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Relevance of Traditional Integrated Pest Management (IPM) Strategies for Commercial Corn Producers in a Transgenic Agroecosystem: A Bygone Era?

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ABSTRACT: The use of transgenic *Bt* maize hybrids continues to increase significantly across the Corn Belt of the United States. In 2009, 59% of all maize planted in Illinois was characterized as a "stacked" gene variety. This is a 40% increase since 2006. Stacked hybrids typically express one Cry protein for corn rootworm control and one Cry protein for control of several lepidopteran pests; they also feature herbicide tolerance (to either glyphosate or glufosinate). Slightly more than 50 years has passed since Vernon Stern and his University of California entomology colleagues published (1959) their seminal paper on the integrated control concept, laying the foundation for modern pest management (IPM) programs. To assess the relevance of traditional IPM concepts within a transgenic agroecosystem, commercial maize producers were surveyed at a series of meetings in 2009 and 2010 regarding their perceptions on their use of *Bt* hybrids and resistance management. Special attention was devoted to two insect pests of corn, the European corn borer and the western corn rootworm. A high percentage of producers who participated in these meetings planted *Bt* hybrids in 2008 and 2009, 97 and 96.7%, respectively. Refuge compliance in 2008 and 2009, as mandated by the U.S. Environmental Protection Agency (EPA), was 82 and 75.7%, respectively, for those producers surveyed. A large majority of producers (79 and 73.3% in 2009 and 2010, respectively) revealed that they would, or had, used a *Bt* hybrid for corn rootworm (*Diabrotica virgifera virgifera* LeConte) or European corn borer (*Ostrinia nubilalis* Hübner) control even when anticipated densities were low. Currently, the EPA is evaluating the long-term use of seed blends (*Bt* and non-*Bt*) as a resistance management strategy. In 2010, a large percentage of producers, 80.4%, indicated they would be willing to use this approach. The current lack of integration of management tactics for insect pests of maize in the U.S. Corn Belt, due primarily to the escalating use of transgenic *Bt* hybrids, may eventually result in resistance evolution and/or other unforeseen consequences.

KEYWORDS: transgenic, *Bt* maize hybrids, integrated pest management (IPM), corn rootworms

INTRODUCTION

The manner in which several key insect pests are controlled in commercial maize fields of the Midwestern U.S. Corn Belt began to fundamentally shift in 1996 when Mycogen Seeds and Novartis Seeds introduced the first *Bt* (*Bacillus thuringiensis*) hybrids. These transgenic hybrids were primarily targeted at the European corn borer (*Ostrinia nubilalis* Hübner), a perennial economic pest of maize.[1] European corn borer larvae that fed on *Bt* maize hybrids (Event 176) were exposed to the Cry1Ab toxin in green plant tissue and pollen and to a lesser extent in silk and kernels.[2,3] Freshly hatched European corn borer larvae that feed on maize tissue expressing the Cry1Ab protein at sufficiently high concentrations are killed due to binding of the protein to the lining of the midgut, resulting in perforations, eventual paralysis of this tissue, and bacterial septicemia. The mode of action of *Bt* endotoxins has been thoroughly reviewed by Gill et al.[4] and Whalon and Wingerd.[5] In 2003, *Bt* maize hybrids were commercialized for corn rootworm (*Diabrotica* spp.) larval control by Monsanto Co.[6] The primary target insect for these transgenic hybrids was the western corn rootworm (*Diabrotica virgifera virgifera* LeConte). The western corn rootworm is arguably the most significant economic insect pest of maize in North America and has become a management challenge in many European countries since the early 1990s.[7] Those hybrids designed to protect maize from corn rootworm larval injury expressed the Cry3Bb1 (Event MON863) protein, a δ-endotoxin, in the root tissue of plants at concentrations most effective against newly hatched larvae; however, Siegfried et al.[8] characterized western corn rootworms as "not extremely sensitive" to this protein. In 2005, another event (Event MON88017) was registered for use in the United States that resulted in the expression of a modified Cry3Bb1 protein in maize hybrids that featured an enhanced promoter.[9] Maize hybrids (Event MON88017) express the Cry3Bb1 protein in above- and below-ground plant tissues with overall quantities of this protein estimated to be approximately 905 g/ha.[9] In recent years, the use of so-called "stacked" transgenic hybrids has escalated significantly across maize-producing regions of the United States.[10]. Stacked maize hybrids typically express one Cry protein for corn rootworm control and one Cry protein for control of several lepidopteran pests and also feature herbicide tolerance (either to glyphosate or to glufosinate). In 2009, 59% of all maize planted in Illinois was characterized by Fernandez-Cornejo[10] as a stacked gene variety. This is a 40% increase since 2006. The use of genetically

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engineered soybean varieties with herbicide tolerance reached 90% of all soybeans planted in Illinois during 2009.[10] Producers have made a striking and fundamental shift toward the use of transgenic crops to control pests within maize and soybean production fields over the past decade.

In 2010, two new developments occurred that will further alter the manner in which producers control insect pests of maize. The U.S. Environmental Protection Agency (EPA), through a cross-licensing agreement between Monsanto Co. and DowAgroSciences LLC, approved the commercialization of SmartStax maize hybrids.[11] These "pyramided" hybrids express several Cry proteins for control of corn rootworms (Cry34/35Ab1, Event DAS-59122-7; Cry3Bb1, Event MON88017) and some lepidopteran pests (Cry1F, Event TC1507; Cry1A.105+ Cry2Ab2, Event MON89034) as well as provide herbicide tolerance to both glyphosate and glufosinate. Because several Cry proteins are expressed simultaneously, with different binding sites, against corn rootworms and the lepidopteran complex, the EPA agreed to reduce the structured refuge (non-*Bt* maize) size for producers who plant these hybrids from the current 20% requirement (for all other transgenic *Bt* maize hybrids) to 5%. A refuge is used to ensure the production and survival of susceptible insects in an attempt to prevent or slow the evolution of a resistant insect strain within producers' fields.[12] The other development, in 2010, included the EPA's approval[13] of a seed mixture (*Bt* seed and non-*Bt* seed) approach to *Bt* resistance management, the so-called "refuge-in-a-bag", for those producers who plant OptimumAcreMax1 Pioneer maize hybrids [seed blend of 90% Herculex Xtra (Cry1F + Cry34/35Ab1) and 10% Herculex 1 (Cry1F)]. This refuge strategy is designed for corn rootworms. Within the past 14 years, producers have transitioned from a more traditional integrated pest management (IPM) paradigm (scouting, use of economic thresholds, and rescue treatments) to that of a less integrated and more insurance-based approach to insect management within the commercial maize production system on the North Central United States.

In 1959, a far-reaching paper was published by University of California entomologists[14] that described an integrated approach to the management of insect pests. The paper was written in response to the indiscriminate use of organic insecticides such as chlorinated hydrocarbons. The authors identified several emerging challenges that had resulted due to overuse of insecticides in several cropping systems: (1) insecticide resistance; (2) outbreaks of secondary insect pests; (3) resurgence of insect populations previously treated; (4) toxic insecticide residues on treated crops; (5) increased health risks to humans and livestock and harm to the natural environment; and (6) legal actions resulting from perceived harm caused by pesticide applications. In addition to the problems associated with the excessive use of insecticides, Stern et al.[14] introduced several concepts that served to shape a modern applied ecological approach to the management of pests (IPM). These concepts, now familiar to IPM practitioners, included terms such as economic injury level, economic threshold, integrated control, and general equilibrium position. Since the publication of the Stern et al.[14] paper, many definitions of IPM have emerged.[15] In general, many of these definitions tend to describe IPM as a management system that promotes pest control tactics that help to ensure desirable economic, ecological, and sociological consequences.[16]

To date, the evolution of field resistance by an insect population to *Bt* maize or cotton has been relatively infrequent.[17, 18] This is likely due to a variety of factors such as the presumed rare and recessive nature of most resistant genes and the implementation of U.S. EPA mandated refuges by a majority of producers. Tabashnik et al.[18] reported "strong evidence" for the evolution of field resistance to *Bt* maize and/or cotton for three lepidopterans in the family Noctuidae: (1) *Busseola fusca* (Fuller) in South Africa (Cry1Ab toxin); (2) *Helicoverpa zea* (Boddie) in some southeastern states of the United States (Cry1Ac and Cry2Ab toxins); and (3) *Spodoptera frugiperda* (J.E. Smith) in Puerto Rico (Cry1F toxin). Reasons for the development of these cases of field resistance range from the lack of implementation of an adequate number of refuges in South Africa of non-*Bt* corn to the nonrecessive inheritance in Puerto Rico by *S. frugiperda* to the Cry1F toxin.[18] Thus far, no cases of field-evolved resistance to *Bt* maize have been confirmed in Illinois.

Slightly more than 50 years have passed since the publication of the Stern et al.[14] paper. The purpose of this paper is to provide the results of a survey of Illinois commercial maize and soybean producers regarding their perceptions on the use of *Bt* hybrids for the management of two key insect pests of corn, the European corn borer and the western corn rootworm. In addition, the perceptions of producers regarding acceptable resistance management strategies will be discussed.

■ MATERIALS AND METHODS

In 2009, a series of regional University of Illinois Extension meetings were conducted in six Illinois locations, Mt. Vernon, Champaign, Bloomington, Springfield, Moline, and Malta, on the following dates, respectively: January 6, 7, 12, 13, 14, and 15. The meetings, referred to as the Corn and Soybean Classics, are popular day-long meetings in which University of Illinois Extension faculty present summaries of their applied-research programs and offer recommendations to producers. The recommendations cover a wide range of topics including agronomy, entomology, nematology, plant pathology, and weed science. In 2009, a diverse group of agricultural clientele attended the meetings such as producers (37%), agricultural input suppliers (23.9%), agricultural chemical company representatives (3.1%), seed company representatives (20.8%), consultants (5.4%), and others (9.9%). The "others" category included members of the media, academic staff, and local extension personnel. Each speaker generally spoke for about 30 min on their chosen topic of expertise. At each location, a series of questions were asked using an anonymous electronic audience response system (TurningPoint, Turning Technologies, LLC, Youngstown, OH) that utilizes hand-held clickers. Speakers used PowerPoint presentations with the TurningPoint software, and audience members were able to answer multiple-choice questions by selecting the most appropriate response for them by pressing a number on the touch pad of their clicker. At the end of a 30 s polling period, a speaker would display the collective responses to the audience using a histograph. For purposes of this paper, I will discuss the responses of the following five questions that I asked of producers in 2009: (1) In your operation, how many acres are dedicated to corn and soybean production? (2) Did you plant a *Bt* hybrid in 2008? (3) If you planted a *Bt* hybrid in 2008, did you plant a 20% refuge according to the suggested guidelines? (4) Would you plant a *Bt* hybrid for corn rootworm or European corn borer control knowing that anticipated damage levels were low? (5) Has the USDA decision to provide reduced crop insurance premiums for producers who plant *Bt* hybrids influenced your decision to use a *Bt* hybrid?

In 2010, the Corn and Soybean Classics were held at six locations in Illinois; however, the results from only five meetings are presented due to a computer malfunction at the Mt. Vernon site. Locations and dates for which data were summarized for 2010 include Champaign, January 8; Springfield, January 11; Bloomington, January 12; Moline, January 13;

Table 1. Anonymous Responses from Maize and Soybean Producers at Regional Extension Meetings Known as the Corn and Soybean Classics, January 2009

In Your Operation, How Many Acres Are Dedicated to Corn and Soybean Production?														
farm size	Bloomington		Champaign		Malta		Moline		Mt. Vernon		Springfield		total	
<500 acres	*n*[a] = 27	27.6%	*n* = 12	14.6%	*n* = 13	28.3%	*n* = 11	21.6%	*n* = 11	16.4%	*n* = 20	20.2%	*n* = 94	21%
500−1000 acres	*n* = 30	30.6%	*n* = 18	22.0%	*n* = 11	23.9%	*n* = 12	23.5%	*n* = 15	22.4%	*n* = 19	19.2%	*n* = 105	24%
1000−2000 acres	*n* = 25	25.5%	*n* = 25	30.5%	*n* = 13	28.3%	*n* = 17	33.3%	*n* = 21	31.3%	*n* = 37	37.4%	*n* = 138	31%
2000−5000 acres	*n* = 14	14.3%	*n* = 20	24.4%	*n* = 5	10.9%	*n* = 7	13.7%	*n* = 15	22.4%	*n* = 18	18.2%	*n* = 79	18%
>5000 acres	*n* = 2	2.0%	*n* = 7	8.5%	*n* = 4	8.7%	*n* = 4	7.8%	*n* = 5	7.5%	*n* = 5	5.0%	*n* = 27	6%
Did You Plant a *Bt* Hybrid in 2008?														
response	Bloomington		Champaign		Malta		Moline		Mt. Vernon		Springfield		total	
yes	*n* = 114	96.6%	*n* = 128	98.5%	*n* = 90	96.8%	*n* = 92	98.9%	*n* = 88	97.8%	*n* = 152	95%	*n* = 664	97%
no	*n* = 4	3.4%	*n* = 2	1.5%	*n* = 3	3.2%	*n* = 1	1.1%	*n* = 2	2.2%	*n* = 8	5%	*n* = 20	3%
If You Planted a *Bt* Hybrid in 2008, Did You Plant a 20% Refuge According to the Suggested Guidelines?														
response	Bloomington		Champaign		Malta		Moline		Mt. Vernon		Springfield		total	
yes	*n* = 93	84.6%	*n* = 106	85.5%	*n* = 67	76.1%	*n* = 68	75.6%	*n* = 72	82.8%	*n* = 137	85.1%	*n* = 543	82%
no	*n* = 17	15.5%	*n* = 18	14.5%	*n* = 21	23.9%	*n* = 22	24.4%	*n* = 15	17.2%	*n* = 24	14.9%	*n* = 117	18%
Would You Plant a *Bt* Hybrid for Corn Rootworm or European Corn Borer Control Knowing That Anticipated Damage Levels Were Low?														
response	Bloomington		Champaign		Malta		Moline		Mt. Vernon		Springfield		total	
yes	*n* = 92	76.0%	*n* = 120	85.7%	*n* = 70	76.1%	*n* = 73	79.4%	*n* = 78	86.7%	*n* = 116	73.0%	*n* = 549	79%
no	*n* = 29	24.0%	*n* = 20	14.3%	*n* = 22	23.9%	*n* = 19	20.7%	*n* = 12	13.3%	*n* = 43	27.0%	*n* = 145	21%
Has the USDA Decision To Provide Reduced Crop Insurance Premiums for Producers Who Plant *Bt* Hybrids Influenced Your Decision To Use a *Bt* Hybrid?														
response	Bloomington		Champaign		Malta		Moline		Mt. Vernon		Springfield		total	
yes	*n* = 17	14.2%	*n* = 30	24.4%	*n* = 19	20.9%	*n* = 18	19.6%	*n* = 11	12.8%	*n* = 29	18.5%	*n* = 124	19%
no	*n* = 103	85.8%	*n* = 93	75.6%	*n* = 72	79.1%	*n* = 74	80.4%	*n* = 75	87.2%	*n* = 128	81.5%	*n* = 545	81%

[a] *n* = number of responses.

and Malta, January 14. Responses from audience members were collected anonymously using methods previously described. Similar to the previous year, producers (34.7%) made up the largest audience participant category followed by agricultural input suppliers (32.8%), “others” (18.5%), consultants (8.3%), and agricultural chemical company representatives (5.7%). Additional questions were directed at producers in 2010 because of the increasing interest of blending transgenic and nontransgenic maize (“refuge-in-a-bag” technology) for resistance management purposes and they were as follows: (1) In your operation, how many acres are dedicated to corn and soybean production? (2) Did you plant a *Bt* hybrid in 2009? (3) If you planted a *Bt* hybrid in 2009, did you plant a 20% refuge according to the suggested guidelines? (4) In 2009, did you plant a *Bt* hybrid for corn rootworm or European corn borer control knowing that anticipated damage levels were low? (5) Did you have access to elite (high yield potential) non-*Bt* corn germplasm in 2009? (6) Would you be willing to use a seed blend (*Bt* and non-*Bt*) as a refuge? (7) If you answered “yes,” would you be willing to use a seed blend that contains non-*Bt* seed in the 2−5% range? (8) If you answered “yes,” would you be willing to use a seed blend that contains non-*Bt* seed in the 6−10% range? Responses to these questions, and those used in 2009, will be presented and discussed with regard to the relevance of traditional IPM strategies in this transgenic era of commercial maize production.

RESULTS AND DISCUSSION

In 2009, the fewest (14.6%) small [<202 ha (<500 acres)] farming operations belonged to those participants who attended the meeting in Champaign, IL (Table 1). In contrast, at the other end of this range, 28.3% of the producers who attended the meeting in Malta described their farm size as <202 ha (500 acres). Farms in the 809−2023 ha (2000−5000 acres) range were the most common (24.4%) for producers in the Champaign area and least common near Malta (10.9%). Overall, 138 producers (31%) indicated their farm size was in the range of 405−809 ha (1000−2000 acres). This was the most common size of farming operation for participants pooled across all meeting locations. The least common farm size across all sites was operations >2023 ha (5000 acres), with only 27 producers (6%) selecting this response. In 2010, the overall distribution of producers was very similar for farms of <202 ha (500 acres), 202−405 ha (500−1000 acres), and 405−809 ha (1000−2000 acres) with the following percentages: 24.9, 23.2, and 24.9%, respectively (Table 2). Nearly 11% of the producers who attended the five meetings reported that their operations exceeded 2023 ha (5000 acres).

When producers were asked if they planted a *Bt* hybrid in 2008, the range of producers who indicated “yes” was 95% (Springfield) to 98.9% (Moline) (Table 1). A total of 664 respondents (97%) across the six locations indicated they had used a *Bt* hybrid in 2008. This is strong confirmation that the adoption of this transgenic technology is very high for maize producers across Illinois. In 2008, the USDA Economic Research Service estimated that 52% of the maize grown in Illinois was a “stacked” gene variety.[10] This government agency also estimated

Table 2. Anonymous Responses from Maize and Soybean Producers at Regional Extension Meetings Known as the Corn and Soybean Classics, January 2010

In Your Operation, How Many Acres Are Dedicated to Corn and Soybean Production?

farm size	Bloomington		Champaign		Malta		Moline		Springfield		total	
<500 acres	n^a= 14	16.5%	*n* = 11	18.6%	*n* = 16	29.1%	*n* = 33	38.8%	*n* = 17	20.7%	*n* = 91	24.9%
500−1000 acres	*n* = 22	25.9%	*n* = 9	15.3%	*n* = 16	29.1%	*n* = 22	25.9%	*n* = 16	19.5%	*n* = 85	23.2%
1000−2000 acres	*n* = 23	27.1%	*n* = 15	25.4%	*n* = 11	20.0%	*n* = 15	17.7%	*n* = 27	32.9%	*n* = 91	24.9%
2000−5000 acres	*n* = 17	20.0%	*n* = 17	28.8%	*n* = 5	9.1%	*n* = 7	8.3%	*n* = 14	17.1%	*n* = 60	16.4%
>5000 acres	*n* = 9	10.6%	*n* = 7	11.9%	*n* = 7	12.7%	*n* = 8	9.4%	*n* = 8	9.8%	*n* = 39	10.7%

Did You Plant a *Bt* Hybrid in 2009?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 122	96.8%	*n* = 81	100%	*n* = 73	94.8%	*n* = 122	95.3%	*n* = 132	97.1%	*n* = 530	96.7%
no	*n* = 4	3.2%	*n* = 0	0%	*n* = 4	5.2%	*n* = 6	4.7%	*n* = 4	2.9%	*n* = 18	3.3%

If You Planted a *Bt* Hybrid in 2009, Did You Plant a 20% Refuge According to the Suggested Guidelines?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 97	78.9%	*n* = 59	72.0%	*n* = 50	70.4%	*n* = 99	78.0%	*n* = 100	75.8%	*n* = 405	75.7%
no	*n* = 26	21.1%	*n* = 23	28.1%	*n* = 21	29.6%	*n* = 28	22.1%	*n* = 32	24.2%	*n* = 130	24.3%

In 2009, Did You Plant a *Bt* Hybrid for Corn Rootworm or European Corn Borer Control Knowing That Anticipated Damage Levels Were Low?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 89	71.8%	*n* = 61	78.2%	*n* = 45	65.2%	*n* = 83	69.2%	*n* = 98	80.3%	*n* = 376	73.3%
no	*n* = 35	28.2%	*n* = 17	21.8%	*n* = 24	34.8%	*n* = 37	30.8%	*n* = 24	19.7%	*n* = 137	26.7%

Did You Have Access to Elite (High Yield Potential) Non-*Bt* Corn Germplasm in 2009?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 68	54.4%	*n* = 53	68.0%	*n* = 39	53.4%	*n* = 78	66.7%	*n* = 80	59.3%	*n* = 318	60.2%
no	*n* = 57	45.6%	*n* = 25	32.0%	*n* = 34	46.6%	*n* = 39	33.3%	*n* = 55	40.8%	*n* = 210	39.8%

Would You Be Willing To Use a Seed Blend (*Bt* and Non-*Bt*) as a Refuge?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 119	77.8%	*n* = 80	83.3%	*n* = 82	81.2%	*n* = 123	82%	*n* = 129	79.1%	*n* = 533	80.4%
no	*n* = 34	22.2%	*n* = 16	16.7%	*n* = 19	18.8%	*n* = 27	18%	*n* = 34	20.9%	*n* = 130	19.6%

If You Answered "Yes," Would You Be Willing To Use a Seed Blend That Contains Non-*Bt* Seed in the 2−5% Range?

response	Bloomington		Champaign		Malta		Moline		Springfield		.	
yes	*n* = 112	91.1%	*n* = 76	90.5%	*n* = 74	93.7%	*n* = 119	88.2%	*n* = 122	88.4%	*n* = 503	90%
no	*n* = 11	8.9%	*n* = 8	9.5%	*n* = 5	6.3%	*n* = 16	11.9%	*n* = 16	11.6%	*n* = 56	10%

If You Answered "Yes," Would You Be Willing To Use a Seed Blend That Contains Non-*Bt* Seed in the 6−10% Range?

response	Bloomington		Champaign		Malta		Moline		Springfield		total	
yes	*n* = 56	47.1%	*n* = 47	58.8%	*n* = 42	52.5%	*n* = 63	50.4%	*n* = 81	57.9%	*n* = 289	53.1%
no	*n* = 63	52.9%	*n* = 33	41.3%	*n* = 38	47.5%	*n* = 62	49.6%	*n* = 59	42.1%	*n* = 255	46.9%

[a] *n* = number of responses.

that 80% of the maize grown that same year could be characterized as a genetically engineered variety. Similar to the preceding year, a very large overall percentage (96.7%) of the producers planted a *Bt* hybrid in 2009 ranging from 94.8% for Malta to 100% for Champaign (Table 2). For 2009, the USDA Economic Research Service[10] estimated that 59% of the maize planted in Illinois was a "stacked" gene variety and 84% was a genetically engineered hybrid (may include glyphosate- or glufosinate-tolerant maize). The use of *Bt* maize hybrids was high across all locations by producers, and no region seemed to be different with regard to producers' receptiveness to this technology. Historically, the most significant insect threat to maize production in Illinois was caused by western corn rootworms and the European corn borer, with northwestern Illinois being particularly prone to economic infestations of corn rootworms.[19] This was an area of the state in which crop rotation was practiced less frequently and more nonrotated maize was grown. Because crop rotation was a very successful cultural management tactic for this insect pest, densities of this pest were often lower in central and southern Illinois counties, where a simple rotation with a nonmaize crop was practiced frequently. In southern Illinois, economic infestations of western corn rootworms are less common than in other areas of the state. Despite this, the use of *Bt* hybrids was very significant in Mt. Vernon (97.8%), the most southern location of our meeting sites (Table 1).

Since the mid-1990s, crop rotation no longer affords a reliable cultural management approach for western corn rootworms in Illinois. Many researchers have hypothesized that the annual rotation of maize and soybeans over several decades selected for a variant western corn rootworm in which females began to lay eggs in the soil of soybean fields.[20] This resulted in larvae hatching the following spring into these same fields that had been rotated to maize. The consequence of this behavioral adaptation is that rotated and nonrotated maize is now susceptible to western corn rootworm larval injury in an expanding area of the midwestern Corn Belt.[7] This unique example of evolution to a cultural strategy has contributed to an expanded use of *Bt* hybrids and/or soil insecticides to control western corn rootworms.

The EPA requires producers who elect to plant a *Bt* hybrid implement a refuge (non-*Bt* maize) according to guidelines that may vary according to the particular Bt hybrid chosen or region of the United States in which the producer resides. For the North Central region of the United States, a 20% refuge has been the standard requirement since the introduction of transgenic maize hybrids into the marketplace in the mid-1990s. For the Cotton Belt, the structured refuge requirement was 50%. The refuge amount for maize in the North Central region of the United States (20%) was the same for *Bt* hybrids aimed primarily at the European corn borer or western corn rootworms. A 5% structured refuge is now required for some *Bt* maize hybrids (SmartStax hybrids). Gould[21] explained the key elements of the high-dose and refuge resistance management strategy for transgenic insecticidal cultivars. In essence, a refuge theoretically ensures that enough individuals who carry susceptible genes will mate with any rare resistant individual(s) that survives a high dose of *Bt* toxin from a transgenic plant. The resulting heterozygous offspring remain susceptible to a high dose of the *Bt* toxin, delaying or preventing the evolution of a field-resistant population. Therefore, planting a refuge is critical in maintaining the long-term durability of *Bt* maize hybrids for producers.

When producers were asked if they planted a 20% refuge in 2008 according to suggested guidelines, 82% responded "yes" (Table 1). The "yes" response ranged from 75.6% in Moline to 85.5% in Champaign. The lack of complete compliance does raise concern that increased selection pressure will heighten the chances that resistance will develop at some point. Proponents of the refuge-in-a-bag approach to resistance management argue that this new strategy ensures 100% compliance for those producers who purchase *Bt* hybrids approved for use as seed mixtures. In 2009, overall refuge compliance was down approximately 6% from the previous year, declining from 82 to 75.7% (Table 2). The range of compliance was 70.4−78.9% for Malta and Bloomington producers, respectively. Conversations with producers and others in the agribusiness community suggest that some producers believe the refuge-in-a-bag (seed mixture) approach to resistance management is imminent for many Bt maize hybrids; therefore, they are less concerned with implementing a 20% structured refuge in what they believe are the last few growing seasons for this requirement.

A large majority (79%) of producers in 2009 revealed that they would still plant a *Bt* hybrid for corn rootworm or European corn borer control even if they anticipated low densities of either pest (Table 1). The range of producers who responded "yes" to this question was from 73% in Springfield to 86.7% in Mt. Vernon. Of the producers sampled, those from the Mt. Vernon area are the least likely to have economic densities of corn rootworms. Each of the other locations is prone to western corn infestations, especially following the evolution of the variant western corn rootworm. At the 2010 meetings, 73.3% of the producers across the five locations indicated they had planted a Bt maize hybrid in 2009 with the knowledge that corn rootworm or European corn borer damage was likely to be low (Table 2). The range in "yes" responses to this question ranged from 65.2 to 80.3% for Malta and Springfield producers, respectively. European corn borer densities for several years have been at historically low levels across Illinois.[22] Despite this fact, producers continue to plant *Bt* hybrids at escalating levels, targeting this pest and some other lepidopterans that could be scouted for and rescue treatments applied if economic thresholds are reached. These other lepidopterans include black cutworms (*Agrotis ipsilon* Hufnagel), fall armyworms (*S. frugiperda* J.E. Smith), corn earworms (*H. zea* Boddie), and southwestern corn borers (*Diatraea grandiosella* Dyar). Transgenic maize plants that express Cry proteins offer control or suppression of these lepidopteran pests depending upon the specific *Bt* hybrid.

The use of *Bt* hybrids may be considered similar to the use of traditionally derived insect resistant cultivars, in essence the use of host plant resistance as an insect management tactic. However, if *Bt* hybrids are considered to be a more elegant, but nonetheless prophylactic, use of insecticides, then this tactic may be considered as an affront to the integrated control principles articulated by Stern et al.,[14] which stress the importance of the integration of a variety of management tactics. This remains an academic debate. These data indicate that most maize producers are more than willing to invest in this type of insect control even though densities of insect pests are likely to be low.

Perhaps one reason that producers make this type of pest management decision is the influence of policies that emanate from the U.S. Department of Agriculture (USDA) Risk Management Agency. On August 14, 2008, the USDA's Federal Crop Insurance Corporation Board of Directors approved reductions in crop insurance premiums for producers who elected to plant certain qualifying transgenic maize hybrids, including many *Bt* hybrids. Producers who elected to participate in this program were required to plant at least 75% of their ensured maize to a transgenic hybrid that qualified for the program. When producers were asked in 2009 whether or not the USDA program to lower insurance premiums had influenced their decision to use a *Bt* hybrid, a large majority (81%) responded "no" (Table 1). Yet, 124 individuals (19%) indicated that this government program did influence their decision to use a *Bt* hybrid. Undoubtedly, there are many other factors such as overall risk aversion and perceived lack of availability of elite (high-yielding) non-*Bt* maize hybrids.

In 2009, overall approximately 40% of producers indicated that they did not have access to elite (high yield potential) non-*Bt* maize germplasm (Table 2). Nearly half (46.6%), of the producers in Malta indicated they did not have access to these elite non-*Bt* maize hybrids. Because it is a logistical challenge and costly enterprise for the seed industry to maintain similar inventory levels of *Bt* and non-*Bt* maize elite hybrids, it would not be surprising to see larger quantities of more profitable transgenic maize hybrids produced, thus limiting the number of non-*Bt* hybrids available to producers. Because the seed industry was required to produce enough non-*Bt* seed that would enable producers to fulfill their 20% structured refuge requirement, one could argue that there was an economic incentive to continue producing elite non-*Bt* maize hybrids. There will be less incentive to produce non-*Bt* seed as the transition to a refuge-in-a-bag (seed mixture) resistance management approach gains momentum. This is particularly true if the seed mixture refuge is approved by the EPA at the 5% (non-*Bt*) level for a majority of maize hybrids. This direction will further remove most maize producers from the traditional IPM paradigm described previously.

As confirmation of the popularity of the seed mixture refuge resistance management strategy, 80.4% of producers across the five meeting locations indicated in 2010 that they would be willing to use a seed blend (*Bt* and non-*Bt*) as a refuge (Table 2). The receptiveness of this approach was generally uniform across the various sites, ranging from 77.8 to 83.3% for Bloomington and Champaign, respectively. For those producers who indicated a willingness to use a seed blend as their refuge, overall 90% indicated they would be receptive to a 2−5% non-*Bt* mix within each bag of seed. Again, the range of responses to this question was very narrow, from 88.2 to 93.7% for Moline and Malta, respectively (Table 2). However, if the non-*Bt* portion of the seed mixture was increased within a range of 6−10%, nearly half (46.9%) of the producers pooled across the sites indicated that they would not be interested in this approach to resistance management. The number of "no" responses to this question varied more across the locations and ranged from 41.3 to 53% for Champaign and Bloomington, respectively. On the basis of these responses, particularly from the Bloomington site, it seems plausible to suggest that many producers would not be receptive to planting OptimumAcreMax1 Pioneer maize hybrids [seed blend of 90% Herculex Xtra (Cry1F + Cry34/35Ab1) and 10% Herculex 1 (Cry1F)] for corn rootworm control due to the number of plants (10%) that would be more susceptible to root pruning. It remains unknown whether or not the EPA will extend the registration for OptimumAcreMax1 Pioneer maize hybrids beyond the current time-limited registration that will expire on September 30, 2010.[13] If this registration is not extended and SmartStax maize hybrids, used in conjunction with a 5% seed mixture refuge, are approved for use by the EPA, a decided competitive advantage may begin to occur. Onstad and Meinke[23] have shown that the evolution of western corn rootworm resistance to Cry proteins was slowed in modeling studies when they used pyramided transgenic plants (e.g., SmartStax maize hybrids) as compared with a single-trait maize hybrid. Thus far, no field level resistance to *Bt* hybrids has been confirmed for either western corn rootworms or European corn borers. Perhaps the introduction of more pyramided transgenic maize hybrids into the landscape will help to ensure the continuing longevity of this impressive technology.

Often overlooked in discussions involving the use of *Bt* hybrids is the fact that transgenic maize seed planted in the U. S. Corn Belt is treated with a neonicotinoid insecticidal seed treatment, either clothianidin or thiamethoxam. These systemic seed treatments are used primarily to protect maize seedlings against secondary soil insect injury [e.g., wireworms (Elateridae), white grubs (Scarabaeidae), grape colaspis (Chrysomelidae)]. With the widespread and annual exposure of soil insects to these neonicotinoids, evolution of resistance to these products seems to be inevitable. In addition, unforeseen negative consequences may result from the indiscriminate use of these products. As an example, Girolami et al.[24] reported that neonicotinoid (clothianidin, imidacloprid, thiamethoxam) guttation drops, collected from maize plants, were toxic to honey bees (*Apis mellifera* L.) in a field experiment conducted near Legnaro, Italy.

As a cautionary suggestion, I believe producers, policy makers, regulatory agencies, and agribusiness corporations should be increasingly concerned about the lack of integrated management tactics and increasing reliance on *Bt* hybrids for the control of insect pests of maize. Some may argue that the "new" integration is the expression of multiple Cry proteins in maize rather than the use of multiple traditional tactics (cultural, biological control, judicious insecticide use). If the evolution of field level resistance to these Cry proteins does not occur over the next decade, perhaps the proponents of this argument will be proven correct. Although the pest management concepts introduced by Stern et al.[14] are just as relevant in the 21st century, now dominated by a transgenic agricultural landscape in the Midwestern Corn Belt of the United States, fewer producers are devoted to scouting fields, using economic thresholds, and applying rescue treatments for the most significant insect pests of maize. Instead, they are increasingly relying on the broad spectrum, insurance-based approach to pest management that transgenic *Bt* hybrids provide.

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