2009 (when the 2007 soybean fields return to soybeans). Regardless, we assume that glyphosate-resistant and PPO-resistant waterhemp biotypes will be encountered across a large geographical area of central and south-central Illinois during 2008. Additionally, it is altogether possible that waterhemp biotypes resistant to both glyphosate and PPO inhibitors soon will be discovered. These biotypes represent a worst-case scenario, in that there are *no postemergence herbicide options for their control in soybean*.

The suggested recommendations for 2008 soybeans (these assume glyphosate-resistant soybeans) are listed. The considerations and justifications employed to develop these recommendations are based on recent and previous research on waterhemp biology and management:

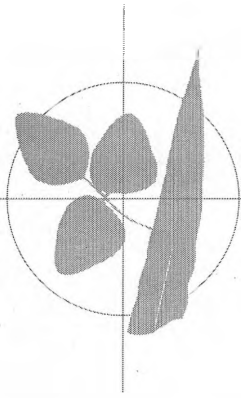
1. Apply a full labeled rate (according to label guidelines for soil type and organic matter content) of a soil-residual herbicide no sooner than 7 days before planting or later than 3 days after planting.
2. The initial postemergence application of glyphosate alone at 0.75 to 1.0 pounds a.e. must occur when waterhemp is 3 to 5 inches tall.
3. Fields *must* be scouted 7 days after the initial glyphosate application to determine treatment effectiveness.
4. If waterhemp control is inadequate and retreatment is necessary, apply a PPO-inhibiting herbicide (lactofen, fomesafen, or acifluorfen) at a full labeled rate as soon as possible.
5. Rescoute the treated field within 10 to 14 days to determine effectiveness of the PPO-inhibiting herbicide treatment. If scouting suggests some treated plants might survive, implement whatever tactics are available or feasible to

rogue these surviving plants from the field *before* they reach a reproductive growth stage.

These recommendations are, in reality, an illustration of the need for an integrated approach to waterhemp management. Integrated weed management introduces multiple tactics to control weeds and slow the rate at which weeds are able to

adapt to a single control tactic. Introducing an integrated weed management approach into glyphosate-resistant cropping systems may well stave off some potential new challenges, enhancing the long-term effectiveness of this valuable weed control strategy.

Is an ounce of prevention worth a pound of cure?



Fungicides on Disease-Free Corn: The Case from 2007

Emerson D. Nafziger

Spurred by the high price of corn and by sales campaigns to sell foliar fungicides as a way to improve “plant health” in a preemptive manner, as many as 3 to 4 million, or 25% to 35%, of the corn acres in Illinois were sprayed with strobilurin fungicides in 2007. Many producers committed to having fungicide applied weeks or months before planting, with the understanding that if they did not sign up early there might be no way to get such applications made in time. As a result of this demand, dozens of spray aircraft from outside of Illinois were brought into the state in June and July.

The start of the season was generally good, with timely planting in most areas. May was warm and dry, with good early corn growth and good stands. The dry weather continued past the middle of June, with 79% of the topsoil rated as “short” or “very short” by June 17 (NASS). With above-normal rainfall the last third of June, that dropped to less than 20% by July 1. The corn crop went from showing moderate to severe symptoms of water stress in mid-June into a period of very rapid growth in late June and early July. As a result, by July 1 the crop was 66 inches tall on average, and about one-third of it was silked.

Faced with a rapidly developing crop and a narrow application window to get fungicides applied by tasseling, applicators in many areas started early, often before the tassels had emerged. Those applying fungicide by ground also started early in order to be able to spray corn before it got too tall. With such rapid growth (statewide, corn grew at an average rate of 2 inches per day during the second half of June), spraying fungicide before tassel emergence was not off-label in most cases; in fact, spraying fungicide on seed corn fields before tasseling is a common practice.

Although there was some foliar disease (primarily gray leaf spot) at the time of fungicide application, the dry weather through mid-June had not provided much opportunity for inoculum to build up, and the incidence of foliar disease was low to zero in most fields at the time of fungicide application. This lack of disease did not cause much alarm, or apparently much cancellation of application, probably because fungicide application had been promoted as a way to improve yields even when disease incidence is low. With high prices and a corn crop that was shaping up to be good to excellent, most producers were eager to invest in what they considered to be yield-increasing input.

Damage from Fungicide

Within a month after application, some producers noticed that ear development was not normal in some fields that had been sprayed with fungicide. Such abnormal development has more than a single cause, but in some cases unsprayed strips showed none of the damage that sprayed areas showed, making it clear that fungicide (or additives) was the primary cause.

Damage took the form of ears whose development seems to have been interrupted at about the time the developing ear was 1 to 1.5 inches long, with some of the terminal portion of the ear showing no silk or kernel development. It appeared as if the fungicide had stopped growth in the developing ear at a very precise time, with older tissue escaping damage and younger tissue arrested instantly. Evidence for this includes the fact that timing of application was a critical factor: Plants sprayed before ears shoots had cleared the leaf sheath in some cases developed no ears at all, while those sprayed after silking had begun often showed no symptoms. Fields

sprayed by ground showed symptoms more often, probably because they had been sprayed earlier, before they reached full height, and also because they usually had more spray volume used—hence, better coverage.

Even though damage from fungicide application in 2007 was unexpected, we had seen some hints in earlier work that suggested that such damage might be possible. We saw very similar damage following pre-tassel fungicide application in several irrigated fields in northern Illinois in 2006. Also, in a year study of effects of Headline fungicide timing on corn, we found a significant yield loss in 2 out of 3 years when the fungicide was applied at the 14-leaf stage, or about a week before tasseling. This loss was about 8% to 10% and occurred only at that timing.

Even though the losses from fungicide application were unexpected and in some fields serious, I consider it likely that the growing and weather conditions were a critical factor in this damage in 2007. There were fields not sprayed with fungicide where similar damage occurred, suggesting that the 2007 crop was just vulnerable to disturbances in ear development. There were some reports of damage on seed corn in 2007, even though many seed fields get sprayed routinely, and such damage, if specific to the pre-tassel stage of application, would have become evident years ago. The fact that labels did not restrict application to tasseling or later suggests that companies who developed and who sell strobilurin fungicide had seen little such damage in the past.

While the loss in yield due to fungicide application in some fields in 2007 was unfortunate and costly, we should probably see such damage as more of a fluke than as something that we should expect to see often. It will be relatively simple to change labels to restrict application to tasseling or later, which should largely rule out such damage in the future. Because damage was more related to ear development than to tassel development, it might be appropriate to relate the beginning of application to ear stage rather than to tassel stage.

What Did Fungicide Deliver When There Wasn't Damage?

The majority of fields sprayed with foliar fungicide in 2007 did not experience damage. At the same time, as noted above, they also did not have much, if any, foliar disease at the time the decision was made to spray. Did the promise of greater yield from better “plant health” materialize, and did fungicide application in 2007 provide a good return on investment?

We conducted a series of fungicide studies in several locations in Illinois in 2007. In most cases, fungicides produced either no yield response or the response was not adequate to cover the cost of the material plus application (Table 1). We are here estimating material plus application (by air) to equal the value of 6 bushels of corn (at \$3.50 per bushel, \$21 per acre). Two of the trials included rotation as a variable,

TABLE 1 • Results from Headline fungicide trials on corn in Illinois, 2007.

Location	Trial also included	Previous crop	Grain yield (bu/A)			Did it pay?
			Without Headline	With 6 oz Headline	Increase from Headline	
DeKalb	N rate	Soybean	218	228	9*	Yes
Monmouth	N rate, rotation	Soybean	237	238	2	No
		Corn	203	206	3	No
Monmouth		Soybean	185	188	3*	No
Urbana	Fertilizer, population	Corn	194	207	13*	Yes
Urbana	N rate	Soybean	203	198	-4	No
Urbana	Planting date, population	Soybean	219	218	-1	No
Perry	Tillage, fertilizer, population	Corn	193	195	1	No
Perry	N rate, rotation	Soybean	133	135	3	No
		Corn	142	141	-1	No

*Indicated significant difference at the 10% error level (*P*).

and results are given for both corn following corn and corn following soybean in these trials.

In none of the trials reported in Table 1 were foliar diseases severe, except at DeKalb, where untreated plots had about 20% incidence. Fungicide reduced this by about two-thirds. In the Monmouth trial, where fungicide increased yield by 3 bushels following soybeans, foliar disease was decreased from about 8% to 2% by fungicide. Hence, fungicide was generally effective in reducing incidence of foliar disease where it occurred.

In eight of the ten trials, there was either no yield increase or, if one existed, it was inadequate to pay for the treatment. In the two trials where yield was increased enough to produce a

profit from fungicide application, one was corn following corn and one was corn following soybeans. On average, application of fungicide over these trials increased yield by 3 bushels per acre, only half enough to pay for the treatment.

These results show that, in a year when there was little foliar disease at the time of fungicide application and when conditions are such that diseases do not become a major factor, the use of foliar fungicide seldom returned its cost. Given that the purported physiological effect of strobilurin fungicide in plants is to reduce respiration and possibly to decrease yield-limiting hormone levels, it also seems likely that good conditions at pollination, which were the rule in Illinois in 2007, reduced the likelihood of a positive yield response unrelated to disease control.



Fungicides: Do They Adversely Affect Beneficial Insect Pathogens in Multiple Cropping Systems?

David W. Ragsdale and Karrie A. Koch

A wide variety of fungi are pathogenic to insects and mites—some 700 species have been described (Hajek and St. Leger 1994). Often, these entomopathogens are key regulators of arthropod populations, and they are particularly important in regulation of twospotted spider mites and aphids in a variety of crops. Most studies that focus on these pathogens also conclude that manipulation of entomopathogen populations is at best difficult. In part, this is because the environmental conditions that favor fungal germination must be met for an epizootic to occur. However, this does not mean that we should ignore the contribution of these insect pathogens in regulation of insect and mite populations. One of the underlying principles in IPM is to be aware of production practices that will conserve beneficial organisms.

It is a common misconception that fungal epizootics only occur when insect or mite populations are very high—at densities well above where plant injury will occur. These spectacular epizootics are easy to observe; this casual observation often leads to the mistaken conclusion that fungal pathogens arrive too late to be reliable control agents. While it is more difficult to observe the role fungal pathogens play in population regulation at lower insect and mite densities, they indeed are active at low host density. So, although we may not be able to stimulate an epizootic to occur, we should avoid farming practices that will disrupt these important, naturally occurring insect pathogens.

This article reviews cropping systems where this disruption has been documented, demonstrates the current research being conducted in Minnesota on the impact of fungicides on the entomopathogenic fungi found attacking soybean aphids, and provides a general understanding of why, in IPM, a pesticide should be used only when a specific pest

is being targeted—one of the fundamental principles of a sound integrated pest management (IPM) program.

Biology of Entomopathogenic Fungi

Insect pathology has a long history, dating back to 2700 B.C., when diseased silkworms were first described in China (Tanada and Kaya 1993). However, the systematic study of insect pathology was not begun until much later—after the germ theory of disease was proposed. The first textbook devoted to the subject of insect pathology wasn't published until 1949 (Steinhaus 1949). The first insect pathogen to be associated with a disease was a fungus associated with silkworms, and this pathogen that Agostino Bassi first worked with was later named *Beauveria bassiana* in his honor (Steinhaus 1956). We would suggest that anyone reading the proceedings of this conference has benefited from the work of early pioneers in insect pathology. The discovery of *Bacillus thuringiensis* and its role in control of corn rootworm and European corn borer has its roots in insect pathology.

Entomopathogenic fungi are found in all four recognized phyla of fungi (Figure 1): Basidiomycota (mushroom and rust), Ascomycota (cup or sac fungi), Zygomycota (zygospores formed from the fusion of two hyphae), and Chytridiomycota (microscopic fungi with motile zoospores) (Roberts and Yendol 1971; Alexopoulos et al. 1996). A large number of fungi representing some 15,000 species are currently in a group that no longer has any systematic standing, the deuteromycetes. This group of asexually reproducing fungi have in the past been called the "Fungi Imperfecti" or "asexual fungi." Molecular studies often reveal that these asexual fungi are the conidial or asexual stage of a species assigned to the Ascomycota or, in some cases, to the Basidiomycota. Some

of the better-known insect pathogens are known only from their asexual stage, including *B. bassiana*.

Many of these deuteromycetes can grow on simple artificial media, their spores are relatively stable, they are common inhabitants of soil, spore dispersal is generally by wind, infection occurs when a droplet of water containing viable spores lands on an insect's integument, and the rather thick-walled spores remain viable for long periods of time under adverse conditions.

In general, insect pathogenic fungi currently assigned to the deuteromycetes are less species specific than species found in the Zygomycota. Insect pathogens such as *B. bassiana* and *Lecanicillium lecanii* (formerly *Verticillium lecanii* (Zimm.)), *Paecilomyces fumosoroseus*, and *Metarhizium anisopliae* are commonly produced and marketed as bioinsecticides (Table 1). These bioinsecticides are not typically used in major row crops because the cost of producing these fungi is too high, as are the costs associated with registering products for use in the United States. However, these bioinsecticides do play a vital role in organic agriculture, greenhouse production systems (flower, fruit, and vegetables), and other high-value production systems where chemical residues are unwanted or not tolerated.

The Entomophthorales

The focus of this paper is on the naturally occurring insect pathogens in the order Entomophthorales (phylum Zygomycota, class Zygomycetes; see Figure 1). The order Entomophthorales comprises fungal species that are obligate

insect and mite pathogens—they are not known to propagate on other organic matter (i.e., they are not saprophytic but rather strictly pathogenic to arthropods). Entomophthorales are often unable to grow on simple media and either require highly enriched media or cannot be cultured at all. Many of these fungal species are involved in the population regulation of aphids and twospotted spider mites in major row crops (corn, soybean, cotton, wheat, sorghum, sunflower, potato).

A unique character of the Zygomycota is that these fungi produce a zygospore, which is a “thick-walled resting spore” (Alexopoulos et al. 1996) formed by the fusion of two specialized structures (gametangia) from two compatible strains into a zygospore. Although production of a zygospore is the defining characteristic of the members of the class Zygomycetes, some species in this class are not known to produce zygospores; thus, other relevant characters are used to place the species within the class (Alexopoulos et al. 1996).

The Entomophthorales are a unique order within the class Zygomycetes and produce conidia as their infective propagules instead of sporangiospores, which are produced by all other Zygomycetes (Alexopoulos et al. 1996). In general, species within the Entomophthorales produce fewer spores than their insect pathogenic counterparts in the deuteromycetes, such as *B. bassiana*. Spores of the Entomophthorales are forcibly ejected from the conidiophore, which is unique to the order Entomophthorales (Alexopoulos et al. 1996). Although spores can be found in the air, and wind-dispersed spores are key to developing an epizootic (Steinkraus et al. 1999), in general, spores of Entomophthorales are less important in dispersal than are infected alate aphids (Feng et al. 2004). In China, movement of insect pathogenic fungi over large distances (miles) is likely accomplished by infected winged aphids dispersing the pathogen rather than by passive dispersal of liberated spores (Feng et al. 2004).

Species identification within the Entomophthorales is accomplished by staining the primary conidia to visualize the number and placement of nuclei, along with the overall size and shape of the spore. Primary conidia often have special mucilaginous material that allows the spore to either adhere to nearby leaf surfaces or to attach to insect exoskeletons (Figure 2). Under favorable environmental conditions—typically high humidity and moderate temperatures—spores absorb water from the environment and germinate. It is during this germination phase

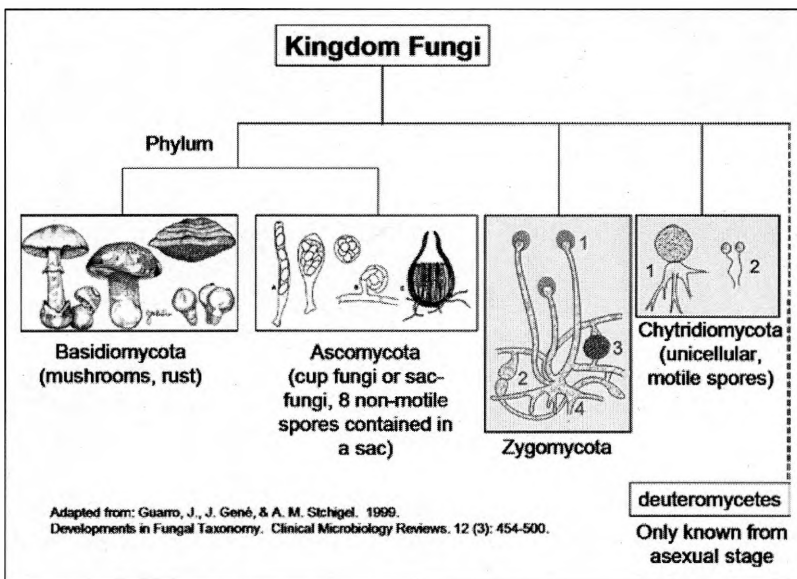


FIGURE 1 • Fungal systematics using the fungal tree of life phylogeny.

TABLE 1 • Bioinsecticides derived from live fungi (spore suspension). Data from U.S. EPA and NPIRS Web sites, October 2007.

Product name	Manufacturer	Fungal species and strain	Target insect/mite
Naturalis-L	Troy Biosciences	<i>Beauveria bassiana</i> ATCC74040	whiteflies, weevils, aphids, thrips, leaf-feeding caterpillars, Colorado potato beetles, mites, white grubs, chinch bugs, ants, and mole crickets
Mycotrol ES, Botanigard ES Botanigard 22WP Mycotrol O	Laverlam International Corp.	<i>Beauveria bassiana</i> GHA, ABG-6178	whiteflies, thrips, aphids, psyllids, mealybugs, scarab beetles, plant bugs, and weevils
BioVL*	Sundaram	<i>Verticillium lecanii</i>	Sucking insects
Vertisoft*	Agriland Biotech, Ltd.	<i>Verticillium lecanii</i>	Sucking insects
PFR-97 20% WDG	Certis U.S.A., LLC	<i>Paecilomyces fumosoroseus</i>	whiteflies, aphids, thrips, and spider mites

*Product not available for use in the United States.

that fungicides are most likely interfering with the infection process.

A different type of secondary conidia, a conidium borne on a long, thin stalk called a capilliconidium (Figure 3), can be formed by certain species of Entomophthorales (Alexopoulos et al. 1996). This type of secondary conidia has the ability to adhere to chitin and may be formed to increase the chance of contact with a susceptible host or with an individual that can transport the spore to a susceptible individual (Alexopoulos et al. 1996).

Most Entomophthorales overwinter in the soil profile via resting spores—thick-walled spores that typically must undergo a cold temperature treatment before they germinate. However, one of the most common aphid-infecting pathogens, *Pandora neoaphidis*, does not form resting spores and either overwinters as hyphal bodies or conidia within the cadaver of the aphid (Feng et al. 1992; Nielsen et al. 2003). Thus, the Entomophthorales are a unique and interesting group of fungi, yet much of their biology and ecology remains unexplored.

Once an insect pathogenic fungus kills its host, fungal growth switches from vegetative to reproductive, during which time rhizoids (structures that secure cadavers to a substrate), conidiophores, and conidia are formed externally on the insect cadaver (Alexopoulos et al. 1996). Once conidia are released from the conidiophores, if environmental conditions are suitable, they will germinate. If the spore lands on a susceptible host, a germ tube will form, penetrating the insect cuticle. A typical life cycle is illustrated in Figure 4.



FIGURE 2 • Scanning electron micrograph (SEM) image of a spore of *Conidiobolus obscurus* attached to the leg of a green peach aphid, *Myzus persicae*. Photo by A. Lagnaoui.

If a suitable host is not available, fungi may continue to produce smaller secondary conidia, and even smaller tertiary conidia may be formed and so on until all energy is depleted (Alexopoulos et al. 1996). Once the germ tube penetrates into the insect hemocoel, yeastlike hyphal bodies are produced and, in the process of vegetative growth inside their insect host, nutrients are absorbed, toxins are produced, and death of the host occurs quickly—typically in a matter of a few days (Tanada and Kaya 1993). Conidia are then again formed, and the process of sporulating spreads the disease. An epizootic can proceed rapidly when insects are at high

density, and a remarkably rapid decline in insect or mite density can be observed.

In general, host specificity is greater with the Entomophthorales, and some isolates of the same species will not easily infect other closely related insect species. *Pandora neoaphidis* is frequently isolated from a variety of aphids, but strains of these pathogens exist, and not all strains or isolates can infect all aphid species. For example, an isolate of *P. neoaphidis* we isolated from pea aphid, *Acyrtosiphon pisum* (Harris), was not able to infect soybean aphid, *Aphis glycines*, under controlled laboratory conditions (Koch, unpublished data).



FIGURE 3 • *Capilliconidium* of *Zoophthora radicans* from soybean aphid, *Aphis glycines*. Magnified 400 \times , stained with aceto-orcein. Photo by D. Ragsdale.

Interference of Fungicide with Entomopathogenic Fungi

It should be no surprise that fungicides applied to plant surfaces to control foliar pathogens might interfere with the infection process of entomopathogens. Indeed, it is well documented in a variety of cropping systems that foliar-applied fungicides are detrimental to the progression of an epizootic, and, at times, insect populations will increase in response to the suppression of entomopathogens (Byrde 1966; Cadatal and Gabriel 1970; Bailiss et al. 1978; Vänninen and Hokkanen 1988; Elkassabany et al. 1992; Smith and Hardee 1993; Majchrowicz and Poprawski 1993; Lagnaoui 1990, Ruano-Rossil et al. 2002).

Other crops where aphid species are commonly regulated by pathogenic fungi include cotton and cotton aphid, *Aphis gossypii* (Steinkraus et al. 1993, 1994, 1995); fava (field) bean and the black bean aphid, *Aphis fabae* Scopoli (Berthelem et al. 1969; Dedryver 1976, 1978; Wilding et al. 1978, 1979; Wilding and Perry 1980); sugar beet and the black bean aphid (Gustafsson 1969); small grains and the complex of grain aphids (Dean and Wilding 1971, 1973; Latteur 1973; Papierok et al. 1984; Latteur and Jansen 2002); and potato and the green peach, *Myzus persicae*, and potato aphid, *Macrosiphum euphorbiae* (Lagnaoui 1990; Ruano-Rossil et al. 2002).

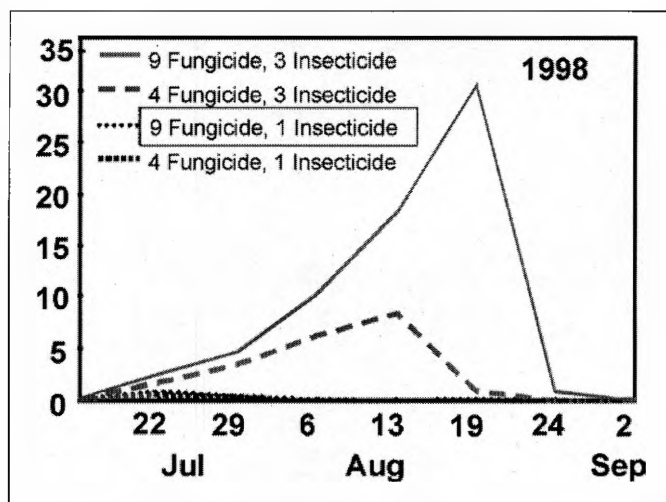


FIGURE 4 • The response of green peach aphid populations on a per-leaf basis when plots were treated with two fungicide regimes (nine vs. four applications) and two insecticide regimes (one vs. three applications). Insecticides used (esfenvalerates) are for control of insects other than green peach aphid, which is resistant to this pyrethroid.

In soybeans it has been documented that multiple fungal species infect soybean aphid (Steinkraus et al. 2002; Nielsen and Hajek 2005). Our research focuses on the extent to which fungicides used to control soybean rust might interfere with these beneficial fungal pathogens of soybean aphid, *Aphis glycines*.

There is a substantial body of literature reporting that pesticides do indeed adversely affect prevalence of entomopathogenic fungi (Byrde 1966; Cadatal and Gabriel 1970; Bailiss et al. 1978; Wilding et al. 1978, 1979; Vänninen and Hokkanen 1988; Lagnaoui 1990; Elkassabany et al. 1992; Majchrowicz and Poprawski 1993; Smith and Hardee 1993). Field studies are often supported by numerous laboratory studies showing that most fungicides, some insecticides, and some herbicides inhibit germination of conidia and growth of mycelia of entomopathogenic fungi (Hall and Dunn 1959; Yendol 1968; Soper et al. 1974; Fritz 1976, 1977; DeLorme and Fritz 1978; Öncüer and Latteur 1979; Wilding and Brobyn 1980; Vänninen and Hokkanen 1988; Lagnaoui 1990; Latteur and Jansen 2002).

We present selected field studies where entomopathogens play a key role in regulating aphid populations and documentation where fungicides adversely affected entomopathogenic fungi.

Case Studies

ALFALFA

The important role that fungal pathogens play in regulation of pea aphid populations in alfalfa in Wisconsin was described in great detail by Hutchison and Hogg (1985). They showed through life table studies that accounting for the proportion of *P. neophidis*-infected individuals was necessary before their stochastic models would accurately describe aphid population dynamics.

The effect of fungal pathogens was as important as measuring the proportion of the population that was emigrating, and it was far more important than mortality associated with predators or parasitoids. Fungicides are rarely, if ever, used in alfalfa production; thus, the alfalfa agroecosystem is ideal for the study of role entomopathogens play in regulating aphid populations. Plus, the dense canopy allows for microclimates to exist that favor fungal epizootics.

POTATO

In Minnesota, Nanne and Radcliffe (1971), Lagnaoui (1990), and later Ruano-Rossil et al. (2002) showed that fungicides commonly used in potato production caused a population response (resurgence or flaring) of green peach aphids. Entomopathogens were severely suppressed, and some species of fungi were essentially eliminated when any fungicide was applied (Figure 5).

One caveat, however, is often overlooked in these field experiments. All fungicide treatments were actually made in combination with various insecticides. The insecticides were used to control other insect pests, such as Colorado potato beetle and potato leafhopper, that, if left untreated, would cause severe leaf damage (hopperburn) or result in complete defoliation. The insecticides used were not toxic to green peach or potato aphids. What was not documented was the impact these insecticides might have on predators and parasitoids associated with the potato-colonizing aphids. Nevertheless, plots treated with a combination of fungicide and insecticide resulted in green peach aphid populations that were from 1.7 to 10.0 times greater than the insecticide-only treated control. And fungal-infected aphids were more common (22.4% to 77.5%) in plots treated with insecticide alone, while aphids in plots treated with fungicides plus insecticide had significantly lower disease prevalence (4.0% to 5.2%).

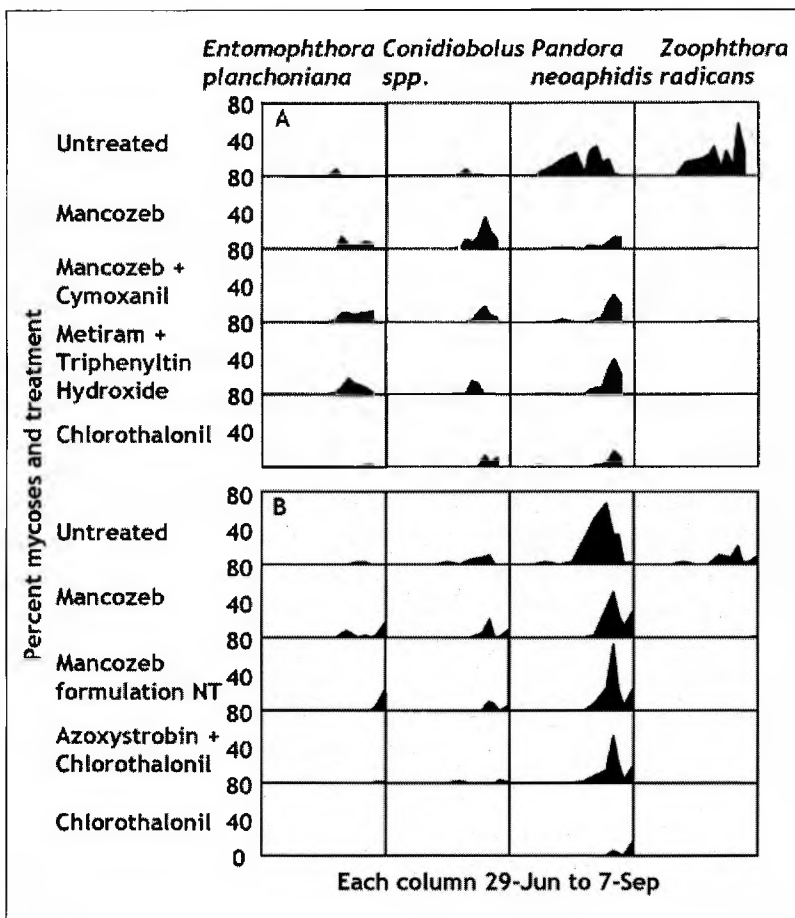


FIGURE 5 • Prevalence of mycoses by causal species in *Myzus persicae* in response to fungicide treatment regimes: percentage prevalence for Rosemount 1998 (A) and 1999 (B). *Conidiobolus* spp. = *obscurus*, *coronatus* (Costantin) Batko, and *thromboides* Drescher.

It is unrealistic to expect commercial potato production to occur without the use of fungicides. This became even more apparent in 1993, when a fungicide-resistant strain of *Phytophthora infestans*, the fungus that causes late blight in potato, became established in the United States, which resulted in potato producers using an even more intensive fungicide application program.

Ruano-Rossil et al. (2002) showed that, in general, using two different fungicides, either tank-mixed or applied sequentially, was more detrimental to the entomopathogen complex. Additional work (Ragsdale, unpublished data) confirmed that it was actually the combination of insecticide and fungicide that caused aphid populations to flare in potato production. The use of fungicides alone, even in an intensive program necessary to combat methylaxyl-resistant *P. infestans*, did not cause aphid populations to flare (see Figure 4).

COTTON

In the mid-South Cotton Belt, the cotton aphid, *Aphis gossypii*, can be a serious pest of cotton. However, the aphid is routinely infected with the fungus *Neozygites fresenii*, one species of entomopathogenic fungus that performs well in the high temperature and high relative humidity found in the mid-South. Research has shown that when more than 15% of the aphid population is infected with this fungus, their population will likely decline. When infection exceeds 30%, progression of the epizootic is almost ensured.

By knowing what proportion a sample of cotton aphids is infected with *N. fresenii*, cotton growers can refrain from making one or more insecticide applications for aphid control. To diagnose whether a sample of cotton aphids is indeed infected requires that aphids be sent to a specialized lab for microscopic analysis. A report is provided to the grower or the crop professional, usually within 24 hours. This “Cotton Aphid Fungus Sampling Service” (Steinkraus 2007) report indicates the level of infection observed and recommends measures to control aphids in that field. This is an example of how knowing the disease prevalence can directly affect the application of insecticides.

The fungicide chlorothalonil was shown to have higher aphid densities, and the epizootic was delayed about 1 week in fungicide-treated plots (Wells et al. 2000); therefore, in the cropping system in this case study, a single application of fungicide interfered with the progression of the epizootic.

SOYBEANS

Field experiments performed from 2005–2007 in Minnesota showed that the most common soybean aphid pathogen was *Pandora neoaphidis*. Other fungal pathogens isolated

included *Conidiobolus thromboides* and *Zoophthora radicans*. In 2005 and 2006 in Lamberton, Minnesota, various fungicide regimes were applied to small soybean plots (Table 2). In 2005, soybean aphid disease prevalence peaked on August 30. Laboratory results found that 31% of apparently healthy aphids in control plots were infected with *P. neoaphidis*. On the same day, prevalence of diseased aphids among fungicide-treated plots was only 3.5% (Figure 6). A similar trend was observed in 2006, but environmental conditions were unfavorable for disease development (hot and dry), and peak prevalence occurred much later in the growing season (September 6), at 4% in the untreated control. Peak prevalence was 2.5% in fungicide-treated plots, which was delayed until September 11. These results confirm that soybean rust fungicides are detrimental to the entomopathogenic fungi that infect soybean aphids under field conditions.

In 2007, we conducted field experiments at our irrigation research center at Becker, Minnesota. We caged single soybean plants, introduced healthy aphids to these cages, and allowed aphid densities to increase in the absence of predation. When aphids were greater than 150 per plant for R2 soybeans and 750 per plant for R5 soybeans, we sprayed plants with water alone (control), a strobilurin fungicide (Headline), or a strobilurin-triazole mix (Headline SBR) of fungicides. Mini-epizootics were created by releasing *Pandora neoaphidis*-infected soybean aphids into the cages. Following the release of *P. neoaphidis*-infected aphids, newly infected aphids were recovered in 50% of the strobilurin-treated plots and 33% of plots treated with a strobilurin-triazole mix, compared to 100% in the control plots (water only) (Figure 7A). This implies that when fungicides are applied prior to the initiation of fungal disease in an aphid population, disease transmission can be significantly reduced.

TABLE 2 • Fungicide treatments applied to small plots in Lamberton, Minnesota, in 2005. All applications were made at the recommended labeled rate.

Treatment	Active ingredients	Product name	Application timing
1	Pyraclostrobin + Tebuconazole Pyraclostrobin + Tebuconazole	Headline SBR Headline SBR	Growth stage R2 14 DAT*
2	Pyraclostrobin + Tebuconazole Pyraclostrobin + Tebuconazole Chlorothalonil	Headline SBR* Headline SBR* Bravo Weatherstik*	Growth stage R2 14 DAT* 28 DAT*
3	Azoxystrobin + Propiconazole Azoxystrobin + Propiconazole	Quilt* Quilt*	Growth stage R2 14 DAT*
4	Trifloxystrobin + Propiconazole	Stratego*	Growth stage R5

*DAT: Days after application of first treatment.

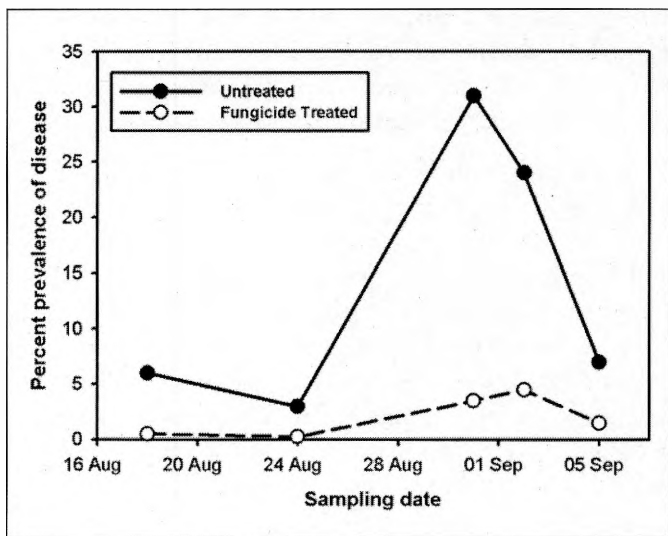


FIGURE 6 • Percentage prevalence of disease in soybean aphid in untreated (solid line) and fungicide-treated (dashed line) plots in Lamberton, Minnesota, in 2005. Fungicide treatment lowered the prevalence of disease up to 89% when compared to the untreated control. All fungicides tested were detrimental to entomopathogens; thus, data were combined for clarity.

When the same fungicides were applied approximately 2 weeks after the release of *P. neoaphidis*-infected soybean aphids, recovery of newly infected soybean aphids was again reduced to 83% and 58% for the strobilurin and strobilurin-triazole mix, respectively (Figure 7B). Thus, the inhibition of disease transmission may extend beyond the first several days following application. Because disease epizootics are believed to be initiated by the immigration of infected aphids, this reduction in establishment has the potential to limit or prevent the establishment of disease in the population, especially when abiotic conditions are less than ideal.

During the same experiment, mini-epizootics were initiated and monitored in the single-plant cages twice during the 2007 growing season, when soybeans were in stage R2 and again in R5. Environmental conditions were poor for disease transmission at the R2 plant stage of the experiment; however, overhead irrigation provided adequate moisture that resulted in moderate disease levels. At the disease peak, which occurred 7 days after the release of infected aphids, the mean percentage prevalence of diseased aphids in the plots treated with fungicides was reduced to 21% and 17% of the water-treated control for the strobilurin and strobilurin-triazole mix, respectively.

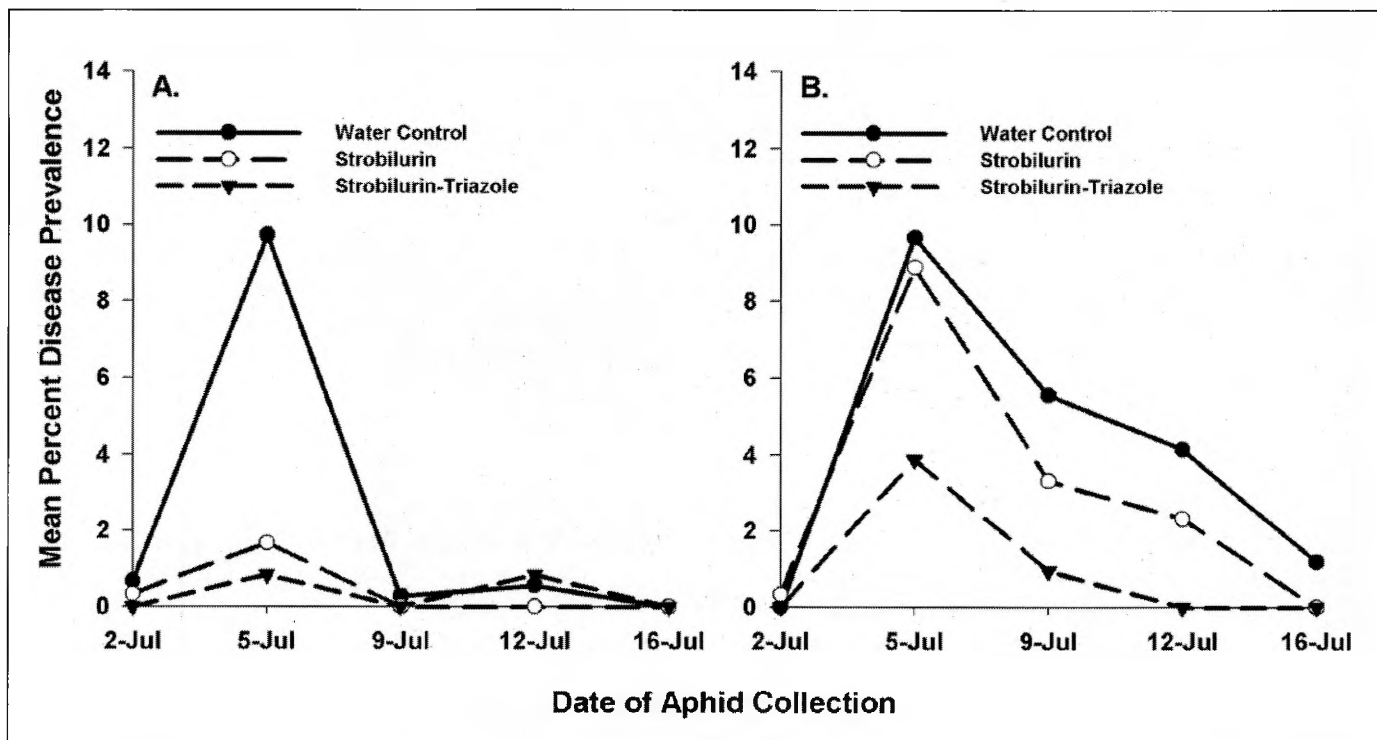


FIGURE 7 • Percentage prevalence of *Pandora neoaphidis* infection in soybean aphid when fungicide is applied prior to placing diseased aphid inoculum (A) or applying fungicide after inoculum is present (B) in Becker, Minnesota, 2007.

Environmental conditions changed drastically when the experiment was conducted during R₅, which included frequent rainfall, heavy dews, and cooler temperatures. This combination of conditions allowed the fungus to overcome the negative effects of fungicide applications, leading to comparable disease levels among all the treatments. During this time period, newly infected soybean aphids were recovered even from cages in which no inoculum was released. Thus, it appears that the detrimental effects of fungicides can be overcome by *P. neoaphidis* if environmental conditions are favorable for an epizootic to occur. However, it should be noted that the August of 2007 was the wettest August in Minnesota history, so these ideal conditions are unlikely to occur frequently.

In summary, soybean rust fungicides have the potential to diminish the prevalence of fungal disease in field populations of soybean aphid. The negative effects of the fungicides seem to be mitigated by environmental conditions in that warm, dry conditions will prohibit epizootics regardless of the presence of fungicides, and, in overwhelmingly beneficial conditions, the fungi can overcome the detrimental effects of the fungicides. Disease establishment within a population seems to be most strongly decreased when fungicides are applied immediately before inoculum introduction.

The results of these studies will become important as the use of these fungicides increases across the landscape. The highest disease levels have been reported from soybean aphids on their overwintering host, common buckthorn (Nielsen and Hajek 2005), implying that these fungi may play their most important role in aphid regulation during the fall, when the aphids are no longer on soybean. The next step in this research is determining if the negative effects of soybean fungicides can continue to act on these beneficial fungi as they move with the aphids to buckthorn.

Conclusion

Fungicides clearly can adversely affect the infection cycle of entomopathogenic fungi that are key regulators of key pests of aphids and spider mites in multiple cropping systems. Although environmental conditions are often less than ideal for an epizootic to occur in many cropping systems, infected aphids can nevertheless be isolated under environmental conditions that are not conducive for widespread epizootics.

There is a growing body of literature that has documented detrimental effects associated with fungicide use and reduced prevalence of infected insects. Many tested fungicides have been shown to have a broad spectrum of activity. More recently, a new class of fungicides, the strobilurins, are being used with greater frequency in crop production. The stro-

bilurins have just a single site of activity; as a consequence, these fungicides are often not used by themselves. A partner fungicide that has a different mode of action is recommended or required as part of a resistance management program.

In general, when more than one active ingredient was used, suppression of entomopathogenic fungi was significantly increased. It is not a foregone conclusion that fungicide use will cause an increase in aphid or spider mite populations. However, there are no studies showing that fungicides enhance these beneficial fungi. The safe assumption, when there is lack of information, would be that suppression is likely and, as a general rule, employing any crop protection chemical should be undertaken only when there is a target pest that will result in crop loss in excess of the cost of control.

Application of fungicides for mere “plant health effects” is not sound pest management and could result in disruption of a suite of natural enemies that provides economic control of aphids or spider mites.

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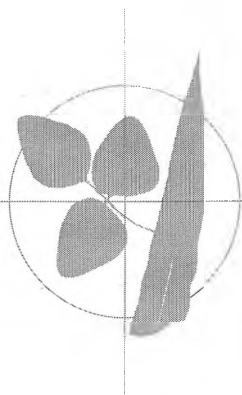
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How to Lose Money Despite High Crop Prices, or Misuses, Misapplications, and Mistakes with Insect Thresholds

Leon G. Higley



In the Catskills of New York (Delaware County, to be specific), where my parents grew up on dairy farms, a common perspective was that the only way to make money in farming was to sell the farm. Most of my relatives were eventually forced to follow this advice or take second jobs.

As a kid, I quickly gained the perspective that dairy farming had to be one of the worst ways to try to make a living: There is a constant smell of cow manure; you are tied to the ceaseless milking schedule twice a day; you have to worry about why this or that cow isn't milking; the barn is full of (1) hay (I'm allergic), (2) cows trying to kick or step on you, (3) flies (or fly strips that stick to your hair if you aren't careful), and (4) manure splashing all over; the milk price is never high enough; and did I mention that all the manure has to be shoveled out? Additionally, the alfalfa and silage corn was planted on slopes a Midwesterner would consider a mountainside, and in fields so full of rocks a sane person would be tempted to open a quarry.

Of course, when we visited, I loved getting up early with my Dad to help with milking or to drive the tractor during haying, but even as a child I could see that Dad and Mom's leaving the farm gave us a chance for a much better life.

When I came to Iowa for graduate school and got to plant my soybean plots in some of the flattest, richest soil I'd ever seen, I initially thought that growing field crops was the way to go. The corn yields were like nothing my Dad had ever imagined! In time, however, I learned that it was just as easy to go broke planting corn and beans as it is to go broke milking 40 cows. In fact, one of the most ironic aspects of American agriculture is that what should be good news, such as record yields, often leads to even greater financial problems, because of low prices.

As I've done agricultural research through my career, I've told myself and my students that, because we work on pest management, we are helping protect the environment and helping protect farmers. I guess I still believe that, but I also know that much or most of what we develop isn't used, and problems I saw 30 years ago still exist today. Sometimes research developments aren't practical, broadly applicable, or of much financial impact, so they are never implemented. Sometimes research developments are practical, broadly applicable, and financially beneficial, and they still aren't implemented. This is another irony of agriculture I still don't understand.

All of which finally brings me to the point of this essay. I am supposed to talk about how high crop prices will impact insect thresholds and related pest management decision making. But rather than offer a conventional (read boring) discussion of insect thresholds, I thought I should instead offer a more realistic perspective. As far as I can tell, farming is mostly about losing money, so the real question should be, How can you lose money when crop prices are at record levels? From an insect management perspective, I can show you that losing money isn't hard.

Historically, the most common way to lose money (or your life from starvation) is through acts of God. I think drought stands out among these events, but we shouldn't forget flooding, wind, hail, disease, and (my favorite) insect plagues. The common theme here is that the crop itself is either destroyed or rendered unusable.

To make matters worse, dependence on a single crop presents lots of opportunities for disaster (remember, if you are an American of Irish ancestry, you are almost certainly here because of the Irish potato famine—dependence on a single crop that led to massive death and emigration when

the potatoes rotted from disease). Lack of genetic diversity can also lead to disaster, as evidenced by the loss of all seed corn in 1970 from southern corn leaf blight. (By the way, how much genetic diversity exists in corn and soybean germplasm nowadays?)

More modern approaches to financial ruin in agriculture involve debt. Specifically, debt for equipment (I started to write “extremely expensive equipment” until I realized the “extremely expensive” part is redundant); debt for land (which typically loses value after you buy it); and, if you are really strapped, even debt for pesticides, fertilizer, and seed.

It would be easy to condemn farmers who assume high debt loads were it not for the observation that achieving large economies of scale (becoming more efficient by having larger farms) is essential to having any chance of economic survival (at least in grain crop production). When prices are high, the seeds of future foreclosures often are sown. Why? Because of a mistaken belief that the high yields or high land values or high crop prices will remain at current levels indefinitely. As casino owners know, no matter how good the winning streak, the odds always favor the house. In agriculture, the odds rarely favor farmers for long. So, Leon’s first recommendation for how to lose money despite high crop prices: Take out new loans for equipment and land.

As we look at insect pests, there are three basic ways to lose money: fail to act, act too late, or act unnecessarily. Actually, we might include a fourth category, because sometimes, by acting unnecessarily, it is possible to create an insect problem where none would otherwise have existed. Let’s look at each of these in more detail, but first let’s consider the insects themselves.

Back in the 1930s a guy named Pierce published a paper (Pierce 1934) in which he asked a question I imagine many people had asked before him: How many insects do I need to have in a field before I do something about them? It took about 40 years before anyone came up with a good answer to this question, and, for lots of insects in lots of crops, the jury is still out. Unless you are growing flowers or Christmas trees or other horticultural crops for which people pay based on how the crop looks, the importance of insects is in how they reduce yield.

The simple answer to Pierce’s question is that you must prevent more in losses than you spend in managing the insects. Benefits must exceed costs. Entomologists developed guidelines called economic injury levels and economic thresholds to put numbers to this cost–benefit stuff, and, ultimately, scouting and sampling for insects rest on these injury levels and thresholds. Because costs and market values change over time, so should the thresholds.

How do high crop values change the situation? Scientists, like me, live for creating complex models and for requiring years of experiments to answer questions like this. However, it turns out that the crop value question is absurdly easy. The relationship between crop value and damaging insect numbers is a simple inverse. Higher crop value; fewer insects to cause injury.

To offer a specific example, if ten bean leaf beetles per row-foot of soybeans are considered damaging when beans sell for \$3 a bushel (ouch), only five beetles are required to cause damage when beans sell for \$6 a bushel. [This is just the inverse relationship: Here, crop value doubles ($\$6/\$3 = 2$), so the number of insects required is proportionally decreased ($10 \text{ beetles}/2 = 5 \text{ beetles}$)]. Another way to look at this is it to remember that an increase in crop prices essentially changes 98-pound-weakling insects into Charles Atlas–muscled insects: It takes few insects to cause big economic losses. Now, on to losing our shirts ...

Failing to act is a common strategy for incurring economic losses from insects. Don’t scout, don’t monitor, and, if you do happen to notice any insects or symptoms in the field, don’t do anything about it. This is a very common way to lose money with lower-value crops, such as alfalfa, which growers tend not to manage intensely. It is also a common strategy with crops that don’t have a history of damaging insect pests.

Soybeans are a good Midwestern example. Most insect pests of soybeans are occasional, but with the introduction of the soybean aphid, potentially damaging insect populations can occur every year. So, maintaining a tradition of not scouting soybeans will almost certainly provide opportunities for large yield losses. With the addition of high soybean prices, low levels of insects that may not have been worth managing in the past may now cause significant economic loss. Leon’s second recommendation for how to lose money despite high crop prices: Don’t scout your crops and don’t adjust your thresholds for new crop prices (= great economic sensitivity to pests).

Acting too late is another great approach for losing money. In the trade, we call this revenge killing. While payback makes a great literary theme (Faulkner’s *The Unvanquished* comes to mind) or concept for film (Quentin Tarantino’s *Kill Bill* movies), revenge doesn’t deter future pest attacks (insects have tiny, little brains and aren’t much for memory). Five paragraphs back I said that “you must prevent more in losses than you spend in managing the insects.” Regarding acting too late, the key word from this quotation is “prevent.” If the insects have already caused a yield reduction, you don’t get the yield back by killing them.

All of these calculated insect thresholds are based on the notion that you take action before the insects do their worst. With caterpillars, most of the feeding occurs during the last stage or stages, so taking action before caterpillars are large will prevent most injury. With adults, feeding tends to occur equally over time, so most injury is prevented by acting as soon as adults show up. In contrast, if you wait to take action until most of the insect feeding has already occurred, you not only lose money through yield loss, but you also lose money on unnecessary pesticide use. Leon's third recommendation for how to lose money despite high crop prices: Act too late, after insects have already damaged the crop. Notice that you can actually lose more money with this recommendation than with the second!

Leon's fourth recommendation for how to lose money despite high crop prices has the potential to cost you the most money yet: Take unnecessary action against pests. Ironically, this recommendation has the appearance of saving money, so it is especially well suited to situations with high crop prices. Over the long term, unnecessary use of any management tactic, such as insecticides, increases the likelihood of resistance developing—and resistance can be hugely expensive. But this is a long-term cost, and here I'd like to focus on more immediate ways to lose the farm.

Acting without need is probably the most common of all ways to lose money from insect management. For example, years of research have shown that most corn rootworm insecticides were unnecessary, but when growers couldn't or wouldn't rotate, then the difficulty in predicting potentially damaging field populations required insecticide use as cheap (?) insurance. Treating early-season bean leaf beetles in soybeans (which are almost never damaging) as a mechanism to reduce late-season bean leaf beetles (which are often damaging) is increasingly common, and research shows definitively that this method doesn't work. So, you lose money from the treatment and from later yield loss or from the treatment, the later yield loss, and a revenge killing (the economic losses triple play!).

An important component of the unnecessary actions is the use of seed treatments, systemic insecticides, and tank mixes. In all of these instances, action is being taken in advance of actual knowledge of the pest's existence. Sometimes, the pest is so common that taking early action is a no-brainer (for instance, we know we'll always have weeds), but, in most cases, these early treatments are marketed as less expensive

forms of insurance. As far as I can tell, the only real forms of pest insurance are regular scouting or real insurance from an insurance agent (assuming you can find a policy against pests). High crop prices make marketing of "insurance" treatments sound like a prudent course of action, and yet these treatments offer another good opportunity to lose money.

So far, our examination of acting without need has focused on losing money from an unnecessary management action, but the real losses come from creating problems where none would otherwise exist. Now we are entering the major leagues for money loss from poor pest management.

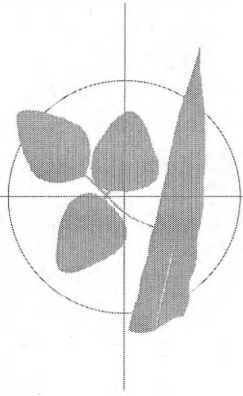
The situation goes like this: First, we take action against a pest when we don't need to, typically before the pest would occur; second, the pest we took action against suddenly appears in high numbers; third, we can choose any of our previous options for losing money by ignoring the pest (big yield loss), treating the pest (losses from an unnecessary and a necessary management action), or acting too late (big yield loss and economic losses from the initial unnecessary action and the revenge killing). Whatever choice we make, we are left with major economic losses that are entirely of our own doing.

The most common current opportunity for this economic train wreck comes with soybean aphid management. Soybean aphid numbers are held in check by natural enemies, and, if we are lucky, these natural enemies can be sufficient to prevent aphids from reaching economic levels. However, many producers have taken to early- or mid-season treatments to kill bean leaf beetles, soybean aphids, and "whatever else" is in the field. The "whatever else" category typically includes natural enemies of soybean aphids; the unnecessary use of insecticide kills the natural enemies, which, in turn, produces an aphid outbreak. The same phenomenon is possible with certain insecticides and spider mites in corn.

Although I've focused on how to lose money, there is always the chance that you'd like to avoid losses. In that case, I also have some advice: Avoid the problems I've outlined here by scouting, using thresholds adjusted for higher crop prices, and taking action against pests only when necessary.

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Tillage and Fertility Placement Aspects of Root Zone Optimization for Corn

Tony J. Vyn

Management decisions about root zone optimization should not be limited to corn hybrid selection, because even triple-stacked hybrids with corn rootworm resistance will not produce satisfactory yields if soil structure or chemical properties limit corn growth or nutrient uptake. Growing high-yield corn is possible without intensive tillage systems—numerous studies have shown no-till yielding equal to chisel or moldboard plowing for corn following soybean.

Although maintaining soil-test P and K concentrations well above critical levels is important to achieving optimal corn yields, strip-till corn has not yielded consistently higher when P and K fertilizers were deep banded versus broadcast applied. The relative yield benefits associated with broadcast versus deep-banded application of these nutrients seem to be related to soil moisture availability in the zones of nutrient placement during growing periods, when plants take up the majority of their P and K requirements.

Corn roots and plant populations suffer when corn rows are positioned too close to anhydrous ammonia or urea ammonium nitrate (UAN) N sources incorporated to shallow depths. Precision guidance is very beneficial for optimal corn row positioning at least 5 inches removed from the N fertilizer zone following spring pre-plant N application at high rates.

The primary way to improve stress tolerance (e.g., tolerance to drought, high plant density, or delayed nutrient availability) in corn plants of a given hybrid is to achieve optimal root zones for unimpeded growth in a given soil and climate situation.

Tillage Aspects

The long-term yield potential of corn with different tillage systems on dark, prairie soils of the Corn Belt has been studied intensively for both the typical corn–soybean rotation as well as for continuous corn. One such study has been ongoing near West Lafayette, Indiana, since 1975 (Table 1). Although equipment, cultivars, and seeding rates were changed periodically, tillage treatments have not been altered during the 32 years of this continuing experiment. The results in Table 1 suggest the following:

- ✦ Corn yields are greater in rotation than in continuous cropping for all tillage systems. The positive response to rotation is greatest for no-till corn (18% higher than for the same tillage system when corn follows corn). The positive response to rotation is least with moldboard plowed corn (just 4% higher).
- ✦ When corn follows soybeans, yields with plow and chisel are likely to be about the same. Yields from the ridge system may be slightly better (3%) than plow and chisel, but not as good as one would think, given the complete avoidance of traffic on the ridges (rooting zones) over this long-term study. No-till corn yields may be slightly reduced (2%) compared to plow and chisel, but the relative yields of no-till are much lower (14% yield reduction) compared to moldboard plowing when corn is grown continuously. Yield reductions with no-till corn are not due to lower plant populations but to inherently higher plant-to-plant variability (Boomsma and Vyn 2007a). Avoiding soil compaction in no-till corn might be one way for root growth not to be constrained by high soil density.

TABLE 1 • Corn yield response to tillage and rotation. Long-term tillage study on a dark, prairie silty clay loam soil near West Lafayette, Indiana, 1975–2006.

Tillage	Corn/soybean		Continuous corn		Yield gain for rotation %
	Bu/A	% of plow yield	Bu/A	% of plow yield	
Plow	179.7	—	172.3	—	4
Chisel	180.0	100	167.7	97	7
Ridge*	184.3	103	169.1	98	9
No-till	175.2	97	148.3	86	18

*Since 1980.

Root zone optimization is inherently more difficult to achieve in fields where corn follows corn. However, strip tillage systems can result in corn yields equal to those after chisel plowing, even in continuous corn systems (Vyn 2006).

One aspect of the influence of tillage systems on root zones is the changes in organic-matter concentrations at various depths. We recently have observed that, although continuous no-till for 28 years improved soil organic matter near the surface, organic matter in moldboard plowed systems is actually enhanced relative to no-till in the zone from 12 to 20 inches below the soil surface (Gál et al. 2007). We understand from previous research at Purdue University that rooting systems tend to be shallower in no-till than in conventional tillage, but the extent of root proliferation in no-till and strip tillage systems with modern hybrids has not been sufficiently evaluated.

Fertility Placement Aspects

Continued improvements in fertilizer management practices for corn are warranted because of the linear increase in corn yields since 1950, rapid adoption of less soil-inverting tillage systems since 1990, and a relatively high percentage of low- to medium-testing P or K soils in the eastern Corn Belt states. Broadcast application of non-nitrogen fertilizers remains the most common method throughout the Corn Belt states, but this practice could conceivably increase vertical stratification of less-mobile nutrients such as P and K when used in conjunction with reduced tillage.

Strip tillage represents a promising tillage system aimed at improving the seedbed environment for early corn growth compared to no-till systems. This new management practice, plus the simultaneous deep banding of P and K, could also build soil-test levels in the intended corn row area to potentially improve fertilizer use efficiency by reducing nutrient adsorption and possibly by maximizing plant nutrient uptake. We provided some guidelines for situations where

deep banding of P and K might be an advantage in a recent paper (Boomsma et al. 2007).

A 7-year study (2001–2007) was established to address the feasibility of combining strip tillage and deep banding of P and K fertilizers. Five fertility placement alternatives [control, broadcast P+K, banded P+K (6–8 inches), banded K alone (6–8 inches), and banded P alone (6–8 inches)] were spring applied (2001, 2002, and 2003) or fall applied (2004, 2005, and 2006) simultaneously with the strip tillage operation. Two hybrids were evaluated each year from 2001 to 2006, and an application of N-P-K-Zn starter fertilizer (based on 9-18-9) was included at planting, with the exception of 2006–2007, when the starter fertilizer (10-34-0) did not include K. The P_2O_5 rate was 88 pounds per acre, and the K_2O rate was 115 pounds per acre; these high amounts were intended to replace the nutrients removed by both corn and soybean in high-yielding situations over the 2-year rotation.

The study was located in two different fields, which were characterized based on their soil-test P concentrations for the standard sampling depth (0–8 inches) in Indiana as very high (>70 ppm) in the site on the even-numbered years but intermediate (10–30 ppm) for the sites in the odd-numbered years. For that reason, we chose to present and analyze the results separately into these two groups.

In most cases, yields for deep-banding and broadcast treatments were not significantly different from each other (Tables 2a and b). Deep-banded P plus K yielded significantly more than broadcast P plus K in only 1 out of 6 years (2004), and these treatments were equally likely to yield significantly more than the check treatment (both yielded more than the check in 3 of 6 years). A significant interaction between hybrids and fertilizer placement was never observed.

The small yield benefit noted from deep banding in 2004 was associated with a year with abundant rain and ample soil moisture availability for root growth and uptake in the zone of nutrient placement during critical growth periods. So, one

TABLES 2A AND 2B • Effects of deep banding and broadcast fertilizer treatments on strip-till corn yields near West Lafayette, Indiana, 2001–2006.

Treatment	YEAR				
	2001	2003			2005
	Yield (bu/ac)				
Broadcast P+K	220	242	a	213	a
Banded P+K	216	236	a	203	ab
Banded K	210	221	b	204	a
Banded P	224	239	a	190	bc
Check	211	221	b	184	c

Hybrid	Yield (bu/ac)				
	2001	2003	2003	2005	2005
Pi 34M95	220	Pi 31N28	223	Pi 31N28	207
Pi 34B24	212	Pi 34M95	240	Pi 31G68	191

Means with different letters are significantly different ($P < 0.05$)

Treatment	YEAR				
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Broadcast P+K	220	242	a	213	a
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Means with different letters are significantly different ($P < 0.05$)

factor in the relative benefit of deep banding may very well be moisture availability for root growth and nutrient uptake in zones of higher nutrient concentrations. Iowa research by Antonio Mallarino has demonstrated fairly conclusively that deep banding of K was most likely to improve corn yields when the month of June was dry. However, if small rainfall events (such as 0.5 inch or less) occur during an otherwise drier than normal month, the broadcast fertilizer may be more available simply because of enhanced moisture availability in the near-surface soil layers.

More recently, we have changed the experiment to test the benefit of deep banding when starter fertilizers are or are not present. The results from 2007 (Figure 1) indicate that corn yields from the broadcast-applied and deep-banded P and K plots were not changed by the presence or absence of starter fertilizer (20 gallons per acre of 10-34-0 in a 2- by 2-inch band). However, starter fertilizer was helpful in improving corn yields in the control plots and those with deep-band K alone.

The most precise, GPS-controlled automatic guidance system currently available for agricultural equipment is the RTK (real time kinematic) system, which allows steering accuracy to within 1 or 2 inches. This tool provides new opportunities for varying crop row position relative to recent (or older) nutrient bands and prior crop rows.

Over the past 2 years, we have evaluated optimal corn row positions following pre-plant UAN application at various N rates. We applied UAN bands with three N rates (50, 100, and 200 pounds per acre) at a depth of 4 inches and seeded no-till corn within 0, 5, or 10 inches from these bands. All plots, including a no pre-plant UAN control, received the same total 200 pounds per acre of N by adjustments made in side-dress UAN application after corn emergence.

In 2006, our first year of research at two locations in north central and northwest Indiana, we determined that corn yields were enhanced by on-row or near-row seeding to the pre-plant UAN band at one location when no starter (10-34-0) was applied at planting. However, at another location, corn yields were reduced 22% at the 100 pound pre-plant N rate and 54% at the 200 pound pre-plant N rate with planting directly over the UAN band (Table 3). Lower plant populations (aggravated by limited rainfall) seemed to be the primary cause of the latter yield reductions, though stunted early growth was also evident.

We tentatively conclude that RTK guidance is advantageous when planting corn soon after banded UAN application and that the optimal corn row position for a “safe” response shortly after UAN application at high rates is about 5 inches from, and parallel to, the UAN band. However, continued research in 2007 and 2008 will likely modify our recommendations somewhat.

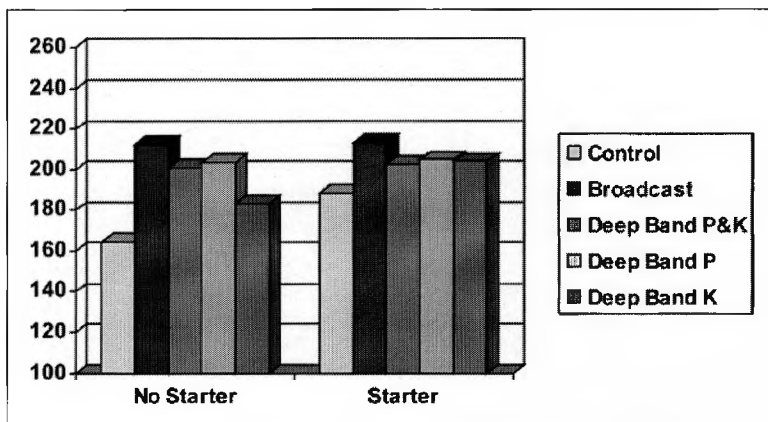


FIGURE 1 • Effects of deep banding and broadcast fertilizer treatments on strip-till corn yields with and without starter fertilizer application near West Lafayette, Indiana, 2007.

It is clear that excessive urea or anhydrous ammonia can stunt corn roots and corn shoots when dry soil situations prevail after planting and when N application rates are high. Part of root zone optimization is ensuring that nutrient availability is optimized in the early development of corn plants. Nutrient limitations, as well as nutrient excesses, can limit corn growth and development. Nitrogen placement is a key part of root zone optimization, and this is especially true in no-till and strip-till systems.

Future Recommendations

Future research in root zone optimization should be much expanded, and it should be done with rootworm-tolerant hybrids as well as for hybrids without insect resistance traits. These studies are inherently labor intensive and costly, but we need to understand corn root responses to management and genotype interactions to provide valid recommendations to crop consultants and growers and to advance our understanding of how to improve corn stress tolerance to drought and other limitations. It is deplorable how little corn root research has been under way in the Corn Belt over the past 2 decades, because so many genetic and management factors have changed.

Perhaps the biggest factor of change in corn root architecture and development rate in a limited soil volume is not the adoption of conservation tillage systems or the rootworm-resistant hybrids but the continued increase in plant density. In the quest for higher yields with modern hybrids, plants, and therefore plant roots, are progressively more

crowded. We know that adequate N availability is one means of ensuring that corn plants at progressively higher plant populations are less variable in per-plant grain yield (Boomsma and Vyn 2007b). Maintaining not only optimal overall conditions for root development on a field basis but uniform soil physical and chemical conditions within the corn row area is even more essential at high plant densities.

Automatic guidance systems provide new opportunities for implementing controlled traffic systems within a field during a given year and from year to year. Controlled traffic leads to lower soil compaction, and it is residual soil compaction from random grain buggies, combines, and other field equipment that is perhaps the biggest yield constraint on corn fields that are adequately fertilized and planted to elite hybrids. Avoiding root zone compaction is essential to improve stress tolerance and increase corn yields further. Whether the corn rows should be placed in exactly the same position from one year to the next when corn is grown in the same field (as is possible with RTK guidance) is also

TABLE 3 • Corn response to pre-plant banded UAN application and RTK-guided corn row placement at Wanatah, Indiana, 2006.

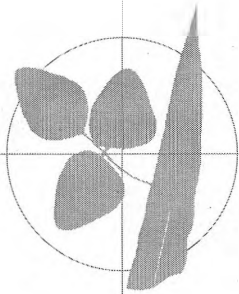
Pre-plant N rate and placement	Stand 4 weeks	Plant height V8	Harvest moisture	Yield at 15.5%
	<i>ppa</i>	<i>in.</i>	<i>%</i>	<i>bu/A</i>
0 pre-plant UAN	34306a	17.3a	24.9abc	171.6a
50 lb on-row	32833a	16.9a	24.5bc	169.2a
50 lb 5 in.	34417a	17.8a	24.6bc	171.6a
50 lb 10 in.	34500a	17.5a	24.6bc	168.3a
100 lb on-row	24417b	14.0b	25.5ab	135.4b
100 lb 5 in.	33861a	17.0a	24.7bc	174.0a
100 lb 10 in.	33944a	17.5a	23.9c	173.2a
200 lb on-row	13306c	9.9c	26.3a	92.6c
200 lb 5 in.	34556a	17.1a	24.8abc	172.0a
200 lb 10 in.	34472a	18.5a	24.4bc	170.8a
LSD (5%)	3809	2.2	1.5	17.8
Significance level	0.01	0.01	NS	0.01

Values followed by different letters are significantly different at $P = 0.05$.

an important question to investigate in studies that include detailed root investigations of root prolificacy.

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Agronomics for Corn: Have We Exhausted the Easy Options?

Roger W. Elmore and Lori Abendroth

Have we picked the “low apples,” or, in other words, the easy options, to improve corn yields up to this point? Corn yields across the country continue to increase approximately 1.9 bushels per acre per year. Yet promises of even larger gains abound among seed industry executives. Robb Fraley, Monsanto’s chief technology officer, spoke recently of that promise:

... conventional plant breeding on average results in 1.5% genetic improvement per year, while molecular breeding—enabled by biotechnology—doubles that rate of improvement. Together, the two approaches promise “to lift the ceiling on yield” (Fitzgerald 2006).

This statement needs clarification. The 1.5% gains cited are not only from genetic improvement. Research identifies that half of observed yield gains are from improved management and half are associated with genetic gains. Therefore, improved national yields from 30 bushels per acre in the early parts of the 20th century to more than 150 bushels per acre today are from improved management *and* genetics.

Realizing that yield improvement has been a combination of these two factors is important to remember as we look to future production and what is possible. Troy Hobbs, Monsanto’s corn biofuel strategy leader announced that “... advances in molecular breeding will push [national average yields] to 250 bushels per acre. Additional biotechnology gains will boost the average to 300 bushels per acre by 2030 (Schill 2007).

Promises of increased potential are not only bold but also unrealistic. To achieve 300 bushels per acre national average corn yield by 2030 will require a rate of gain of 6.3 bushels per acre per year. This is more than a threefold increase from the current 1.9 bushels per acre per year.

Projections of this magnitude are made for several reasons, yet we must realistically examine the potential for our future corn acres. Norman Borlaug said at the recent American Society of Agronomy meetings, “You can’t eat potential.” Stating that a 300 bushels per acre average crop is possible 2 decades from now is only going to cause long-term problems if agribusinesses and political processes ramp up based on this projection.

Projections of this magnitude are made in light of food versus fuel discussions and to alleviate pressure that resources will be limited in the future. Corn grain will be limited in the future if we do not increase the actual yield ceiling of corn. Currently, this is not occurring; average yields are simply getting closer to that ceiling and are expected to plateau somewhere below it. Therefore, to meet the demand for corn in the future will mean that we must continue to increase corn acres or increase corn yields. It is likely that a combination of these approaches will be necessary.

The “Low Apples”

Unfortunately, we’ve picked the low apples on the corn yield “tree.” We have nearly exhausted many of the management practices that have contributed to the rate of yield gain experienced since the hybrid revolution of the mid-20th century. These “low apples” include the following.

CROP ROTATION

We understand and, to a large extent, are capitalizing on the yield advantages of rotating corn with other crops, primarily soybeans. Increased acreage allotted to corn following corn is expected to stifle the amount of yield increase observed due to the rotation effect.

PLANTING DATE

Corn growers across the Corn Belt are planting earlier than ever before. Increased seed quality and seedling cold tolerance contribute to this trend. Seed treatments, seed placement systems on planters, larger planters, high-residue planting systems, and less spring tillage, among other changes, have also contributed to earlier planting dates. Planting earlier than the optimum window has proven fairly stable in terms of yield potential.

Although there is some discussion on the use of seed polymers (which could allow even earlier planting dates by delaying germination until soil temperatures are appropriate), the real question is whether we can plant that much earlier without significantly comprising yield.

ROW SPACING

Row spacing has varied over the years but has currently stabilized at 30 inches in the central Corn Belt. Further reductions in row width are not expected to increase yields as long as these “wide” rows intercept 95 percent of the available light during pollination and silking. Narrow rows are expected to yield more only if light interception is limited in a particular year. With current planting rates and hybrids, this amount of light interception occurs in an average year.

SEEDING RATES

Seeding rates continue to increase approximately 400 seeds per acre per year in the central Corn Belt. A final population of 28,000 plants exist on a typical Illinois farm. A significant portion of the yield increases we have experienced in the past 5 decades come from breeders’ ability to improve the stress tolerance of plants. Hybrids today are better able to tolerate plant-to-plant competition and produce an ear with less allocated area than ever before.

The question for the future is how much more we can crowd plants together until they will simply not produce a sizeable ear. If a producer is seeding corn at the same rate as 5 years ago, it is still likely that seeding another 2,000 seeds per acre will increase yields.

So, it is possible to continue picking this “low apple” and see increased yields for many producers. But, as seed prices continue to increase, many farmers look at economic returns to seed. Does planting an additional 1,000 seeds cover the cost of the seed? Because most seeding rate curves are relatively flat near the optimum seeding rate, increasing the seeding rate may not increase returns.

HYBRIDS

At least half of the yield increase experienced in the past 5 decades came from genetic modifications, such as leaf architecture changes and improved stress tolerance. Transgenic hybrids now are a significant portion of new genetics available to the producer. Yet we must remember that transgenics, up to this point, are yield-protection mechanisms and not yield-increasing mechanisms.

Transgenic hybrids have been extremely helpful in protecting the inherent yield potential of a crop in the presence of stress factors (such as herbicides or insects). They have no doubt had some impact on improving average yields, yet they have not improved yield potential (or pushed past the existing yield ceiling) for our very best yielding producers.

SOIL FERTILITY AND pH

Our understanding of these important variables has increased dramatically in the past 5 decades. The recommendation to use lime is typically based on long-term economics because it improves soil pH over time. Interestingly, recommended nitrogen rates have not increased since the 1980s. Yield gains we have seen since the 1980s have not come from an overall increase in nitrogen applied—although placement and timing have probably been improved—because hybrids today are producing high yields with the same amount of nitrogen as 2 decades ago.

The discussion in progress is whether new hybrids use nitrogen more efficiently. We are currently researching this question along with others. Returns on the use of additional nitrogen (based on the price of corn and the price of the fertilizer) often suggest that current nitrogen application rates are less than those needed to maximize corn yields. Average yields may stagnate or increase less dramatically if producers reduce nitrogen application rates.

WEED MANAGEMENT

Most producers would agree that weed management is not only easier than ever before, but it is also better than ever before. Although technology is available to allow for excellent weed control, some fields still have weed problems, whether due to improper chemicals used or from spraying too late in relation to crop and weed size. There is clearly room for improvement on the part of some producers, but tools are available to limit yield reductions resulting from weed pressure.

Management steps that are becoming increasingly important are proper stewardship of herbicides and wise resistance management. These actions will help ensure longer use of chemicals and reduce the possibility of weed competition.

INSECT MANAGEMENT

Producers now manage two key corn insects in the central Corn Belt with transgenic hybrids. Although we will continue to have “escapes” in specific fields and will need to continue to investigate new options and resistance management techniques, we know how to well manage both European corn borer (ECB) and the various strains of the corn rootworm (RW). Other insect pests are present from year to year, but their control in the future is expected to have only a slight impact on yield relative to the impact that controlling ECB and RW has had.

DISEASE MANAGEMENT

Hybrid improvements in disease tolerance over the decades, coupled with the use of modern fungicides (seed treatments and foliar applied) when pressure exists, have allowed for greater management of diseases better than ever before.

Although many of the yield gains associated with these “low apples” have been realized, it is not possible to start ignoring them. We must continue to work in these areas to continue to manage and maximize their benefits. However, the easy “pickings” from these practices have been realized, and the hardest work lies ahead as we strive to maintain yield improvements with these management techniques.

The “High Apples”

It is time to get the ladder out! We assert that the secret to improving corn yields lies in the small things that many overlook.

Corn yield contest winners are vigilant about the small and the large issues they can control. Although location plays an important role in yield obtained on small plots, the people involved are in their fields several times a day scouting.

So, what is the difference between average producers and those who produce 300-bushel yields? Location and better management. Producing this amount of grain requires more attention, whether by the producer or a consultant, than what many producers currently give or are willing to give.

Based on the situations we have seen in the past couple of years, here are a few issues that some producers are not paying enough attention to.

SEEDING DEPTH

Ideal planting depth varies with soil and weather conditions, although a 2-inch depth is ideal for most conditions. Plant-

ing depth should never be shallower than 1.5 inches. Some fields have too much variability in depth, which results in variable emergence.

Careful control and attention to planting depth will improve stands and produce more even plant emergence. Uneven emergence will not disappear when the crop gets taller; smaller plants are not able to compete against taller neighbors.

POOR PLANTING CONDITIONS: SIDEWALL COMPACTION AND OTHERS

Paul Jasa (2007) writes,

Many factors contribute to sidewall compaction. While wet soil is often given as the main reason, planting too shallow is the primary problem. Most corn planters were designed for a planting depth of 2 to 3 inches, especially those with angled closing wheels. When you properly close the seed-vee, the sidewalls of the furrow should be fractured as the soil closes around the seed, eliminating the sidewalls and providing seed-to-soil contact.

Most sidewall compaction problems on wet soils occur when the press wheels are set with too much downpressure, overpacking the seeds into the soil. When planting shallow, this press wheel compaction is below the seeding depth, making it difficult for the seedling roots to penetrate the soil. ... Make sure that the planter is properly leveled, or even slightly tail down, for the angled closing wheels to have a pinching action to close the seed-vee.

Another contributor to sidewall compaction is the lack of soil structure in many tilled fields. Producers may put extra pressure on the closing devices to close the seed-vee when in wet conditions. Without soil structure, the standard closing wheels “pinch” the sidewalls closed over the seed, particularly in heavier soils. However, as the soil dries, it shrinks and the seed-vee may open back up, exposing the seeds. This often occurs when there is a hot, windy period after planting, drying out the seed zone and reducing the stand. This is less of a problem in higher organic matter soils and in continuous no-till soils with improved soil structure. ... If there is a dry layer on top of the soil at planting time and good soil moisture at planting depth, don't use residue movers or furrow openers to remove the dry soil ... Also, when possible, leave residue over the row to reduce drying of the soil and protect the seed zone from raindrop impact.

Corn that is placed into a wet seed furrow can have restricted root growth, resulting in “rootless” corn (also referred to as rootless corn syndrome), among other problems that will become apparent as the season unfolds. Rootless corn occurs in plants with poorly developed root systems and is usually observed in plants from about the three- to eight-leaf stage of development. During this time, corn exhibiting rootless symptoms have either lodged and are lying on the ground or are about to lodge. Sometimes the corn will be anchored in the soil by only a single nodal root or by seminal roots. Affected plants lack all or most nodal roots. Due to a lack of root mass, the affected plants can wilt, have stunted growth, or die in extreme conditions.

Recovery is severely hampered if conditions are dry. Cultivation to move soil around exposed roots will aid the corn's recovery, yet this is extremely difficult if plants are lying on the ground or in a no-till situation.

The main concern with sidewall compaction and other poor planting conditions is their impact on shoot and root growth of the plants. Stressful early-season environments will reduce yield through several mechanisms: reducing plant populations, increasing plant-to-plant variability, and limiting root growth and/or mass.

PICKET FENCE SPACING: IMPORTANT OR NOT?

How critical is plant-to-plant spacing for corn? And how does planter speed impact that spacing? Research has shown plant spacing to have variable impact on yield. Some research shows that for every 1 inch in variation from the targeted spacing, yields were reduced 2.5 bushels per acre. Other researchers report even higher losses, while others report significantly less. National yield contest winners often state that slow planter speeds improve plant spacing uniformity and are part of their formula for success.

Fifteen Nebraska producers compared grain yields across different planter speeds in 2001 and 2002. Each location had three to four replications of three planter speeds: 2, 4, and 6 mph. The same study was conducted in 2002 with faster planting speeds: 4, 5.5, and 7 mph. Planter speed did not affect corn grain yield, but it did affect plant spacing accuracy. Grain yields were excellent at all locations, with averages around 200 bushels per acre. Generally, faster speeds resulted in less accuracy than slower speeds; there were more doubles and skips with faster speeds.

We collected spacing variability data from two Iowa farms in 2006 with planter speed trials. Although plant spacing variability was affected by planter speed in the 2006 trials, yields were not consistently affected.

Faster planter speeds affect plant-to-plant spacing. In average (180 bushels per acre) to above-average environments, planter speed does not affect grain yield. But, although not tested, we hypothesize that in very high-yield environments, more-variable spacing will reduce yield potential because of limited space and resources to some plants.

Summary

We have harvested the low apples on the corn management tree. For yield trends to continue into the next decades, we must pick the high apples, which are harder to get. To maximize grain yield in high-yielding environments, each plant must look like every other plant. Producers should target factors that decrease plant-to-plant variability.

We are convinced that corn management must focus on the small things in order to reach the next phase of corn yields. Management techniques, coupled with genetic improvements that push strongly against or beyond the current yield ceiling, will, we hope, continue corn yields across the Corn Belt. This will, however, require greater effort on the part of producers, agronomists, consultants, and researchers. It time to stretch the ladder out!

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For More Information

Seeding depth

www.extension.iastate.edu/Publications/PM1885.pdf

Side wall compaction

http://cropwatch.unl.edu/archives/2007/crop8/sidewall_compaction.htm

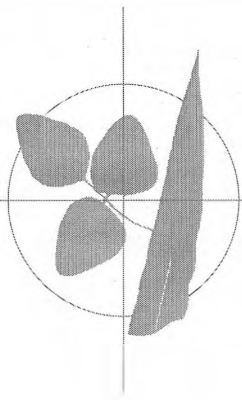
Planter speed

www.agronext.iastate.edu/corn/production/management/planting/planter.html

Uneven heights and yield impacts

www.agronext.iastate.edu/corn/production/management/early/heights.html

www.agronext.iastate.edu/corn/production/management/early/height.html



Corn Nematode Management

Terry L. Niblack

Every corn plant in every field is host to an array of plant-parasitic nematodes. Some of the very common species we see in Illinois are capable of causing significant corn yield loss under certain conditions. Yet we don't often hear about nematode injury to corn, and nematodes are usually the last item on the list when corn growers or consultants are searching for the cause of poor corn yields. This is partly because it is difficult to diagnose corn nematode injury and partly because there are few options for managing nematode problems once they are diagnosed.

Why Corn Nematode Problems Are Becoming an Issue Now

Changes in corn production practices in the recent past have increased the risk for yield loss due to nematodes. As most growers have probably heard by now, these risk factors include no-till, continuous corn, and the use of GMOs for corn insect management.

- ❖ No-till, while an excellent choice for a number of reasons, increases the risk for injury by certain types of plant-parasitic nematodes, including those commonly known as dagger, stubby root, and the very damaging needle nematodes. Research on nematode communities in a number of ecosystems has shown us that nematodes in this group are very sensitive to soil disturbance. Remove the disturbance, and populations of these nematodes are able to increase.
- ❖ Continuous corn encourages the increase of corn parasites of all kinds, of course. But it is most encouraging for corn-parasitic nematodes for two interconnected reasons. First, many of the corn parasites have long life cycles or produce few offspring (in comparison with soybean

cyst nematode), and they take a long time to build up to damaging levels. Second, many of the corn parasites are not well adapted to soybeans (although they may be able to survive well enough), so when the fields are rotated, these nematodes have less opportunity to increase.

- ❖ Genetic modifications effective for management of corn root insects are not effective for root-feeding nematodes. Some of the carbamates and organophosphates that were used formerly in insect pest management programs had the added side benefit of suppressing nematode infection.

Symptoms of Corn Nematode Damage: The "Hidden Enemy"

Nematode damage is usually suspected when stunted, yellow plants are seen in irregularly shaped areas varying in diameter from a few square yards to several acres. However, typical symptoms may be much more subtle. Plants may exhibit uneven growth; nutrient deficiencies; wilting during bright, hot days, followed by recovery at night; small ears with poor grain fill; poor yields not associated with other problems such as insect damage, fertility, or other agronomic factors; and areas of excessive root or stalk rots.

Root injury symptoms vary with the nematode species, population density, soil conditions, and plant age. Symptoms of nematode root damage include the following:

- ❖ Short and thick ("stubby") roots, often arranged in clusters. The injury may resemble damage from dinitroaniline herbicides. This damage is associated with needle, stubby root, and sting nematodes.
- ❖ Shallow root systems with few fine feeder roots. This damage may be observed on old and young plants. Damage

by grape colaspis larvae may resemble this type of nematode damage on young seedlings. This damage may be associated with dagger, stunt, and sting nematodes.

- ✿ Root systems with few fine roots, with root lesions, and root rot. This type of injury is often associated with invasion by other microorganisms. Damage by lesion, dagger, lance, and spiral nematodes may be of this type.

Diagnosis

Because corn nematode damage resembles so many other problems, the only way to get a positive diagnosis is to take a soil sample and submit it to a qualified lab for analysis. For general information on soil sampling for nematodes, see http://web.aces.uiuc.edu/vista/pdf_pubs/1100.PDF. In addition, consider the following points:

- ✿ Sample as deeply as possible, when the soil is moist but not wet. A good time to sample is early in the season (say, a month to 6 weeks after emergence), but samples can be collected at any time. Although it's usually recommended to sample somewhere between 6 and 12 inches deep, it may be necessary to take deeper samples if the plants are large or the soil is dry.
- ✿ Treat the samples *gently* while they're being taken and afterward, because some corn nematodes are very sensitive to manipulation and can be killed before they reach the lab. Dead nematodes are often very difficult to identify and are often ignored during analysis.
- ✿ Sample around the edges (not in the centers) of "hot spots" in the field.
- ✿ Place the sample in a plastic bag—not a paper bag—to help keep it moist during transport, and store the sample in a cooler to keep the nematodes from being cooked!

In addition to the sample itself, include information on previous field history, soil fertility, soil condition, herbicide

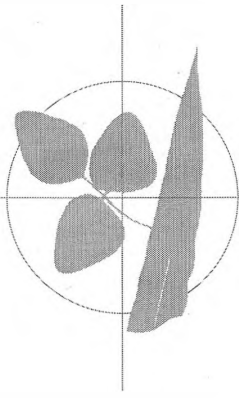
use during the current and preceding year, distribution of the problem, and appearance of above- and below-ground parts of the plant. Corn nematode management depends on the nematode species involved and how high their numbers are, so it's very important to get a good sample as the basis for a reliable diagnosis.

Management of Corn Nematode Problems

This point cannot be emphasized strongly enough: *specific recommendations depend absolutely on getting a good diagnosis.* Each of the following general recommendations must be tailored to the diagnosis.

- ✿ Avoid stress. Water infected plants, if irrigation is available. Fertilize according to soil tests. Stress makes plants more susceptible to injury from nematode feeding.
- ✿ Control weeds, especially grasses. Weeds are hosts for many nematodes and may serve as "réservoirs" for damaging nematodes.
- ✿ Rotate "hot spots" to a crop other than corn, but be aware that many nematodes that attack corn also attack soybeans, wheat, or other crops.
- ✿ Use chemical control if possible. Registered chemicals for nematodes may be found by searching for "nematode" on the Illinois Department of Agriculture Web site at www.kellysolutions.com/IL/searchbypest.asp.

Many companies have become aware that corn nematode problems are increasing in high-yield production areas. Several are currently evaluating new products, or re-evaluating old ones, for nematode control on corn. At this writing, the results from the 2007 field evaluation season have not yet been analyzed, but several products look at least promising. New information and recommendations should be forthcoming in the near future.



Foliar Fungicides in Corn Production: A Look at Local and Regional Data

Carl A. Bradley and Keith A. Ames

In 2007, a record number of corn acres were sprayed with a foliar fungicide in Illinois and other midwestern states. High market prices and an increasing demand for ethanol made from corn, along with more corn-on-corn production, were factors that influenced this sharp increase in foliar fungicide use. Despite dry conditions and low levels of disease in much of Illinois in 2007, many fields received a foliar fungicide application.

No “hard and fast” IPM-based fungicide guidelines or disease thresholds have been developed for commercial hybrid corn production in the Midwest. This is due, in part, to the historical lack of foliar fungicides used in corn and the lack of foliar fungicides registered for use in corn until recently.

Tilt (propiconazole; Syngenta Crop Protection) was the first systemic fungicide registered for use on corn in the United States. More recently, fungicides in the “strobilurin” chemistry class such as azoxystrobin, pyraclostrobin, and trifloxystrobin have become registered on corn. These strobilurin fungicides are either marketed alone [e.g., Quadris (azoxystrobin; Syngenta Crop Protection) and Headline (pyraclostrobin; BASF Corp.)] or are in a pre-mix combination with the “triazole” fungicide propiconazole [e.g., Quilt (azoxystrobin + propiconazole; Syngenta Crop Protection) and Stratego (trifloxystrobin + propiconazole; Bayer CropScience)].

Munkvold et al. (2001) reported that a foliar application of propiconazole to control gray leaf spot (caused by *Cercospora zea-maydis*) could be profitable in Iowa, but the profitability of a propiconazole application was strongly influenced by the susceptibility of the corn hybrid to gray leaf spot. In other words, it was more likely to receive a positive return on the fungicide investment if it was applied to a susceptible hybrid. Similarly, Ward et al. (1997) reported that gray leaf spot severity and yield loss could be reduced with a propiconazole application to a susceptible hybrid in South Africa.

Although “hard and fast” fungicide guidelines do not exist for corn, fungicide application decisions can be made, in part, based on risk factors. A gray leaf spot risk-assessment model developed by Paul and Munkvold (2004) indicated that corn residue on the soil surface, planting date, and hybrid resistance to gray leaf spot were among the best predictors for gray leaf spot. Risk of gray leaf spot increases with increasing corn residue on the soil (de Nazareno et al. 1993), later planting date (Rupe et al. 1982), and greater hybrid susceptibility. These three risk factors can be determined prior to planting. A “post-planting” risk factor is weather, where rainfall and relative humidity play a role in providing an environment favorable for disease (Rupe et al. 1982).

Along with these risk factors, it is still important to scout the crop and collect disease observations. If low levels of disease are present, it is unlikely that a fungicide will provide an economic benefit despite the presence of pre-plant risk factors.

A Look at 2007 Corn Foliar Fungicide Data from Illinois

Several foliar fungicide trials were conducted on corn across several locations in Illinois in 2007. Some of these trials were basic fungicide trials that examined the effect of different fungicides on disease control and yield of one corn hybrid. Other trials were more complicated and evaluated multiple factors such as previous crop, different corn hybrids, simulated hail damage, and fungicides.

“BASIC” FUNGICIDE TRIALS

Trials located near Urbana (Champaign County), Ridgway (Gallatin County), and Dixon Springs (Pope County) were conducted to test different foliar fungicides on a corn hybrid

moderately susceptible to gray leaf spot. In the Urbana trial (Table 1), all of the foliar fungicides significantly reduced gray leaf spot severity compared to the untreated control; however, none of the fungicides provided a significant increase in yield over the untreated control. In the Ridgway trial (Table 2), no significant differences occurred among the different treatments for gray leaf spot severity or yield. In the Dixon Springs trial (Table 3), foliar fungicides significantly reduced gray leaf spot severity compared to the untreated control; however, no significant differences were observed for yield. In all three of these trials, foliar disease pressure was low, with the highest observed severity rating being only 20%.

TABLE 1 • Effect of foliar fungicides applied at tassel emergence on gray leaf spot severity and yield of a moderately-susceptible corn hybrid near Urbana, Illinois, in 2007.

Fungicide	Rate/A	GLS severity ¹	Yield (bu/A)
Untreated		20	214
Quilt	14 fl oz	10	191
Headline	6 fl oz	6	208
Stratego	10 fl oz	10	217
Stratego	12 fl oz	9	215
	LSD ²	4	19

¹ Gray leaf spot severity (0-100% scale).

² Fisher's protected least significant difference ($\alpha = 0.05$).

TABLE 2 • Effect of foliar fungicides applied at tassel emergence on gray leaf spot severity and yield of a moderately susceptible corn hybrid near Ridgway, Illinois, in 2007.

Fungicide	Rate/A	GLS severity ¹	Yield (bu/A)
Untreated		15	153
Quadris	6 fl oz	15	158
Quadris	9 fl oz	11	164
Headline	6 fl oz	10	155
Headline	9 fl oz	13	160
Stratego	10 fl oz	9	162
Stratego	12 fl oz	9	159
Quilt	14 fl oz	10	164
	LSD ²	NS ³	NS

¹ Gray leaf spot severity (0-100% scale).

² Fisher's protected least significant difference ($\alpha = 0.05$).

³ Not significantly different ($P \leq 0.05$) according to *F*-test.

TABLE 3 • Effect of fungicides applied at tassel emergence on gray leaf spot severity and yield of a moderately-susceptible corn hybrid near Dixon Springs, Illinois, in 2007.

Fungicide	Rate/A	GLS severity ¹	Yield (bu/A)
Untreated		15	183
Quadris	6 fl oz	7	167
Quadris	9 fl oz	5	179
Headline	6 fl oz	7	192
Headline	9 fl oz	7	171
Stratego	10 fl oz	7	169
Stratego	12 fl oz	8	159
Quilt	14 fl oz	5	171
	LSD ²	2	NS ³

¹ Gray leaf spot severity (0-100% scale).

² Fisher's protected least significant difference ($\alpha = 0.05$).

³ Not significantly different ($P \leq 0.05$) according to *F*-test.

SIMULATED HAIL × FUNGICIDE TRIAL

From the authors' perspectives, recommendations to apply a foliar fungicide to a corn field after a hail storm have not been based on data from replicated research trials. A trial was conducted near Champaign to evaluate the effects of foliar fungicides on gray leaf spot and yield under simulated hail damage and no hail damage conditions.

Hail damage was simulated by damaging corn plants with a weed-eater type gasoline string mower at tassel emergence, and foliar fungicides were applied the following day. In this trial (Table 4), foliar fungicides significantly reduced gray leaf spot severity compared to the untreated control in both the simulated hail damage and no hail damage plots. Within simulated hail damage and no hail damage plots, foliar fungicides did not significantly affect yield compared to the untreated controls. Overall, yields from the simulated hail damage plots were significantly lower than yields from the no hail damage plots.

PREVIOUS CROP × HYBRID × FUNGICIDE TIMING TRIAL

A trial was conducted near Urbana to evaluate the effect of previous crop (soybeans or corn), corn hybrid, and fungicide timing on gray leaf spot severity and yield. To establish this trial, corn was planted no-till into either corn or soybean

stubble. A hybrid moderately resistant to gray leaf spot and a hybrid moderately susceptible to gray leaf spot were used in this trial. Stratego fungicide was applied at either VT or R1. An untreated control was also included. In this trial (Table 5), significant differences in gray leaf spot severity were observed between the two hybrids; however, Stratego did not significantly reduce gray leaf spot severity compared to the untreated control within each previous crop-hybrid combination. No significant differences in yield were observed.

FUNGICIDE × CORN HYBRID TRIALS

Munkvold et al. (2001) reported that hybrid susceptibility to gray leaf spot influenced the probability of a profitable fungicide application. To evaluate the effect of foliar fungicides on different corn hybrids, two trials were conducted. One trial, conducted at both Monmouth (Warren County) and Champaign, investigated the effects of eight fungicide treatments (including an untreated control) on five different corn hybrids. At the Monmouth location (Table 6), some of the foliar fungicides significantly reduced gray leaf spot severity compared to the untreated control for hybrid 3; however, fungicides did not affect gray leaf spot severity within any of the other hybrids. Within hybrids at Monmouth, the only fungicide that provided a significant yield increase over the untreated control was Stratego applied at 10 fl oz/A for hybrid 2.

At the Champaign location (Table 6), foliar fungicides generally provided a significant reduction in gray leaf spot severity; however, severity was very low across all hybrids. Some foliar fungicides provided a significant yield increase over the untreated control for hybrid 1 and hybrid 4, but fungicides did not affect yield compared to the untreated control in any of the other hybrids.

Conclusions

Based on University of Illinois corn fungicide trials conducted in 2007, “automatic” significant yield increases with the use of foliar fungicides did not occur. Even though the fungicides tested had good efficacy against gray leaf spot, a

TABLE 4 • Effect of simulated hail damage and foliar fungicides applied at tassel emergence on gray leaf spot severity and yield of a susceptible corn hybrid near Champaign, Illinois, in 2007.

Simulated hail ¹	Fungicide	Rate/A	GLS severity ²	Yield (bu/A)
No	Untreated		57	174
	Headline	6 fl oz	33	179
	Quadris	6 fl oz	42	170
	Quilt	14 fl oz	40	155
Yes	Untreated		62	141
	Headline	6 fl oz	48	144
	Quadris	6 fl oz	47	142
	Quilt	14 fl oz	35	140
		LSD ³	12	11

¹ Hail was simulated by damaging corn plants with a weed-eater type string mower.

² Gray leaf spot severity (0-100% scale).

³ Fisher's protected least significant difference ($\alpha = 0.05$).

reduction in disease severity did not always translate into a yield benefit. This could have been due, in part, to the fact that almost every trial conducted in 2007 had low disease pressure and never reached disease levels that could cause economic yield losses. Using the pre-planting risk factors (i.e., amount of corn residue, hybrid susceptibility, and planting date) along with the post-planting risk factors (i.e., weather conditions, scouting observations) to make fungicide application decisions will increase profitability and reduce unwarranted fungicide applications.

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TABLE 5 • Effect of previous crop, corn hybrid, and Stratego fungicide on gray leaf spot severity and yield near Urbana, Illinois, in 2007.

Previous crop	Hybrid ¹	Fungicide, rate/A	Timing	GLS severity ²	Yield (bu/A)
Corn	Mod Res	Untreated		7	200
		Stratego, 10 fl oz	VT	5	198
			R1	5	205
	Mod Susc	Untreated		13	208
		Stratego, 10 fl oz	VT	10	213
			R1	13	208
Soybean	Mod Res	Untreated		5	205
		Stratego, 10 fl oz	VT	4	211
			R1	4	213
	Mod Susc	Untreated		10	219
		Stratego, 10 fl oz	VT	8	222
			R1	10	225
		LSD ³		4	NS ⁴

¹ One hybrid was moderately resistant to gray leaf spot, and the other hybrid was moderately susceptible to gray leaf spot.

² Gray leaf spot severity (0-100% scale).

³ Fisher's protected least significant difference ($\alpha = 0.05$).

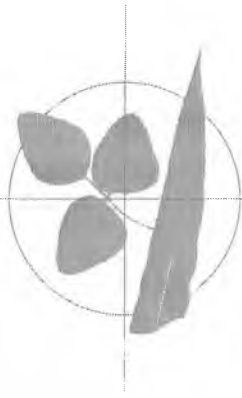
⁴ Not significantly different ($P \leq 0.05$) according to *F*-test.

TABLE 6 • Effect of corn hybrid and foliar fungicides applied at tassel emergence on gray leaf spot severity and yield near Monmouth and Champaign, Illinois, in 2007.

Hybrid	Fungicide	Rate/A	Monmouth		Champaign	
			GLS severity ¹	Yield (bu/A)	GLS severity ¹	Yield (bu/A)
1	Untreated		19	231	4	163
	Quadris	6 fl oz	13	236	3	173
	Quadris	9 fl oz	13	234	2	181
	Headline	6 fl oz	14	236	2	176
	Headline	9 fl oz	14	239	2	182
	Stratego	10 fl oz	14	233	2	181
	Stratego	12 fl oz	15	230	3	174
	Quilt	14 fl oz	14	233	2	185
2	Untreated		22	252	6	178
	Quadris	6 fl oz	18	249	2	178
	Quadris	9 fl oz	15	244	2	183
	Headline	6 fl oz	17	263	2	182
	Headline	9 fl oz	16	268	2	183
	Stratego	10 fl oz	15	270	2	178
	Stratego	12 fl oz	17	246	3	189
	Quilt	14 fl oz	17	252	3	177
3	Untreated		43	239	6	181
	Quadris	6 fl oz	28	240	3	175
	Quadris	9 fl oz	37	237	3	194
	Headline	6 fl oz	29	240	4	187
	Headline	9 fl oz	33	243	3	187
	Stratego	10 fl oz	43	237	4	186
	Stratego	12 fl oz	36	239	4	184
	Quilt	14 fl oz	25	245	4	186
4	Untreated		21	237	6	150
	Quadris	6 fl oz	22	240	3	163
	Quadris	9 fl oz	21	234	3	162
	Headline	6 fl oz	21	242	4	158
	Headline	9 fl oz	19	239	3	165
	Stratego	10 fl oz	21	242	4	160
	Stratego	12 fl oz	18	240	3	157
	Quilt	14 fl oz	23	236	3	155
5	Untreated		25	255	5	188
	Quadris	6 fl oz	18	263	3	182
	Quadris	9 fl oz	22	254	4	185
	Headline	6 fl oz	18	262	5	174
	Headline	9 fl oz	18	263	4	195
	Stratego	10 fl oz	22	257	3	192
	Stratego	12 fl oz	24	256	3	184
	Quilt	14 fl oz	24	269	4	175
	LSD ²		9	18	2	15

¹ Gray leaf spot severity (0-100% scale).

² Fisher's protected least significant difference ($\alpha = 0.05$).



The Seven Wonders of the Corn Yield World

Fred E. Below

An Introduction to the Seven Wonders

I developed the “Seven Wonders of the Corn Yield World” as a tool to teach farmers and crop consultants the relative importance of management factors that can impact corn productivity. The seven wonders ranks the top seven factors that can positively impact corn yields and assigns an average bushel per acre value to each wonder. It is based on a compilation of research conducted by the Crop Physiology Laboratory at the University of Illinois over the past 10 years. Because the bushel values are averages of ranges, farmers of course could experience different values, and, because the research for this ranking was conducted mostly in Illinois, the relative ranking or value of a particular wonder could change slightly with geography.

There are some practices that are clearly important, but I don’t consider them yield wonders because they are one-time improvements (e.g., tile drainage or waterways), they protect rather than increase yield (e.g., weed or pest control), or they involve decisions that do not need to be made every year (e.g., soil pH and nutrient levels). In my view, good weed control, along with proper soil pH and adequate levels of P and K, are prerequisites for crop production and are necessary to allow the seven wonders to express their positive impact on grain yield.

One nuance of the seven wonders is that they can interact with each other to either magnify or lessen a single wonder’s impact on yield. Also, as a rough rule, the higher the ranking of a particular wonder, the more control it can exert over the wonders below it. Understanding a wonder’s ranking, and its interaction with other wonders, gives farmers an opportunity to further increase grain yields through crop management.

Least Control on Wonders One and Two

Unfortunately, the first wonder of the corn yield world is the one that farmers have the least control over, the **weather**. Weather, largely in the form of rainfall and temperature, is a major determinant of when the crop can be planted, and it has a huge impact on plant growth and yield potential (Thompson 1986; Anderson et al. 2001). Even with the other yield wonders optimized and constant, our research shows a 70+ bushel variation in grain yield due to the weather. All farmers know that weather can circumvent their best management plans, because it so strongly interacts with each of the other yield wonders.

Especially affected by weather is **nitrogen** fertilization (N), the number two wonder of the corn yield world. The ability to apply fertilizer N, its availability or susceptibility to loss, and its impact on grain yield are all heavily impacted by weather. As a result, weather and the availability of N are usually the two factors exerting the greatest impact on corn yields. They can act independently, or be closely linked, and their effects can be to either increase or decrease crop growth and yields. A lot of research has been conducted to try to understand and manage the interaction between weather and N (IPNI 2007).

One example of the many possible interactions between weather and N is shown in Figure 1. There is a considerable impact of year (weather) on the maximum yield, and on the response to N, for corn grown at the same location. In this case, low July rainfall limited yield in 2005 and lowered the need for and the response to fertilizer N. Other examples could just as easily show increases in the magnitude of response to N due to excess rainfall causing N losses. Because N fertilizer increases grain yield by an average of 70 bushels, and because most of

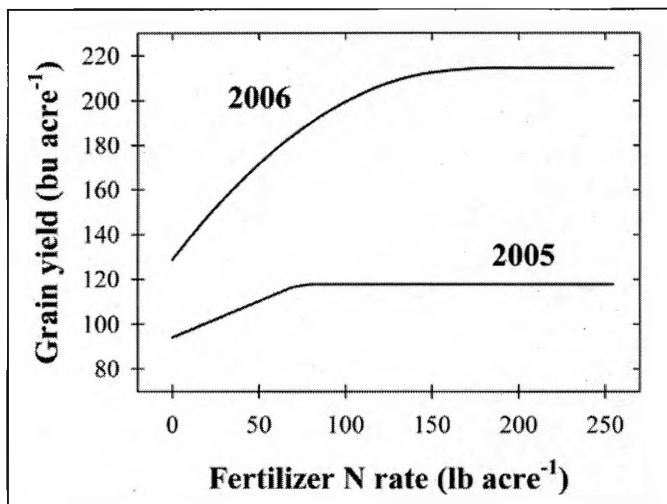


FIGURE 1 • The interaction between weather and N on the grain yield of corn. Data are the average of multiple hybrids grown at the same site in Champaign, Illinois, in 2005 and 2006.

the other yield wonders can also impact the availability or the use of N, N fertilizer management continues to receive considerable attention in the research world.

Wonders Three and Four Gaining in Importance

Nitrogen use also interacts strongly with the third wonder of the corn yield world, **hybrid** selection, and there is considerable interest in improving the efficiency of N use with genetics or biotechnology (Hirel et al. 2007). Hybrid selection is probably the most important decision made by farmers, and most do not realize the large difference in yield potential among elite commercial hybrids. Arrays of commercial hybrids, grown under conditions where the other

TABLE 1 • Variation in grain yield of commercial hybrids over a 4-year period at Champaign, Illinois. Values for each hybrid are at the N rate that optimized yield.

Year*	Average	Range bu/A	Delta
2004	200	178–229	51
2005	119	94–136	42
2006	188	152–215	63
2007	196	173–221	48

*24, 22, 17, and 15 hybrids in each respective year.

wonders are presumed to be optimized, typically exhibit a 50-bushel range in grain yield. An example of this difference is shown in Table 1. The weather effect on average yield is clear, but in each year the hybrids still exhibit close to a 50-bushel range in yield. Clearly, hybrids respond differently to growing conditions, and hybrid selection will become even more important in the future, when biotechnology adds stress and input traits such as drought tolerance and improved N use.

There is a hint that biotechnology may have already altered hybrid N use via Bt rootworm resistance. I have seen big yield advantages conferred by the rootworm trait that are hard to attribute entirely to rootworm control. One of these studies is shown in Figure 2, which illustrates the results of our comparison of N response for the same hybrid with varying biotech trait combinations. Plots had fairly low rootworm pressure and were treated with soil insecticide at planting, so it is hard to believe that the 50+ yield advantage of the triple-stack version was solely attributable to rootworm control. The triple-stack hybrid performed better at low N and had an even higher maximal yield at high N, but it required more total N to achieve its maximum yield (Figure 2). Additionally, we have seen cases where inclusion of the

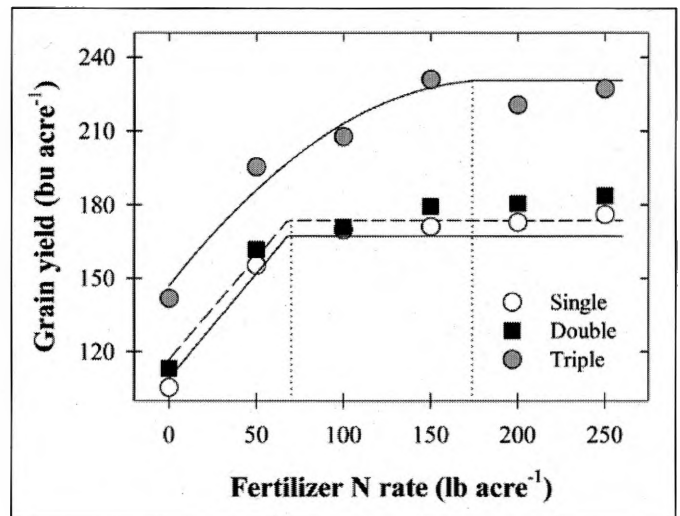


FIGURE 2 • Influence of combinations of biotech traits on the response of corn grain yield to fertilizer N. The same hybrid genetics were used for the single (herbicide resistance only), the double (herbicide resistance and corn borer Bt), and the triple (herbicide resistance, corn borer Bt, and rootworm Bt) stack versions. All plots also received soil insecticide at planting. The dashed lines at the inflection points indicate the N rate associated with maximum yield. Data are from a 2006 experiment conducted at Champaign, Illinois.

rootworm trait increased yield without altering the N level needed for maximum yield, and where yield increases along with a decrease in the N level needed for maximal yield (data not shown). Although more work needs to be done to ascertain the full impact of the rootworm Bt trait on N use, these examples bode well for future improvements with biotechnology.

The fourth wonder of the corn yield world, **previous crop**, is gaining in importance as the acreage of continuous corn has steadily increased. This is despite the 25-bushel per acre yield penalty associated with continuous corn, and the higher input cost, especially fertilizer N. Previous crop clearly interacts with the first and second wonders, and, if sufficient N is available in a good growing year, we have found that the continuous corn yield penalty can be reduced or eliminated (Becker et al. 2007) (Figure 3). Conversely, in the poorer growing year (2005), the yield penalty from continuous corn could not be overcome with additional N.

Although it makes sense that some hybrids might perform better than others under continuous corn, our research has not shown this (Becker et al. 2007). When each hybrid's average yield in continuous corn is plotted against its yield in rotation, none performs better under continuous corn in either year—all are above the 1:1 line (Figure 4). For both years, there is a highly significant linear association between a hybrid's yield in rotated and continuous corn ($r = 0.92$ and 0.99 for 2005 and 2006, respectively), which means that the best hybrid for rotated corn is also the best one for continuous corn.

Are Interactions the Key to Wonders Five, Six, and Seven?

Wonders five, six, and seven have a smaller individual impact on yield, but a larger possibility for interactions with wonders one through four (weather, N, hybrid, and previous crop). It is well known that the fifth wonder of the corn yield world, **plant population**, has increased steadily over the past 20 years (Duvick 2005). But what probably is not known is how well modern hybrids are at flexing their ear components (i.e., kernel number and weight) to account for differences in plant stand. Because of this, we find similar yields between 28,000 and 40,000 plants per acre, although there is a big difference in the size of individual kernels. An example of this is shown in Figure 5 for a series of on-farm variable rate population studies. Thus, most of the 20-bushel yield benefit that we see from plant population comes from correcting stands that are too low.

Plant population, however, interacts heavily with most of the other yield wonders, with high plant populations being particularly susceptible to unfavorable weather conditions. Similarly, some hybrids are clearly more tolerant to high populations than others, and previous crop and tillage can impact plant population by altering seed germination and seedling emergence. One interaction we do not observe, however, is between plant population and N rate (Figure 6). Contrary to what many farmers and crop consultants think, we do not see a requirement for higher N rates as plant populations increase.

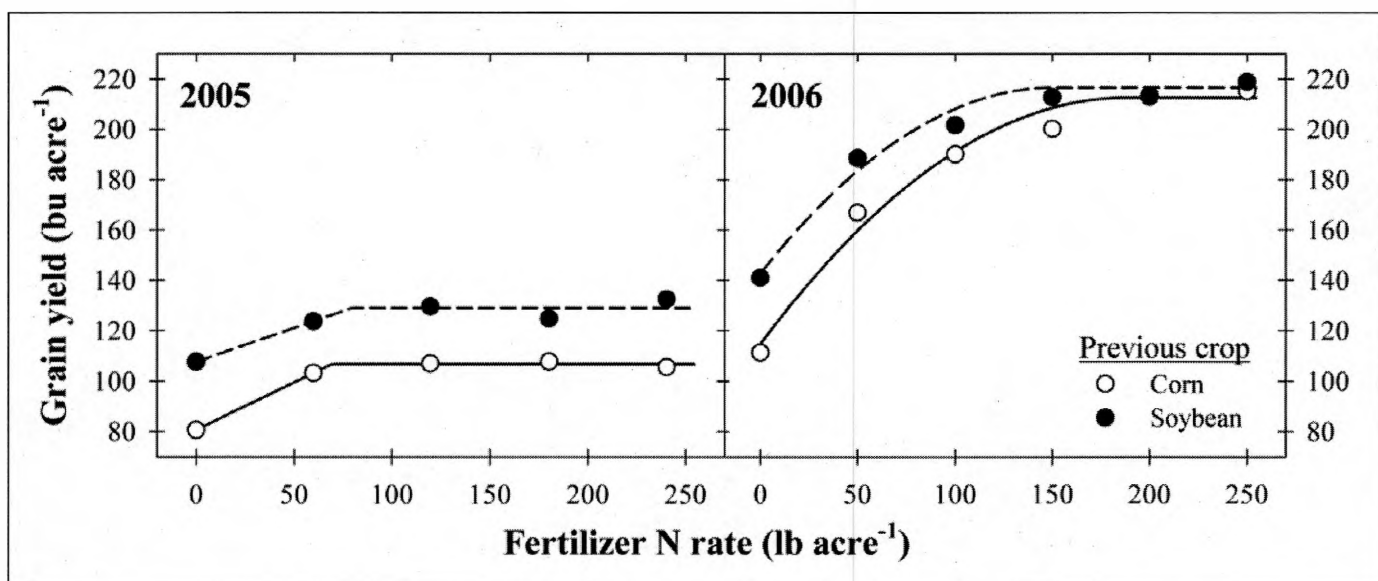


FIGURE 3 • Effect of previous crop and fertilizer N rate on grain yield for two contrasting years at Champaign, Illinois. Yields are averaged over 22 hybrids in 2005 and 12 in 2006.

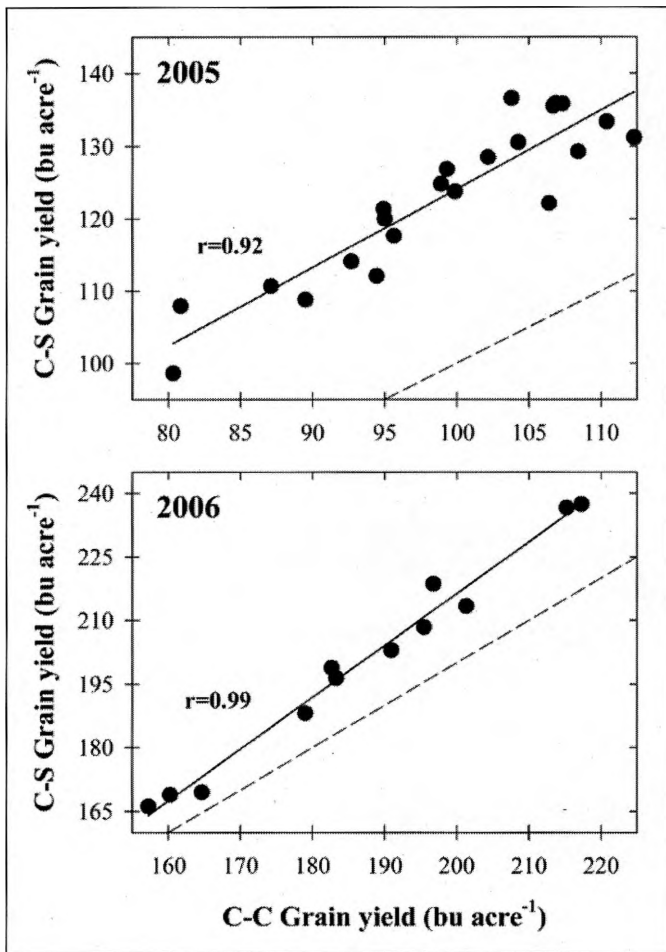


FIGURE 4 • The relationship between a hybrid's yield in continuous corn (C-C) and its yield when rotated with soybean (C-S) for the 22 and 12 hybrids evaluated in 2005 and 2006, respectively. Hybrid values are averaged over N rates. The dashed line depicts the one-to-one relationship, and the solid line the linear regression among hybrids for 2005 ($y = 1.085x + 15.58$) and for 2006 ($y = 1.2227x - 28.24$).

The sixth wonder of the corn yield world, **tillage**, comes in varying degrees, or at differing times. Both aspects interact heavily with the other yield wonders, with the relative advantages or disadvantages of a particular tillage system or time depending largely on the weather, and often interacting with N availability and hybrid. An example of the interaction between tillage and N rate is shown in Figure 7. At low N rates, tillage systems have an advantage over no-till, while the opposite is true at high N rates. This interaction is likely due to the impact of tillage on N availability and the water-holding capacity of the soil. The degree of tillage and the time of tillage can also make a big difference with previous crop because most of the yield penalty associated with

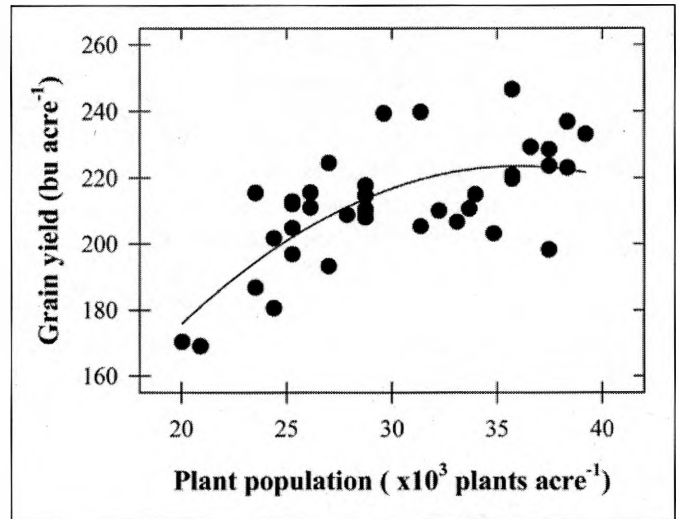


FIGURE 5 • The effect of varying plant populations on grain yield of corn. Data were collected on-farm from a large-scale variable rate seeding study conducted near Beardstown, Illinois, in 2005.

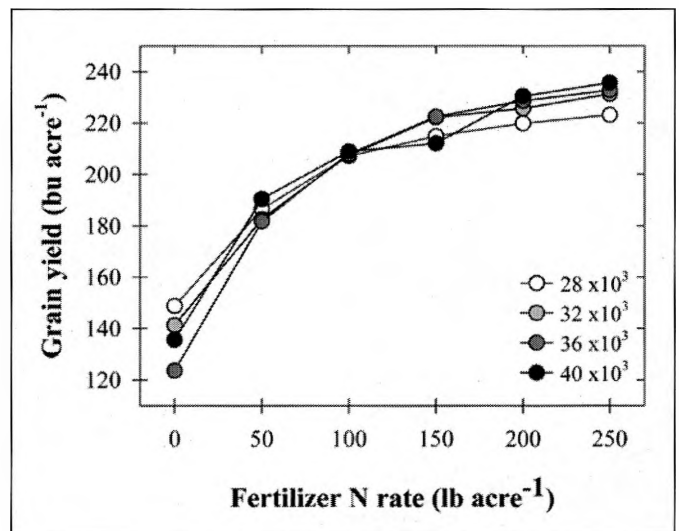


FIGURE 6 • The interactive effect of plant population and N rate on grain yield of corn. Yields are averaged over 12 hybrids grown at Champaign, Illinois, in 2006.

continuous corn is due to the residue (Gentry et al. 2001). Similarly, the tillage system can have a big impact on plant population. Overall, our research shows a 15-bushel yield range from the various tillage systems.

The seventh wonder of the corn yield world is a catch-all that I call **chemicals**. This includes plant growth regulators and compounds that exert growth regulator-like effects that, as a result, lead to a positive change in growth or yield determina-

tion. Late-season leaf-greening from certain foliar fungicides and ethylene-sensing technologies that make the plant less sensitive to environmental stresses fit into this category.

An example of the late-season greening effect induced by Headline fungicide is shown in Figure 8. Leaves below the ear of Headline-treated plants exhibited a slower rate of decline during the later stages of grain fill, while the leaves above the ear were much less affected. Translation of leaf greening into higher grain yield, however, was highly dependent on the weather, particularly July rainfall (Figure 9). The likelihood of a Headline effect on grain yield was closely related to the site's total rainfall in July, which explained 82% of the variability in the magnitude of yield change. Leaf-greening, however, was only beneficial to yield when July rainfall was greater than normal, and it did not overcome the yield limitation imposed by low July rain. Thus, like all plant growth-regulating compounds, there is also the possibility for detrimental effects depending on how the other wonders are altering plant growth at the time of application. Although the overall average is a positive 10 bushels, the success of these compounds is highly dependent on the other yield wonders, especially weather and hybrid, and this category has the widest range.

They All Add Up

Each of the seven wonders and its average impact on yield is shown in Table 2. By optimizing all of the seven wonders and using my average number for each wonder's value, grain yields of 260 bushels should be the result. This does not take interactions among the wonders into account, which in some cases could drive yields even higher. By the same token, a nonoptimized yield wonder lowers yield. Although I realize that my seven wonders concept is a vast oversimplification of all the complicated factors that make a high-yielding corn crop, I still hope that it gives you a better perspective on how your management decisions can impact grain yield.

Acknowledgments

I express my gratitude to all the students and staff of the Crop Physiology Laboratory who helped to compile these data,

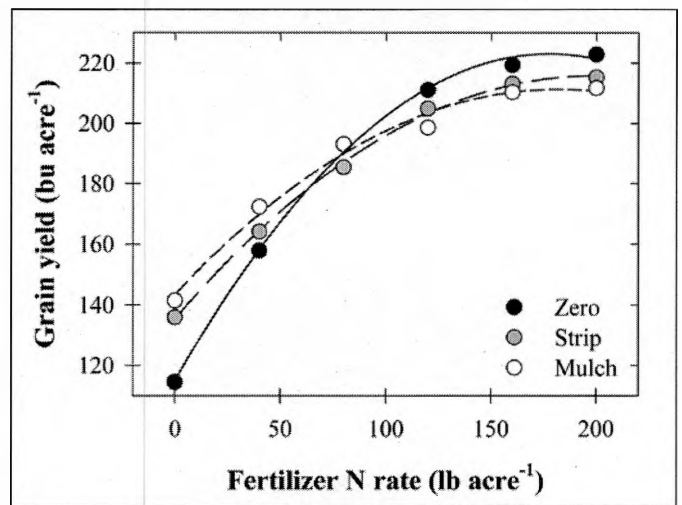


FIGURE 7 • The interactive effect of tillage type and N rate on grain yield of corn. Yields are averaged over 6 site-years in northern and central Illinois between 1999 and 2000.

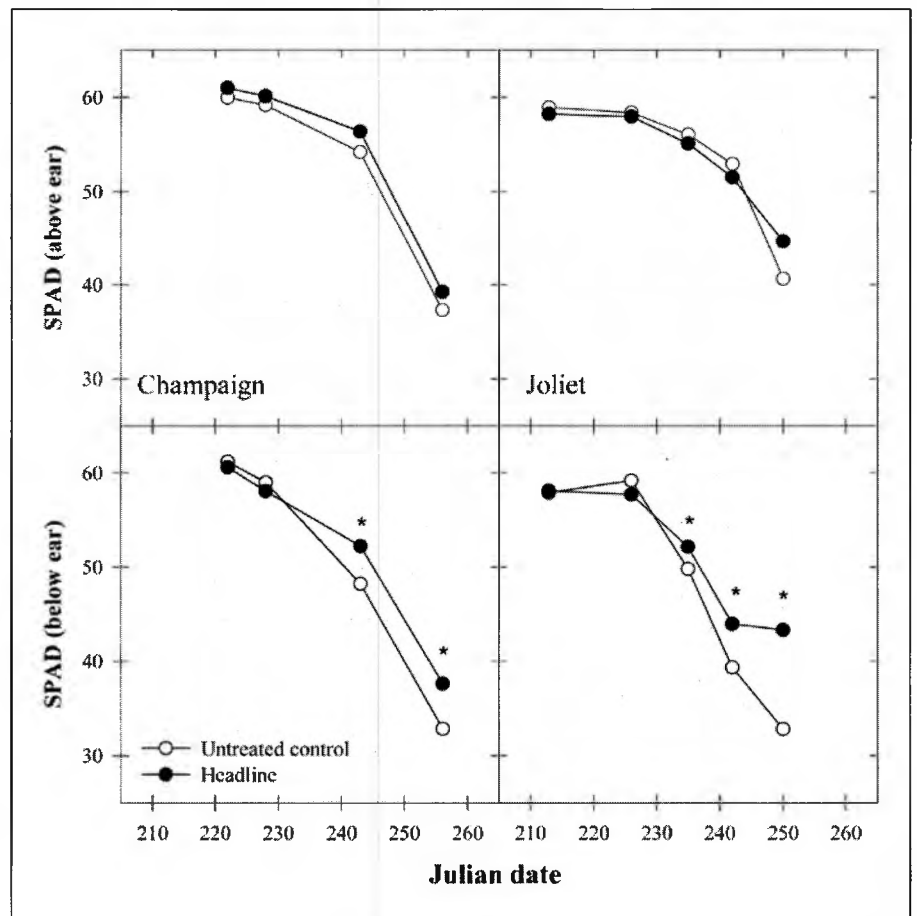


FIGURE 8 • The effect of Headline application (near stage VT) on leaf relative greenness (SPAD) during grain fill (measured above and below the ear) for corn grown at Champaign and Joliet, Illinois, in 2006. (*) Indicates significant differences between control and Headline-treated plants for any given sampling day.

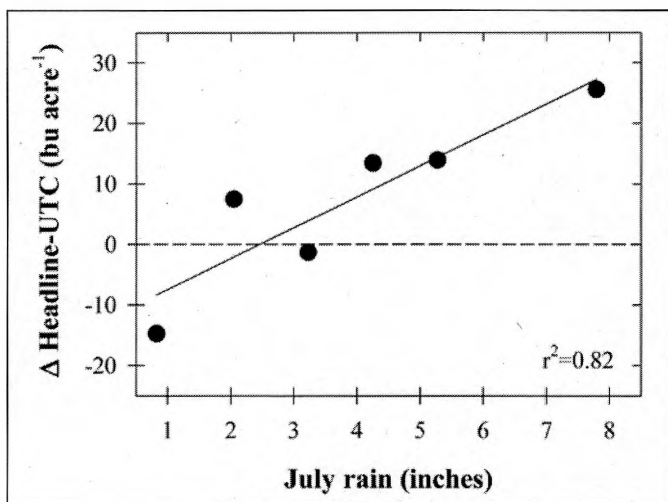


FIGURE 9 • The relationship between total rainfall in July and the magnitude of yield response to a Headline application (near stage VT) for corn grown at six sites in Illinois in 2006.

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TABLE 2 • The seven wonders of the corn yield world.

Rank	Factor	Value bu/A
1	Weather	70+
2	Nitrogen	70
3	Hybrid	50
4	Previous crop	25
5	Plant population	20
6	Tillage	15
7	Chemicals	10

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