Pest resistance: An Overview

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"And this, perhaps, might have been anticipated: for, as varieties, in order to become in any degree permanent, necessarily have to struggle with the other inhabitants of the country, the species which are already dominant will be the most likely to yield offspring which, though in some slight degree modified, will still inherit those advantages that enabled their parents to become dominant over their compatriots." (Darwin 1859).

The universal truths of the survival of the fittest and the inevitability that organisms will adapt to whatever environmental factors they encounter have been the most important management considerations to achieving success in agronomic endeavors since mankind transitioned from a hunter/gatherer existence to the agrarian society that has existed for more than six millennia. Predictions of the evolutionary adaptation of pests to the environment in which they exist were made more than 150 years ago (Darwin 1859). More recent discussions about selective adaption or evolved resistance in pests were published as early as 1914 for insects, 1914 for diseases and 1950 for weeds; although it has been suggested that earlier citations are undoubtedly available (Jones 1914; Melander 1914; Blackman 1950).

Unfortunately, there appears to be another universal truth that suggests that agriculture, defined to include all sectors (e.g., farmers, agricultural retailers and technology providers) typically do not address pest adaptation (evolution) until resistance has become of great economic importance. This is likely because the benefits of resistance management are highly uncertain and are discounted because they are more distant in the future. Only when pest control costs increase significantly because of developing resistance do users appreciate the potential benefits of resistance management. In other words, it may be well into the future before the uncertain benefits of resistance management are realized. If a pest control technology fails well before replacement technology is developed, then the benefits of resistance management would be more pronounced. Unfortunately, resistance management may be very costly to control at this point.

There may be a role for the government (e.g., USDA, EPA, state agencies) to response to pest adaptation and evolved pesticide resistance. For example, USDA recently announced a program to help farmers diversify weed control efforts through NRCS programs (EQIP and CIG) and support related education and outreach programs with the Weed Science Society of America. USDA is also funding research on the socio-economic aspects of diverse weed control tactics by communities of farmers. Efforts such as these could, in coordination with state agencies, support development of voluntary, community-based resistance management programs. EPA can also employ a variety of regulatory approaches, potentially with state-specific flexibility to manage resistance if it determines the benefits of a pest control technology are significant in terms of agricultural production and/or protection of human health and the environment (e.g., EPA registration decisions for Bt corn.

Agricultural scientists and evolutionary biologists have attempted to join together and investigate an essential question about the success of future food production; are there strategies that can anticipate and manage to a degree, pest evolutionary responses (Gould 1991)? It is suggested that the correct answer to this question is a qualified yes. Indeed, pest responses to selection pressure can be anticipated but the strategies needed to resolve these adaptations are typically not effectively adopted and implemented.

There are a number of reasons that agriculture has thus far found it difficult to manage, much less prevent, the inevitable evolution of pest resistances. Interestingly, most of the reasons appear to be other than biological considerations but rather reflect socio-economic aspects of modern agriculture, as noted above (Mortensen, Egan et al. 2012). By the time the existence of a pest resistance is accepted, the spread of the pest resistance complex is such that effective management is no longer a simple or inexpensive prospect. It is important that a better understanding of pest resistances reflect not just the biological factors but also the practical features of production agriculture, market demands, and the changing social demographics of Iowa agriculture.

References

Blackman, G. E. (1950). "Selective toxicity and the development of selective weedkillers." Journal of the Royal Society of Arts **938**(4820): 499-510.

Darwin, C. (1859). On the origin of species by means of natural selection or the preservation of favoured races in the struggle for life. London, England, Penguin Books.

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Jones, L. R. (1914). "Problems and progress in plant pathology." American Journal of Botany **1**(3): 97-111.

Melander, A. L. (1914). "Can insects become resistant to sprays?" Journal of Economic Entomology **7**: 197-232.

Mortensen, D. A., J. F. Egan, et al. (2012). "Navigating a critical juncture for sustainable weed management." BioScience **62**(1): 75-84.

Stakeholder Group Representatives' Perspectives on Pesticide Resistance Management

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Key points:

1. Representatives from three stakeholders groups—agricultural retailers and advisors, farmer and commodity associations, and pesticide/biotech companies—completed an online survey consisting of pesticide resistance questions adapted from recent Iowa Farm and Rural Life Poll farmer surveys.
2. Nearly all stakeholder representatives who contributed to the meeting planning are concerned about pesticide resistance.
3. They are also concerned about the impact of pesticides on beneficial organisms.
4. They believe that farmers' actions play a major role in the evolution of resistance.
5. They understand that farmers look first to agricultural retailers for information to help them make pest management decisions.
6. They believe that multiple stakeholders, including farmers, private firms, and public universities and agencies, bear responsibility for resistance management.
7. The survey results show that stakeholder group representatives (and farmers) have similar perspectives on pesticide resistance and management, suggesting that there is much common ground on which to build coordinated approaches to resistance management.

Reference publications:

1. Farmer Perspectives on Pesticide Resistance (PM3070)
2. National Academies report: Impact of Genetically Engineered Crops on Farm Sustainability in the United States

Online resources:

1. Iowa Farm and Rural Life Poll
2. Twitter: @IowaFarmPoll

Background

As pesticide resistance become more prevalent in Iowa, it is increasingly recognized that actions must be taken to improve resistance management. Resistance management is a complex process that requires cooperation between multiple stakeholders in the agricultural sector. To facilitate the development of effective resistance management strategies, Iowa State University (ISU) and the Iowa Department of Agriculture and Land Stewardship (IDALS) invited a number of stakeholder groups to convene for a resistance management workshop.

To prepare for the workshop, ISU conducted teleconference calls with representatives from three broad groups of stakeholders: agricultural retailers and advisors, farmer and commodity associations, and pesticide/biotech companies. The purpose of these calls was to discuss resistance management and each stakeholder group's perspectives on the issue.

Prior to each teleconference, stakeholder group representatives completed a short online survey. The survey was adapted from questions that had been posed to Iowa farmers in the 2012-2014 Iowa Farm and Rural Life Poll surveys. Thus, the survey was not a scientific, random sample survey, but rather a purposive survey of selected individuals from key stakeholder groups.

Overall, 20 representatives both completed the survey and participated in the calls. This short report presents the survey results to provide workshop participants with an understanding of key stakeholder group perspectives on resistance management issues. It is hoped that a shared understanding of areas of common ground and divergence will help lay a foundation for productive dialog during the workshop.

Attitudes and Concerns about Pesticide Resistance

Ten survey items assessed stakeholder perspectives on several aspects of resistance evolution and management. A short introductory text, "Over the past several years, a number of weeds, plant pathogens, and insect pests have evolved resistance to pesticides that were previously effective. Please provide your opinions on the following questions about resistant weeds, pathogens, and insect pests," was provided. Participants were asked to rate their agreement with each item on five-point scale from strongly disagree to strongly agree.

Results show that nearly all participants were concerned about pesticide resistance (table 1). This was the case for both herbicide-resistant weeds and Bt-resistant insect pests. Two items asked participants to rate their agreement with statements positing that pesticide resistance is "not a concern because new technologies will be developed to manage them." Nearly all respondents disagreed with the statements, indicating that faith in potential new technologies is not sufficient to temper concern about resistance. In addition, most were concerned about the impact of pesticides on beneficial organisms.

Table 1. Perspectives on pest resistance management, part 1

	Strongly Disagree	**Disagree**	**Uncertain**	**Agree**	**Strongly Agree**
	-Percentage-				
I am concerned that herbicide-resistant weeds will become a problem in Iowa	0	0	5	40	55
I am concerned that Bt-resistant insects will become a problem in Iowa	0	5	5	55	35
Herbicide-resistant weeds are not a major concern because new technologies will be developed to manage them	65	30	5	0	0
Bt-resistant insect pests are not a major concern because new technologies will be developed to manage them	45	45	5	5	0
I am concerned about the impact of pesticides on beneficial insects, microorganisms, etc.	5	5	15	65	10

Nearly all participants agreed that the way farmers manage pests impacts the rate at which resistances evolve (table 2). Most agreed that pest management seems like a “never-ending treadmill,” and that when new pest management technologies are introduced, it is only a matter of time before resistance evolves.

Table 2. Perspectives on pest resistance management, part 2

	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
	-Percentage-				
The way that farmers use pest management technologies does not really impact the rate at which resistance evolves	80	15	5	0	0
Poor management by a few farmers leads to premature evolution of resistant pests	0	25	5	50	20
I feel like pest (weed, disease, and insect) management is a never-ending technology treadmill	0	20	15	55	10
When new pest management technologies are introduced, it is only a matter of time before pests evolve resistance	0	25	10	60	5

Another question set focused on the sources of information that farmers depend on to assist them with pest management decisions. The 2014 Iowa Farm and Rural Life Poll showed that nearly all farmers go to private sector sources first for such information, and the most important source by far is fertilizer and agricultural chemical dealers. Stakeholder responses mirrored the farmer results (table 3).

Table 3. Sources of information that farmers would go to first for information

	Fertilizer or Ag Chemical Dealer	Seed Dealer	USDA/NRCS/SWCD Service Center	Private Crop Consultant	Iowa State University Extension	A Commodity Association	A Farmer Organization	Other/NA
	-Percentage-							
Insect pest management	65	20	0	10	0	0	0	5
Weed management	85	5	0	5	0	0	0	5

Responsibility for Resistance Management

A third question set asked teleconference participants to rate the degree to which various stakeholders in the agricultural community bear responsibility for resistance management. The introductory text, “Many people and entities can play a role in helping to prevent weeds, pathogens, and insect pests from becoming resistant to pesticides. In your opinion, how much responsibility do each of the following bear in efforts to reduce the evolution of resistance?”, was followed by a list of stakeholders. Participants were asked to rate stakeholder level of responsibility on a four-point scale ranging from “no responsibility” to “much responsibility.”

Farmers were rated as most responsible, followed closely by crop advisors and agricultural retailers (table 4). Pesticide manufacturers and seed companies were also seen to bear substantial responsibility. University scientists, land management firms, and commercial pesticide applicators were viewed as less responsible. Commodity groups and government agencies were rated lowest on the responsibility scale.

Table 4. Who bears responsibility for resistance management?

	No Responsibility	Little Responsibility	Some Responsibility	Much Responsibility
	-Percentage-			
Farmers	0	5	5	90
Crop advisors	0	0	20	80
Agricultural retailers	0	0	25	75
Pesticide manufacturers	0	0	30	70
Seed companies	0	5	35	60
University scientists	0	10	35	55
Land management firms	0	15	45	40
Commercial pesticide applicators	5	20	35	40
Commodity groups	0	30	55	15
Government (e.g., EPA, USDA)	5	45	30	20

Concluding Points

The results of this survey of stakeholder group representatives provides initial insight into where key members of the agricultural community stand on pesticide resistance and resistance management. Nearly all surveyed stakeholder representatives were concerned about pesticide resistance. They were also concerned about the impact of pesticides on beneficial organisms. All believed that farmers' actions play a major role in the evolution of resistance. All stakeholders understood that farmers look first to agricultural retailers for information to help them make pest management decisions. They all believed that multiple stakeholders, including farmers, private firms, and public universities and agencies, bear responsibility for resistance management. Overall, the survey results show that stakeholder group representatives have similar perspectives on pesticide resistance and management. Their responses also largely echo results from Iowa farmers. Taken together, the data suggest that there is much common ground on which to build coordinated approaches to resistance management.

Implications on evolved herbicide resistance in Iowa

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Key points:

- All aspects of crop production create selective pressure(s) that influence the weed community
- Continuous cropping systems result in the greatest selection pressure and the quickest change within the weed community
- Herbicides exert the most specific pressure and thus causes faster evolution within the weed community and weeds inevitably adapt to herbicides
- The evolution of herbicide resistance is not a herbicide problem, a trait problem but rather a management problem
- The extent of herbicide-resistant weeds in Iowa highlights the mobility of weed populations and the socio-economic changes in Iowa agriculture – fewer farmers, larger farms with considerable distances between fields and time constraints that hamper the adoption of fundamental weed management tactics (i.e., scouting)

Reference publications:

Baldwin, F. L. and P. W. Santelmann (1980). "Weed science in integrated pest management." BioScience 30(10): 675-678.

Norsworthy, J. K. (2013). Best management practices and recommendations. Weed Science Society of America Abstracts, Baltimore, MD, Weed Science Society of America.

Online resources:

- www.weeds.iastate.edu
- www.weedscience.org
- www.weedscience.net

Herbicide-resistant weeds in Iowa

Approximately 900 waterhemp (*Amaranthus tuberculatus*), horseweed/marestail (*Conyza canadensis*), and giant ragweed (*Ambrosia trifida*) weed populations have been collected in 2011, 2012 and 2013 and are currently being screened for herbicide resistances in a project supported by the Iowa Soybean Association. An important consideration for the 2011 and 2012 collections was that the field sites were not selected randomly and in fact likely represent a worst case scenario with regard to weed populations with evolved resistance to herbicides. Thus, the lack of random selection precluded any ability to make an assessment about the relative frequency of herbicide resistance in Iowa soybean fields. In order to resolve this problem, 2013 weed population were collected from fields selected randomly across Iowa based on reported CRD soybean acres (Figure 1).

The key factors for fields to be included in the 2011 and 2012 weed population collections were whether or not the fields 1) were planted to soybean and 2) if there were weeds visible above the soybean canopy. If these criteria were fulfilled, the inclusionary probability of 1 was assigned to the field and the weed population was collected and assessed for evolved herbicide resistance(s).

Fields in 2011 and 2012 that did not meet these criteria were assigned an inclusionary probability of 0 and were not included in the collections. Thus, a procedure was used in 2013 to estimate the percentage of all available Iowa soybean fields in 2011 and 2012 that were included in the weed population collections, relative to those fields with an inclusionary probability of 1 and from this statistic, an estimate of herbicide resistance for all soybean fields could be developed.

It was arbitrarily decided that the margin of error for the estimate of all soybean fields with herbicide resistance that was acceptable in these calculations was 5% which provided acceptable precision of herbicide resistance estimates but also accommodated logistical concerns; based on the statistical calculations, 400 fields should be visited in 2013 and the inclusionary probability determined. The Iowa State University GIS Laboratory provided the GPS field locations based on 2011 soybean planted acres information and selected 399 fields of 100 acres or larger randomly (Figure 1).

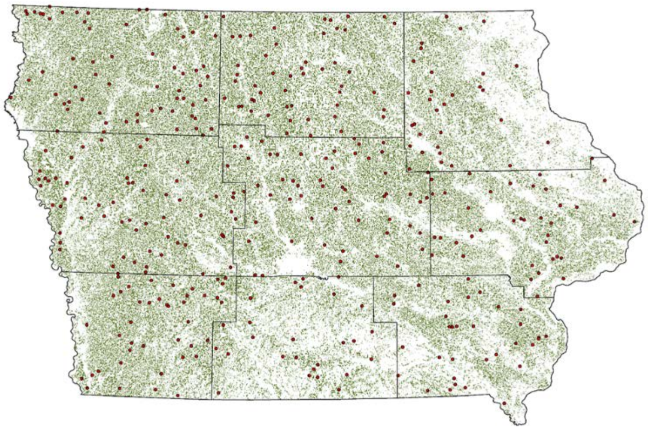

Figure 1. Randomly selected field locations for the 2013 weed population collections. Project supported by the Iowa Soybean Association.

Approximately 98% of the 399 randomly selected fields were visited in 2013; 69% of the fields visited were planted to soybeans and 56% of these fields had weeds visible above the soybean canopy and were sampled for assessment of herbicide resistance(s). The percent of fields with weeds visible above the soybean canopy was used to estimate the overall herbicide resistance(s) in Iowa soybean fields based on the 2011 weed seed collections. Resistance was based on results from bioassays in which herbicides were applied postemergence to 3 to 4 inch waterhemp plants in the greenhouse.

The levels of herbicide resistance(s) detected in the 2011 waterhemp collections are surprisingly high (Table 1). Group 2 (imazethapyr) resistance was detected in 62% to 77% of the populations. Group 5 (atrazine) resistance was 44% to 51%, while Group 9 (glyphosate) resistance was 42% to 48% of the waterhemp populations. Group 14 (lactofen) resistance was 10% to 12% and Group 27 (mesotrione) resistance was estimated to be 24% to 27% of the waterhemp populations (Table 1).

Table 1. Estimated resistances based on 2011 waterhemp population. Herbicide rate reflects the existing label*

Herbicide Group	Herbicide rate*	Estimated herbicide resistance (95% Confidence limit)
Group 2	1X	62% to 77%
Group 5	1X	44% to 51%
Group 9	1X	42% to 48%
Group 14	1X	10% to 12%
Group 27	1X	24% to 27%

Based on the statistical assessment of the inclusionary probability at the 95% confidence limit, Iowa fields are likely to have "weeds visible above the canopy of soybean fields" 65% to 74% of the time and thus could be selected for an assessment of herbicide resistance(s) (Philip Dixon, personal communication). It could be argued that this range of "weeds visible above the soybean canopy" might be low; considering that growers may have employed more diverse and thus more effective weed management practices in 2013 due to previously observed "weeds visible above the soybean canopy" which could be putatively herbicide resistant. These fields with effective weed management would not be included in the survey based on the failure to meet the inclusionary probability of 1.

All of the 2011 waterhemp populations were evaluated for evolved resistance to five herbicide groups and the assessments demonstrated that multiple herbicide resistance was found in 88% of the populations evaluated which provides an estimated frequency of herbicide resistance of 56% to 65% of the Iowa soybean fields that likely have waterhemp populations with multiple herbicide resistances based on the statistic generated from the randomly selected 2013 fields (Table2). Only 2% of the 2011 waterhemp populations evaluated did not demonstrate any herbicide resistance (Table 2).

Table 2. Estimated multiple resistances (herbicide groups 2, 5, 9, 14, and 27) based on 2011 waterhemp population collections

Herbicide resistance(s)	Percentage of populations	Estimated herbicide resistance frequency (95% Confidence limit)
None	2	1% to 2%
1 way	9	6% to 7%
2 way	26	17% to 19%
3 way	33	23% to 24%
4 way	19	12% to 14%
5 way	10	6% to 7%
Total multiple	88	57% to 65%

The most common multiple herbicide resistance was 3-way and was estimated to be 23% to 24% of Iowa soybean fields having waterhemp populations; the most common 3-way herbicide resistance is for Group 2, 5, and 9 herbicides. Five-way herbicide resistance was estimated to be in 6% to 7% of the waterhemp populations.

Conclusions

Given the tenets of evolutionary adaptation and the significant selection pressures imparted by agriculture on pest complexes, it should be no surprise that pest management is essentially a moving target. Importantly, evolved herbicide resistance within a species will remain in the species even if management tactics (e.g., a different herbicide) change. Note that multiple herbicide resistances were detected in 88% of the 2011 waterhemp samples screened for resistance to five herbicide groups. In many of these waterhemp populations, the selection from Group 2 herbicides has not been imposed for a number of years, and the only tactic used for management was glyphosate.

The keys to addressing issues with pest adaptation are the reverse of what caused the evolutionary change; simple and recurrent tactics select quickly for traits in pests that overcome the tactic. Thus, increasing the diversity of tactics is essential. For example, the same weed management practices that were developed and recommended more than thirty years ago are now being revisited (Baldwin and Santelmann 1980; Norsworthy 2013). Unless a more diverse crop production system is developed, weed evolution to herbicides will increase at an increasing rate.

It is important to recognize that herbicide resistance is not the problem of individual farmers but rather a community problem. Importantly, other weed problems are also examples of how agricultural demographics are impacting pest management. Consider that Palmer amaranth (*Amaranthus palmeri*) has been discovered in Iowa and is a result of the high mobility of weed populations. Given that farms are larger, farmers may now manage fields that are distant from one another (and consequently move equipment between widely dispersed fields) combined with the prevalence of custom farming operations (i.e., harvesting), weed populations are more mobile than ever before. Thus, when an individual within an area has a herbicide-resistant weed problem, it is highly probable that the issue will spread quickly to adjacent fields and become a community problem. Fundamental tactics based on integrated pest/weed management should become a focus of community-based weed management. Currently, Iowa State University Weed Science has a federal grant to investigate aspects of farmer decisions and what can be done to modify behaviors such that weed management becomes more community oriented and involves more diverse tactics. These tactics include but are not limited to scouting and monitoring, sanitation, cultural and mechanical practices, developing longer term weed management programs and lessening the focus on herbicides as the primary approach to weed control. Ideally, efforts to manage herbicide-resistant weeds, and weeds in general, should be coordinated within communities and include not just farmers but land managers, land owners, commercial input providers and private pesticide applicators.

Herbicide Group Herbicide Group

Resistance to Bt Corn by Western Corn Rootworm

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Key Points:

- Western corn rootworm resistance to Cry3Bb1 corn and mCry3A corn is present in Iowa.
- Cross-resistance has been identified between Cry3Bb1 corn and mCry3A corn.
- Laboratory studies indicate that three generations of selection is sufficient to generate Bt-resistant western corn rootworm.
- Field populations of western corn rootworm with Bt resistance are typically associated with a history of continuous corn cultivation and continuous use of the same Bt trait.
- Fields with Bt-resistant western corn rootworm will typically display high levels of pest survival and high levels of feeding injury to Bt corn in subsequent growing seasons.
- Rotating among a diversity of management tactics over multiple growing seasons and using non-Bt refuges will help to delay the evolution of Bt resistance.

Reference Publications:

Cullen, E. M., Gray, M. E., Gassmann, A. J. and Hibbard, B. E. 2013. Resistance to Bt corn by western corn rootworm (Coleoptera: Chrysomelidae) in the U.S. Corn Belt. Journal of Integrated Pest Management 4(3): doi: dx.doi.org/10.1603/IPM13012

Dun, Z, Mitchell, P. D., and Agosti M. 2010. Estimating *Diabrotica virgifera virgifera* damage functions with field trial data: applying an unbalanced nested error component model. Journal of Applied Entomology 134:409-419.

Gassmann, A. J., Petzold-Maxwell, J. L., Clifton, E. H., Dunbar, M. W., Hoffmann, A. M., Ingber, D. A. and Keweshan, R. S. 2014. Field-evolved resistance by western corn rootworm to multiple *Bacillus thuringiensis* toxins in transgenic maize. Proceedings of the National Academy of Sciences USA 111:5141-5146

Gassmann, A. J. 2012. Field-evolved resistance to Bt maize by western corn rootworm: predictions from the laboratory and effects in the field. Journal of Invertebrate Pathology 110:287-293

Gassmann, A. J., Petzold-Maxwell, J. L., Keweshan, R. S., and Dunbar, M. W. 2011. Field-evolved resistance to Bt maize by western corn rootworm. PLoS ONE 6(7): e22629. doi:10.1371/journal.pone.0022629

Gray, M. E., Sappington, T. W., Miller, N. J., Moeser. J., Bohn. M. O. 2009. Adaptation and invasiveness of western corn rootworm: intensifying research on a worsening pest. Annual Review of Entomology 54: 303-321.

Gould, F. 1998. Sustainability of transgenic insecticidal cultivars: integrating pest genetics and ecology. Annual Review of Entomology 43: 701-726

Meihls, L. N., Higdon, M. L., Siegfried, B. D., Miller, N. J., Sappington, T. W., Ellersieck, M. R. Spencer, T. A. and Hibbard, B. E. 2008. Increased survival of western corn rootworm on transgenic corn within three generations of on-plant greenhouse selection. Proceedings of the National Academy of Sciences USA 105: 19177-19182.

Summary:

The western corn rootworm is among the most serious pests of corn in North America (Gray et al. 2009). Corn producing insecticidal toxins derived from the bacterium *Bacillus thuringiensis* (Bt) was commercialized for management of western corn rootworm in 2003. The first commercially available Bt hybrids produced Bt toxin Cry3Bb1. Beginning in 2009, severe feeding injury to single-trait Cry3Bb1 corn in Iowa was observed, and subsequent bioassays revealed that this feeding injury was associated with Bt resistance (Gassmann et al. 2011). Fields with severe feeding injury contained Bt corn with greater than one node of root injury, which translates to an average yield reduction of 17% (Dun 2010). Fields with Cry3Bb1-resistant western corn rootworm had a history of continuous corn cultivation and three or more years in which Cry3Bb1 corn had been grown. These observations parallel laboratory experiments that were able to generate Cry3Bb1-resistant strains of western corn rootworm following three generations of selection (Meihls et al. 2009). In 2011, cases of severe feeding injury by western corn rootworm to Bt corn in Iowa expanded to include mCry3A corn in addition to Cry3Bb1 corn. Subsequent bioassays found resistance to both mCry3A corn and Cry3Bb1 corn, and cross-resistance between these Bt toxins (Gassmann et al. 2014 and Fig. 1). Since 2009, fields distributed across several counties in Iowa have been found with greater than one node of feeding injury to either mCry3A corn or Cry3Bb1 corn (Fig. 2). Studies conducted in fields identified as harboring Cry3Bb1-resistant populations of western corn rootworm have found high levels of survival on Cry3Bb1 corn and high levels of feeding injury to Cry3Bb1 corn (Gassmann 2012).

Adult western corn rootworm exhibit limited dispersal, travelling less than 40 meters per day, however, longer distance dispersal also occurs. This limited adult dispersal facilitates resistance evolution if a farmer uses the same management tactic continuously, because adult female rootworm tend to oviposit eggs into the same field from which they emerged, completing their entire life-cycle in a single field. Initially, resistance is expected to exist in a patchwork among fields, occurring in fields where the same management practices have been used repeatedly (Gassmann et al. 2011). Over time, however, the movement of Bt-resistant adults within the landscape can lead to the presence of Bt-resistant western corn rootworm, and substantial feeding injury to Bt corn, in fields without a history of continuous use of the same Bt trait and continuous corn cultivation (Gassmann et al. 2014). As a result, although an individual farmer may bear the immediate costs when a population of Bt-resistant western corn rootworm evolves, over time neighboring farmers also may experience costs associated with the presence of Bt-resistant rootworm.

To delay the evolution of Bt resistance, farmers should plant non-Bt refuges and apply Integrated Pest Management by rotating among a variety of tactics for management of western corn rootworm (Gould 1998; Cullen 2013). Integrated Pest Management for western corn rootworm includes rotating fields out of corn production to alternative crops such as soybean. Because rootworm larvae cannot survive on soybean roots, crop rotation breaks the lifecycle of rootworm and is highly effective at reducing pest abundance. Additionally, farmers should consider alternating between corn hybrids with rootworm active Bt traits and non-rootworm Bt corn with a soil-applied insecticide. Because of resistance to Cry3Bb1 corn and mCry3A corn in Iowa, it is advisable for farmers to use corn pyramided with Cry34/35Ab1 and either Cry3Bb1 or mCry3A. By applying a diversity of management tactics, selection for resistance to any single tactic will be reduced and the evolution of resistance delayed.

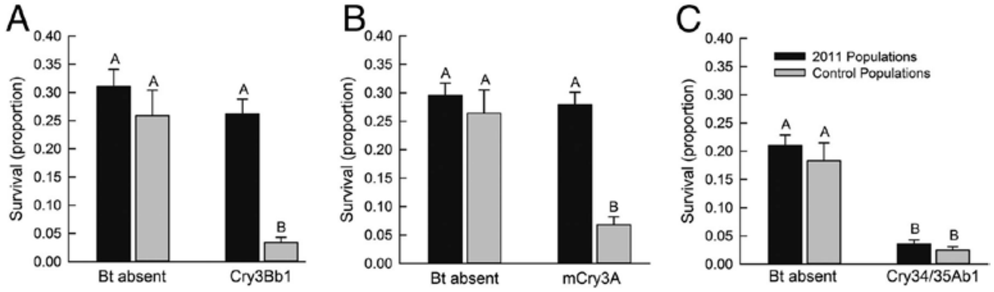

Figure 1. Survival of western corn rootworm larvae on (*A*) Cry3Bb1 corn, (*B*) mCry3A corn, and (*C*) Cry34/35Ab1 corn. Control populations were never exposed to Bt toxin, and 2011 populations were from fields in Iowa with greater than one node of injury to either Cry3Bb1 corn or mCry3A corn. Bar heights are sample means and error bars are the standard error of the mean. Letters indicate pairwise differences within each graph. Figure from Gassmann et al. (2014).

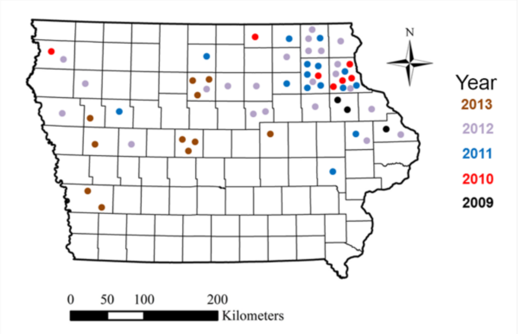

Figure 2. Distribution of fields with greater than one node of feeding injury to either mCry3A corn or Cry3Bb1 corn from western corn rootworm. On average, one node of feeding injury reduces yield by 17%. Colors indicate the year in which the feeding injury was observed with locations accurate to the level of an individual county.

The Risk of Fungicide Resistance for Corn and Soybean Production in Iowa

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Key points:
1. No confirmed reports of fungicide resistance for corn and soybean pathogens in Iowa to date
2. Fungicide-resistant pathogens have been identified for some soybean pathogens in neighboring states (Illinois and Missouri).
3. Fungicide "failures" often may be applicator error or poorly timed applications.
4. Fungicide resistance management strategies include managing diseases using other strategies (e.g. resistant hybrids) and applying fungicides only when the risk of disease is elevated.
5. Premix fungicides have a lower risk for fungicide resistance compared to single mode of action fungicides.

Reference publications:
1. Fungicides for Field Crops (CSI 009)
2. Corn Diseases (CSI 005)
3. Soybean Diseases (CSI 004)
4. Corn Field Guide (CSI 001)
5. Soybean Field Guide (CSI 010)
6. Wise and Mueller (2011), www.apsnet.org/publications/apsnetfeatures/Pages/fungicide.aspx

Online resources:
1. ICMNews
2. Twitter: @alisonrISU; @dsmuelle

Introduction

Fungicides may be used to manage various diseases of corn and soybean caused by fungal pathogens. There are several important factors to consider before applying fungicides to reduce fungicide resistance development.

Fungicide resistance development

Strains of a fungus that are resistant to fungicide can be chosen for when selective pressure is placed on a fungal population. Fungicides that have a single site of action typically are more at risk for selection of resistance than those that have multisite activity. Fungi that are more prone to developing resistance to fungicides include those that regularly undergo sexual reproduction since there is likely to be greater genetic variability in the population. Furthermore, fungal pathogens that produce spores continually throughout the growing season (polycyclic) are more likely to develop resistance to a fungicide, in part because of the number of spores produced within a season. Another factor is the genetic makeup of the pathogen; some pathogens, including the soybean rust and several common pathogens of foliar diseases of corn, have a genetic makeup that prevents a common mutation that leads to a high level of resistance to strobilurins. While this does not prevent these pathogens from selecting other mutations, this may negatively affect the development of fungicide resistance. Once a fungicide-resistant pathogen has been selected, the pathogen's ability to move from field-to-field greatly depends on the pathogen. Remember pathogens can be dispersed by wind or water. Thus, there is a possibility of these resistant pathogens moving out of fields, but to what extent has not been studied.

Fungicide-resistant strains of a couple of soybean pathogens have been discovered in the U.S. In the Midwest, there are strains of the causal organism of frogeye leaf spot, *Cercospora sojina*, that are resistant to strobilurin fungicides. No corn pathogens with reduced sensitivity to fungicides have been found to date anywhere in the U.S.

Disease matters

University and on-farm research continues to show that a greater yield response to fungicides occurs when disease is present (Figure 1). Over the past several years, there have been outbreaks of foliar diseases on either corn or soybean (Table 2). Since some of these diseases are not fungal (e.g., Goss's wilt on corn or soybean vein necrosis virus on soybean), or may not be managed by foliar fungicides (e.g., sudden death syndrome of soybeans), an important first step in managing foliar diseases is proper identification. ISU has several resources available for helping to identify common corn and soybean foliar diseases.

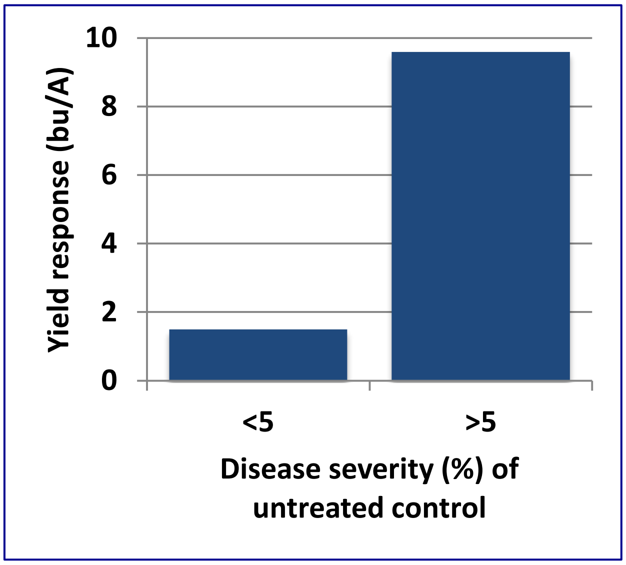

Figure 1. Corn yield response to strobilurin fungicides applied between V15 and R3 growth stages from 2008 to 2010. Number of observations for <5 = 347 and >5 = 266. (Wise and Mueller, 2011)

Table 2. Common diseases in corn and soybean fields in Iowa over the past 6 years

Year	Prevalent corn diseases *	Prevalent soybean diseases *
2009	**Eyespot**, **Gray leaf spot**	Sudden death syndrome, **brown spot**
2010	Goss's wilt	**White mold**, sudden death syndrome
2011	Goss's wilt	**Frogeye leaf spot**
2012	**Southern rust**	None
2013	**Northern corn leaf blight**	Soybean vein necrosis virus, tobacco streak virus
2014	**Northern corn leaf blight,** Goss's wilt	Sudden death syndrome, stem canker, **brown spot**

***bold** = diseases that can be managed with foliar fungicides

Risk of disease

Unfortunately there are not well-developed models for forecasting when outbreaks of diseases will occur. Because of the complexity behind disease epidemics, predicting when diseases will be a problem will always be a challenge. Here are some simple steps to help determine fields that are higher risk for disease.

- Plant pathology in the news – check your favorite crops newsletter, follow plant pathologists on Twitter, or talk to your local agronomist to find out what diseases are showing up near you.
- Check the weather – know how much rainfall has fallen since planting and pay attention to the forecasted weather. Risk for fungal diseases is greater when it is rainy.
- Variety/hybrid genetics – know the susceptibility of your variety/hybrid to common foliar diseases.
- Previous crop, amount of surface residue, other production practices (e.g., irrigation) can affect disease development.

Consider all of the above together. If fungal diseases are prevalent near you, you have planted a susceptible variety/hybrid, and it is rainy, a foliar fungicide application may be needed.

Fungicide resistance management

Minimizing selection pressure is key to prolonging the effectiveness and lifespan of a fungicide. Plant resistant varieties/hybrids and use cultural practices to help manage diseases. Apply foliar fungicides to manage diseases only when warranted based on scouting and disease risk factors. Other considerations for fungicide resistance management include

(i) Properly identify the disease to determine if it can be managed by fungicide
(ii) Use fungicides early in disease development in response to predicted disease threat.
(iii) Avoid single applications of single site MOA fungicides or alternate fungicides from different FRAC groups to reduce the selection pressure being placed on fungal populations.
(iv) Know which fungicides to use for which diseases and know which pathogens are more prone to develop resistance.
(v) Scout fields and identify disease levels before and after fungicide applications to determine if fungicide resistance is a possibility.

Factors that determine the success or failure of a fungicide application

There are many factors that may affect the success of a fungicide application and should be considered before fungicide resistance is blamed. These include improper disease diagnosis, improper mixing of fungicides, sprayer not calibrated correctly, wrong rate of fungicide used, or fungicide application not made at the ideal timing. Furthermore, a fungicide may not be effective against the targeted disease. Do your homework on which fungicides work best for each disease.

Future needs

While we have a fairly good grasp on how fungicides can manage particular diseases, more research is needed to fully understand the risk of disease development, for example, how do fungicides differ in efficacy, what is the baseline sensitivity of common corn and soybean pathogens, how diverse is the pathogen, what mutations occur in the pathogen to reduce sensitivity to fungicides. These data will improve our understanding of the risk and management of fungicide resistance.

Glossary

Active ingredient (a.i.): the molecule that provides biological activity to control the fungus.

Adjuvants: compounds tank-mixed or included in pesticide formulations in order to improve pesticide coverage on the plant and/or penetration into leaf tissue. Also known as spreader-stickers and surfactants.

Baseline sensitivity: the amount of fungicide that is able to effectively control a fungal plant pathogen population that has never been exposed to the fungicide.

Biological fungicide (biofungicide): fungicide that is composed of living organisms or living organisms' metabolites.

Chemical group or chemical class: the name given to a group of chemicals that share a common biochemical mode of action, and may or may not have similar chemical structure.

Common name: a less technical name of the active ingredient (e.g., azoxystrobin).

Cross-resistance: a term used when a fungus becomes resistant to more than one fungicide within a FRAC code.

Contact fungicide: a fungicide that remains on the surface of the plant where it is applied but is not absorbed into plant tissue; these fungicides have no post-infection activity.

Early-infection activity: occurs when the active ingredient of a fungicide can penetrate the plant and stop the pathogen in plant tissues, usually most effective 24 to 72 hours after infection occurs, depending on the fungicide. This type of activity is sometimes referred to as "curative" or "kickback" activity. Most fungicides that have early-infection activity also have preventative activity and are most effective when applied before infection occurs.

FRAC code: FRAC stands for the Fungicide Resistance Action Committee, which is an organization developed to address the issue of fungicide resistance. This organization developed a code of numbers and letters that can be used to distinguish the different groups based on their target site of action. This code is known as the FRAC code.

Fungicide: a chemical agent that kills or inhibits the growth of fungi or fungal-like organisms.

Fungicide resistance: the reduction in sensitivity to a fungicide by an individual fungus. Fungicides with single-site modes of action are at relatively high risk for resistance development compared to those with multi-site modes of action.

Integrated Pest Management (IPM): using a combination of management strategies to prevent yield loss from pests.

Mode of action (MoA): The mode of action is how a fungicide kills or suppresses a fungus; that is, the specific biochemical pathway in the fungus that the fungicide interferes with.

Examples are damaging cell membranes, inactivating critical enzymes or proteins, or interfering with key processes such as energy production or respiration.

Monocyclic: pathogens that produce only one life cycle in a growing season.

Multi-site fungicide: fungicide that affects a number of different metabolic sites within the fungus.

Pathogen: organism that causes disease. Pathogens can refer to fungi, bacteria, viruses, and nematodes. A fungicide is only active on fungal pathogens.

Preventative activity: occurs when a fungicide is present on the plant as a protective barrier before the pathogen arrives or begins to develop, that is, the fungicide prevents infection from occurring (also referred to as a protective activity).

Polycyclic: pathogens having multiple life cycles in a growing season. Fungal pathogens with multiple life cycles are often referred to as having repeating spore stages.

Single-site fungicide: fungicide active against only one point or function in one of the metabolic pathways of a fungus or against a single critical enzyme or protein needed by the fungus. These fungicides tend to have systemic properties.

Selective pressure: the influence exerted by some factor (such as a fungicide) on natural selection to promote one group of organisms over another. In the case of fungicide resistance, fungicides impose selective pressure by killing susceptible fungi, thereby allowing fungicide-resistant fungi to survive and multiply.

Systemic fungicide: a fungicide that is absorbed into plant tissue and may offer some post-infection activity. Very few fungicides are truly systemic (i.e., move freely throughout the plant); however, some are *upwardly systemic* (i.e., move only upward in the plant through xylem tissue), and some are *locally systemic* (i.e., move into treated leaves and redistribute to some degree within the treated portion of the plant).

Target site: The specific step in a biochemical pathway and/or enzyme that a fungicide active ingredient interferes with.

Trade name: the patented name under which a product is commercially available (e.g., Quadris®). The active ingredient may be marketed under several different trade names.

Economics of Pest Management Decision-making
and Role of Resistance Management

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Key Points:

- Standard practice (SP) of using a single mode of pest control may be simple, flexible, convenient, and less costly in the short run. Long known that single mode of action pest control tends to increase likelihood of pest resistance development, e.g., glyphosate resistant (GR) corn and soybean plants and GR weeds; Bt corn plants and resistant Western corn rootworms; fungicide resistant Frogeye leaf spot pathogen in soybean.
- If farmers adopt resistance management practices (RMPs) in pest control, costs are immediate and certain, but many benefits of RMPs come later and are uncertain.
- What are the direct costs and benefits of adopting resistance management RMPs in corn and soybean production?
- If pests were immobile between farms, farmer would independently bear costs and capture benefits of pest control decisions. Many weed, insect, and fungus pests in corn and soybean production are mobile between farms and therefore benefits and costs of pest management are influenced by neighbors' behaviors. Thus, increased resistance management costs by a farmer may benefit their neighbor, while a neighbor's SP may impose spillover costs on a farmer already employing RMPs.
- What resistance management options are available to address "common" or shared mobile pest problems?

References:

- Edwards, Jordan, Owen, Dixon, Young, Wilson, Weller, and Shaw. 2014. Benchmark study on glyphosate-resistance crop systems in the United States. Economics of herbicide resistance management practices in a 5 year field scale study. *Pest Management Science*, www.wileyonlinelibrary.com.
- Hurley and Frisvold. 2014. Knocking Down Economic Barriers to Herbicide Resistance Management. Presentation at North Central Weed Science Society Annual Meeting, December 4, 2014.
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Economics Discussion:

Most input management decisions are relatively short run in nature, recurring annually. The farmer decides to produce a crop with the least cost combination of variable inputs, including pest control, to produce a given level of output. Over time, some pests may become resistant to a specific pesticide input (i.e., a single mode of action), especially with widespread use and greater frequency of application (e.g., glyphosate, Bt corn).

Initially, each pesticide is endowed with a stock of efficacy (i.e., killing potency or target pest control power) that is gradually depleted with the level and frequency of use. In the longer run, the farmer may face increasing pest control costs as efficacy is depleted and has to shift to crop rotations, supplemental tillage, different modes of action, residual pesticides, and related practices. If RMPs are adopted early in the process, the long run profitability of pest control may be greater than if more extreme adjustments are needed as efficacy is depleted. Unfortunately, the rate of resistance development is highly uncertain and with rapid, widespread adoption of new technologies and with variable implementation of resistance management practices.

What do resistance management programs cost the farmer?

Not all costs are easily monetized, especially when it comes to simplicity, convenience, and flexibility in larger-scale farming operations. At the same time, adoption of modern knowledge-based management systems may reduce the cost of monitoring resistance or increase returns to adopting RMPs. Costs are up front and benefits are typically more distant in the future and uncertain. The long-run distribution of costs and benefits from RMPs and the uncertainty surrounding resistance may discourage adoption. Further, costs are incurred by the individual farmer but benefits may spillover to neighbors if the pest is mobile. Alternatively, if the neighbor does not practice resistance management, then the farmer may end up sharing the resistance problem created by nonparticipating neighbors. Finally, in the 2014 Farm Bill, crop insurance subsidies increase relative to conservation and commodity program payments. Increasing expenditures on crop insurance premium subsidies provide incentive for increased adoption of this risk management tool. Because the insurance program provides premium discounts for triple stack corn and related rootworm control to remain eligible for indemnity payments, it may provide a disincentive for adopting corn RMPs. Further, conservation and commodity programs provide incentives for adoption of conservation practices and include environmental compliance sanctions as a condition of participation.

If farmers use recommended resistance management practices, do they provide improved yields, net returns, and increased profitability over the longer-run?

Recent economic studies of the resistance management benefits of adopting RMPs are limited, especially in the context of actual field evaluations. Two studies do provide some evidence on RMP use in glyphosate weed management. The Benchmark study of glyphosate resistance,[1] a 2006-10 study of 156 growers in 6 states (including Iowa) compared control costs, yields, and net returns between SP and RMPs. The RMPs were limited to alternative residual herbicides and a post tank-mix application that contain multiple modes of action. RMP weed control costs for GR corn and soybean were slightly higher than with SP of glyphosate only, but there was not a significant statistical difference in net returns over the six years. This field study also considered conservation till, minimum till, no till, and crop rotations, and found no significant difference in net returns between RMPs and SP. The RMP approach may have cost slightly more per year but taking weed control costs and yield differences into account, net returns were not significantly different between the two approaches. An earlier study on weed

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[1] Edwards, Jordan, Owen Dixon, Young, Wilson, Weller, Shaw (2014).

management costs, RMPs, and glyphosate,[2] concluded that the use of residual pesticides on soybean and not rotating another GR crop (like soybean or corn) on previously GR corn acreage were the most cost-effective weed management options.

If the pest is highly mobile (i.e., insects and weed seeds move between farms by flight, wind, water, wildlife, and transport on farm equipment) in a common area, then the pest becomes a common property problem for farmers in the area. If a farmer decides to manage herbicide use to protect herbicide efficacy and manage weed resistance, it may do little good if weed seed is mobile and a neighbor does not act to protect herbicide efficacy. This is the dilemma that farmers face with weed resistance to glyphosate and insect resistance to Bt PIPs. Without an option to manage common property pesticide efficacy, free-riders on common pest problem/property will deplete efficacy for everyone. Managing common pest problem through alternative approaches, including a community-based system, have been proposed.

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[2] Hurley, Mitchell, and Frisvold (2009).