

Chapter 2

Integrated Pest Management, Bt Crops, and Insecticide Use: The U.S. Experience

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Abstract Bt crops have features amenable to IPM systems and their incorporation into such systems has been quite successful in some institutional settings. Widespread adoption of Bt cotton and maize in the United States has contributed to dramatic, unprecedented reductions in insecticide use. When introduced into settings with less-developed IPM systems, however, secondary pest outbreaks and field-evolved resistance have become problems. Pest resistance to Bt has yet to become a serious problem in the United States but remains a concern. A major industry response to potential resistance and grower non-compliance with resis-

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tance management regulations has been development of pyramided Bt varieties and seed mixtures. These address some immediate problems, but may take some discretion in pest management away from growers. IPM principles that recognize the biological complexities of pest management may prove essential for sustaining the benefits of Bt crops.

Keywords Bt · Cotton · Maize · Insecticides · IPM · Resistance · Biotechnology · Pesticides · Genetically modified

2.1 Introduction

Bt crops have been genetically modified to enable those crops to produce crystalline (Cry) insecticidal proteins from the soil bacterium *Bacillus thuringiensis* (Bt). The Cry toxins effectively control a narrow range of insect pests (such as some from the orders Lepidoptera and Coleoptera) while showing little to no activity against other species (National Research Council 2010). Because Bt is highly selective and breaks down quickly in the environment, foliar Bt sprays have been widely used in organic farming in the United States. Such foliar Bt sprays have had long history of safe use (Sanchis 2011). Bt cotton and maize varieties first became commercially available in the United States in 1996. Since then, adoption has been rapid and pervasive. Most U.S. cotton and maize acreage are now planted to Bt varieties (National Research Council 2010).

Bt crops show great promise, but have also raised concerns. By reducing reliance on broad-spectrum insecticide applications, they hold the promise of reducing negative environmental impacts of farming, while increasing farm yields and incomes. The rapid rise of Bt crops, however, has raised questions about their impacts beyond adoption rates, direct economic returns, and chemical applications directed at target pests. These include questions about effects on non-target pests and thus total insecticide use, effects on non-pest species, and about the evolution of pest resistance to Bt toxins and the implications of resistance for organic farming.

Evidence suggests that Bt cotton and maize adoption in the United States has contributed to substantial reductions in insecticide use for both crops (National Research Council 2010). It is important, however, to look beyond insecticide applications to target species. Applications to control target pests of Bt have diminished, while those for non-target pests have increased in some areas (National Research Council 2010; Luttrell and Jackson 2012; Naranjo 2011). This has occurred because overall reductions in broad-spectrum insecticide applications have led, in some cases, to the emergence of new secondary pest problems. Nevertheless, the net effect has been a significant reduction in overall insecticide use (Luttrell and Jackson 2012; Williams various years; Hutchinson et al. 2010). Field-evolved resistance to some Cry toxins, in the United States and abroad, remains a concern (Tabashnik et al. 2009; Tabashnik and Carrière 2010; Tabashnik and Gould 2012). Failure to delay resistance could mean that the current benefits of Bt crops may not be sustainable.

Rather than focus narrowly on target pest applications, we suggest it is better to ask how Bt crops fit into an overall system of integrated pest management (IPM). Kogan (1998) has defined IPM as “a decision support system for the selection and use of *pest control tactics*, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment. (emphasis added).” Note the term “pest control tactics” as opposed to “pesticides.” While pesticides are important, they are one pest control tactic, among many. IPM is not a “buy and apply approach” where growers are passive consumers, buying products to address the pest problem of the moment. Bajwa and Kogan’s (2004) compendium lists 67 different definitions of IPM. A recurring theme in these definitions is substituting knowledge and information for insecticides. IPM is a systems approach that requires intensive use of knowledge about agronomy, plant genetics, economics, pest population dynamics, and ecology (Frisvold 2009). The question is then, how do Bt crops fit among many pest control tactics in complex agro-ecological systems?

The chapter proceeds as follows. Section 2.2 introduces key features of an IPM framework. Section 2.3 discusses trends in U.S. Bt crop adoption, insecticide use, and pest management in cotton and maize. Section 2.4 addresses potential problems of pest resistance to Bt crops and the role of integrated resistance management (IRM). Section 2.5 introduces a case study from Arizona illustrating the successful incorporation of Bt cotton into an area-wide IPM program. Section 2.6 concludes by drawing lessons from the U.S. Bt crop experience.

We draw three major lessons from the experience of Bt cotton and Bt maize in the United States. First, Bt crops have certain features that make them amenable to incorporation into IPM systems and such incorporation has been quite successful in *some* institutional settings. This has led to significant and unprecedented reductions in insecticide applications, with attendant environmental benefits. Second, however, the compatibility of Bt crops with IPM is not a given. When introduced in weaker institutional settings with less-developed IPM systems, secondary pest outbreaks and field-evolved resistance have become problems (Frisvold and Reeves 2010; Tabashnik et al. 2009; Huang et al. 2011). Resistance to Bt has yet to become a significant problem in the United States, but remains a concern. Third, IPM principles may prove essential for sustaining the benefits of Bt crops. Integrated resistance management (IRM) has emerged as a critical part of IPM. A major private industry response to potential resistance problems and grower non-compliance with IRM regulations has been the development and marketing of pyramided Bt varieties (containing multiple Cry toxins) and seed mixtures. The latter, also called “refuge in a bag” addresses problems of grower non-compliance of refuge requirements to delay resistance, but raises other concerns. New, multi-trait seed varieties and mixtures may simplify grower decision making in the short run. In some cases, however, it can take discretion in pest management away from growers. In the case of genetically modified, herbicide resistant crops, “simplifying” weed management decisions led to rapid evolution of herbicide resistance in weeds (Frisvold and Reeves 2010). Cropping systems *are* complex. An IPM system recognizes this and may be the best means to delay Bt resistance.

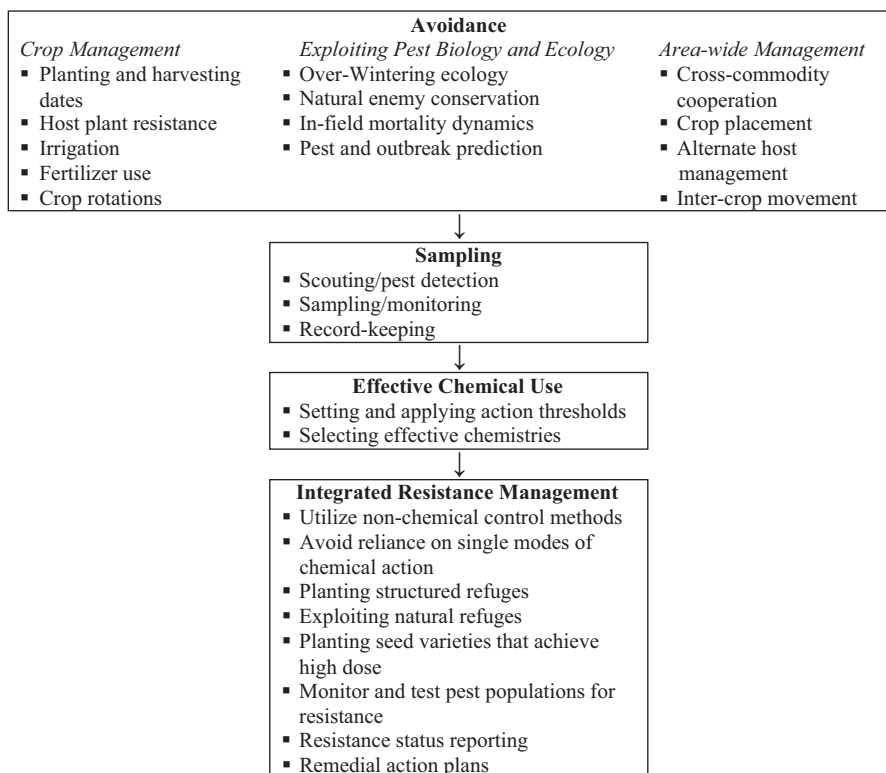


Fig. 2.1 Conceptual model of IPM accounting for incorporation of Bt crops. (Adapted from Ellsworth and Martinez-Carrillo (2001) and Naranjo (2011))

2.2 Building Blocks of IPM: A Conceptual Framework

Following Ellsworth and Martinez-Carrillo (2001) and Naranjo (2011), one may think of IPM in terms of a set of building blocks (Fig. 2.1). The primary tactic for preventing pests from causing economically significant damage is avoidance. This includes a variety of methods to prevent pest populations from growing or becoming established in the first place. Avoidance tactics include crop management, exploiting pest biology and ecology, and area-wide crop management to limit pest populations. Different crop management practices such as choice of planting and harvesting dates, irrigation and fertilizer application practices, and use of crop rotations are all non-chemical choices that can affect pest populations. Another important practice is the host plant resistance of crops and crop varieties selected to plant. Pest control can be improved by using knowledge of pest over-wintering ecology, natural enemy conservation, and in-field mortality dynamics, along with tools to predict pest outbreaks. At an area-wide scale, knowledge of pest movement between crops can facilitate cross-commodity cooperation to control polyphagous

pests. The spatial configuration of different crops can affect overall crop damage in a region.

Another key aspect of IPM is the use of economic thresholds to make decisions regarding chemical applications. Instead of prophylactic or calendar-based spraying, this requires scouting and pest detection. Sampling, monitoring and record keeping are important to assess the success of avoidance practices. Action thresholds limit insecticide applications to cases where expected damages avoided outweigh application costs. In addition to the timing and level of insecticide applications, it is important to choose the appropriate chemistry. This includes not only consideration of how effective a compound is at controlling the target pest, but also its effects on natural enemies and scope for creating secondary pest outbreaks. Thus, a knowledge of pest biology and ecology is needed, not just the dose-response relationship between a chemical and a target pest.

Finally, integrated resistance management (IRM) involves avoiding selection pressure that depletes the susceptibility of pests to chemical compounds. Chemical pest control, although a final step in the above IPM framework remains an important step. The effectiveness of compounds, however, is an exhaustible resource, which IRM seeks to conserve. This can be done first by using non-chemical controls. Avoidance practices have both short-run control benefits and longer-term, resistance delaying benefits. Avoiding reliance on any single chemical mode of action is also a key component of IRM. Figure 2.1 extends the approach of Ellsworth and Martinez-Carrillo (2001) and Naranjo (2011) by explicitly including IRM practices for Bt crops. These include planting structured refuges, exploiting natural refuges, planting seed varieties that deliver a high dose of the Bt toxin, monitoring and testing pest populations for resistance to both Bt toxins and applied insecticides, reporting the status of resistance, and developing and implementing remedial action plans to address field-evolved resistance and field failure of Bt crops.

Bt crops have certain attributes that are consistent with IPM, but others that raise some questions. On one hand, Bt crops rely on selective control of specific species. Bt crops substitute for broad-spectrum chemical insecticides for their target species. Lundgren et al. (2009) warn, though, that one must look beyond how Bt crops affect application rates for target pests. IPM relies on predators, parasitoids, and pathogens to control pest populations. It is important to consider how Bt crops affect this entire system of non-target species. Evidence suggests, however, that compared to the insecticides they replace, Bt crops have less harmful effects on non-target species (Marvier et al. 2007; Naranjo 2009; National Research Council 2010).

Another question raised is the extent to which Bt crops represent a movement away from the threshold concept (Hellmich et al. 2008; Kennedy 2008). Because the Bt toxin is ever-present in the genetically modified plants, pests receive greater exposure to the toxin. A counterargument is that Bt crops are just an enhanced form of host plant resistance (HPR), which growers have long used as an IPM strategy (Hellmich et al. 2008; Kennedy 2008). There has been limited success developing crop varieties with improved HPR through conventional plant breeding methods. Recombinant DNA technology simply represents a more efficient means of improving HPR (Kennedy 2008).

The economic realities of commercial Bt crops mean that the threshold issue may be less important than it would first appear. Seed suppliers charge premiums for Bt seeds that can exceed the cost of up to three insecticide applications per hectare. Adoption rates for Bt crops will only be high in areas where target pest populations regularly surpass thresholds. In areas where thresholds are infrequently exceeded, adoption of Bt crops will be low.

Continuous pest exposure to the Bt toxin, however, does raise questions about the selection pressure this creates and the implications for pest evolution of resistance to Bt. Bt foliar sprays are among the most important insecticides used in U.S. certified organic crop production (Hutcheson 2003; Walker et al. 2003; Walz 1999). U.S. federal standards allow crops using low-toxicity insecticides to be certified as organic. In the mid-1990s, U.S. organic growers raised concerns that widespread planting of Bt field crops would accelerate resistance to Bt, threatening the effectiveness of Bt foliar sprays. In response, the U.S. Environmental Protection Agency (EPA) regulates Bt crops under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). EPA requirements include: (a) refuge requirements; (b) resistance monitoring; (c) grower education and grower agreements; and (f) annual reports from technology suppliers (Walker et al. 2003; Matten et al. 2008).

The cornerstone of Bt resistance management is the high dose/refuge strategy. Here, Bt crops express enough of the Bt proteins to deliver a high dose that kills all the susceptible homozygous individuals and nearly all of the resistant heterozygous individuals. Refuges of non-Bt crops planted nearby allow the abundant susceptible individuals to mate with any surviving resistant individuals that survive on the Bt crops. If inheritance of resistance is recessive, then the progeny of this mating will be susceptible to Bt toxins, slowing the evolution of resistance (Tabashnik and Gould 2012; Tiwari and Youngman 2011; Huang et al. 2011).

To implement the high dose/refuge strategy, EPA requires biotechnology firms to provide evidence supporting claims their crop varieties provide a high dose of the Bt protein. EPA has also required growers to plant refuges of non-Bt cotton or non-Bt maize near Bt fields. Regulations cover the spatial configuration of refuges, their size relative to Bt fields, their distance from Bt fields, and what insecticides may be applied on them (Walker et al. 2003; Matten et al. 2008). For pests that move between crops, it is possible for acreage of other crops to serve as a “natural refuges.” EPA has waived structural refuge requirements in cases where it has been determined that sufficient natural refuge acreage exists. One may think of the high dose component of this strategy as part of the “selecting effective chemistries” tactic in an IPM system (Fig. 2.1). Refuges are also similar to IPM strategies of crop placement, alternate host management, and accounting for inter-crop movement of pests (Fig. 2.1).

Bt crops *can* fit well into an IPM framework. In the United States, they have reduced pesticide use and conserved natural pest enemies. The high dose/refuge strategy, where carried out as intended, has successfully prevented resistance problems. In the United States and elsewhere, however, field evolved resistance has emerged as a result of a high dose of the Bt toxin not being delivered, poor compliance with

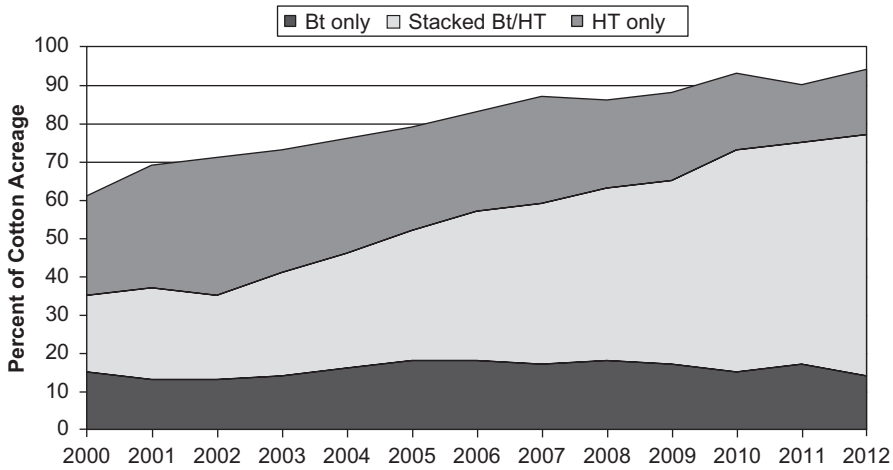


Fig. 2.2 Adoption of genetically modified cotton in the United States. (Source: USDA, ERS 2013)

refuge requirements, or both (Gassman et al. 2012; Huang et al. 2011; Tabashnik et al. 2009; Tabashnik and Carrière 2010; Tabashnik and Gould 2012).

2.3 Trends in Bt Crop Adoption and Pest Management Practices

2.3.1 Cotton

The first generation of Bt cotton varieties, approved for commercial use in 1996, contained a single Cry toxin. In the United States, the three main target pests of these Bt varieties were cotton bollworm, *Helicoverpa zea*, tobacco budworm, *Heliothis virescens*, and pink bollworm, *Pectinophora gossypiella*. They also provided some limited control of other lepidoptera. These first Bt varieties were highly effective at controlling budworm and pink bollworm, but less effective against cotton bollworm.

U.S. growers adopted Bt cotton quickly and pervasively. The percentage of upland cotton hectares planted to Bt varieties reached 35% by 2000 and rose to 77% by 2012 (Fig. 2.2). Most Bt hectares are planted to “stacked” varieties that are also genetically modified for herbicide resistance (HR). The second generation of Bt varieties, such as Bollgard II® and Widestrike® contained two Cry toxins. This “pyramiding” of different Cry toxins is intended to improve control against cotton bollworm, show more activity against a wider range of lepidoptera, and prove more effective at delaying insect resistance than single-toxin varieties (Head and Greenplate 2012; Naranjo et al. 2008). Bollgard II varieties first became available in

Table 2.1 U.S. cotton insecticide application rates in pre-Bt cotton and post-Bt cotton years. (Source: Williams (various years))

Period		All cotton pests	Boll weevil	Main Bt target pests ^a	All other cotton pests
Pre-Bt cotton 1986–1995	Applications/hectare	5.53	2.70	2.95	2.88
	Percent of total applications		31	35	34
1996–2008	Applications/hectare	3.17	0.52	0.74	2.92
	Percent of total applications		16	23	60
2009–2012	Applications/hectare	2.34	0.01	0.27	2.07
	Percent of total applications		0 ^b	11	88

^a Three main target pests are tobacco budworm, cotton bollworm, and pink bollworm

^b Less than 0.25%, numbers of applications/hectare may not sum exactly due to rounding

2003, with Widestrike varieties following in 2005. In 2009, Monsanto's registration of Bollgard I varieties with the EPA expired and use of single-toxin Bt cotton varieties was phased out. Single-toxin Bt varieties accounted for 28 % of Bt cotton acreage in 2009, 9 % in 2010, and was discontinued by 2011 (Williams various years).

The 1996 introduction of Bt cotton immediately followed a period where budworms and cotton bollworms exhibited resistance to pyrethroid insecticides in the Mid-South (Falck-Zepeda et al. 2000; Livingston et al. 2004). Bt cotton's introduction also overlapped with a bollworm eradication program that extended throughout U.S. cotton-producing states. In the decade before the introduction of Bt cotton, boll weevils (*Anthonomus grandis*), the three target pests of Bt (budworm, cotton bollworm and pink bollworm), and all other cotton pests accounted for roughly a third each of all cotton insecticide applications (Table 2.1). Because of the Boll Weevil Eradication Program, applications to control boll weevil have declined dramatically (Table 2.1, Fig. 2.3). The share of U.S. cotton acreage infested by boll weevil fell from 44 % in 1986 to less than 0.2 % in 2012. Insecticide applications to control boll weevil fell from 2.7 per hectare from 1986–1995 to 0.01 per hectare from 2009–2012. There has also been a decline in insecticide applications to control the three target pests of Bt. Applications to control budworm, cotton bollworm, and pink bollworm fell from 2.95 per hectare from 1986–1995 to 0.27 per hectare from 2009–2012.

Because of the Pink Bollworm Eradication Program, initiated in the Southwestern United States and Northern Mexico, insecticide sprays for pink bollworm have essentially ceased in the United States. Today, insecticide applications for Bt's target pests are directed primarily at cotton bollworm.

The reduction in broad-spectrum insecticide applications to control boll weevil and Bt target pests has led to an increase in pressure from non-target cotton pests. Lygus (*Lygus hesperus*) and stinkbugs (*Euschistus servus*, *Acrosternum hilare*, and *Nezara viridula*) have become more of a control problem (Naranjo et al. 2008; Luttrell and Jackson 2012). This is reflected in the increase in applications to control

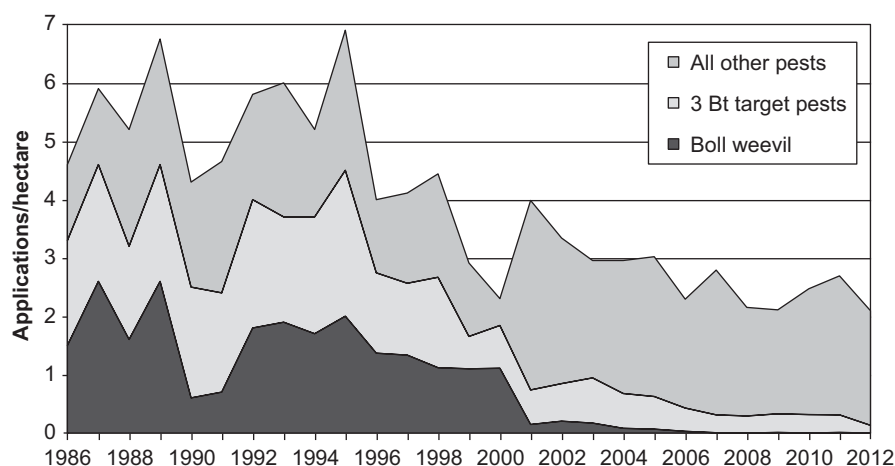


Fig. 2.3 Insecticide applications per hectare, U.S. upland cotton. (Source: Williams various years)

“all other” pests since 1986–1995 (Table 2.1, Fig. 2.3). These other pests accounted for 34% of cotton insecticide applications before Bt cotton. Since 2009, they have accounted for 88% of applications. Despite increased spraying for all other pests, total cotton insecticide applications have declined. Total application rates fell from 5.5 per hectare 1986–1995 to 2.34 per hectare from 2009–2012, the period when single-toxin Bt varieties were being replaced by pyramided varieties.

Luttrell and Jackson (2012) carried out pair-wise comparisons of Bt and conventional cotton for selected states reported by the National Cotton Council’s Cotton Insect Losses Survey from 2000 to 2007. They found Bt hectares had a statistically significant, lower rate of total insecticide applications than conventional hectares—2.1 fewer applications per hectare, on average. Applications for non-target lepidoptera were only significantly lower for Arizona Bt acreage. Applications for non-target, non-lepidoptera were lower on conventional hectares, but the difference was statistically insignificant. There was no significant difference in pre-planting insecticide applications or insect monitoring costs between Bt and conventional acreage.

Marra et al. (2003; p. 44) summarized findings on effects of Bt cotton from “field trials, farmer and consultant surveys, expert opinion and secondary data, and studies reporting ex ante estimates of economic impacts.” Assessing 24 studies from 10 states, they found Bt cotton contributed to a 2.3–3.4 per hectare reduction in insecticide applications. Klotz-Ingram et al. (1999) estimated an econometric model of insecticide use on Bt and conventional cotton acreage controlling for sample selection (the fact that Bt adopters are likely to face higher pest pressure). They found no statistically significant difference between Bt adopters and non-adopters with respect to organophosphate or pyrethroid applications. They did find that Bt cotton adopters applied significantly less of other synthetic insecticides (e.g., aldicarb, chlorpyrifos, oxamyl, and endosulfan). Following a similar approach, Frisvold

Table 2.2 Trends in insecticide applications for 19 major U.S. maize-producing states. (Source: USDA, NASS Agricultural Chemical Usage Survey)

	2001	2005	2010
Insecticides applied in metric tons of active ingredient (a.i.)	4,082	2,177	726
Percent of planted hectares treated with insecticides	29	23	12
kg of a.i. applied per planted hectare	0.15	0.07	0.02
kg of a.i. applied per treated hectare	0.49	0.31	0.19

(2004) estimated Bt cotton adoption reduced insecticide applications for bollworm, budworm, and pink bollworm by 0.5 sprays in per total cotton hectares in 1996 and by 2.8 sprays in 2003.

2.3.2 Maize

The first Bt maize varieties became commercially available in 1996. These single-toxin varieties, using Cry1 proteins controlled stalk-boring Lepidoptera (Hellmich et al. 2008; Tiwari and Youngman 2011). The main U.S. targets were European corn borer (*Ostrinia nubilalis*) and southwest corn borer (*Diatraea grandiosella*). Many growers elect not to treat maize with insecticides for European corn borer because insecticides are ineffective once the pest has tunneled into the stalk. These Bt events also offered limited control of *Helicoverpa zea*, which is called the cotton bollworm when feeding on cotton and the corn earworm when feeding on maize. In 2003, Bt maize varieties became available that used Cry3 proteins to control coleopteran pests, specifically, different species of corn rootworm (*Diabrotica* spp). Since then, stacked varieties have been approved with both Cry1 and Cry3 proteins as well as in combination with herbicide resistant traits.

Adoption rose from 35% of maize hectares in 2000 to 77% in 2012. As with cotton, stacked Bt-HT varieties dominate, accounting for 63% of U.S. maize acreage in 2012. Data from the U.S. Department of Agriculture's (USDA's) *Agricultural Chemical Use* survey show a significant reduction in the share of maize acreage receiving insecticide applications, total metric tons (MT) of active ingredient applied, kilograms (kg) applied per planted and treated hectare for major maize producing states (Table 2.2). The survey does not always survey the same number of states. Table 2.2 reports results from years with the most states, common for each year (19). In the 19 states surveyed, applications fell from 4,082 metric tons of active ingredient in 2001 to 726 metric tons in 2010, a more than 80% reduction. Over the same period, the percentage of maize hectares receiving any insecticide applications fell from 29 to 12%.

In a 3-year, multi-state study of U.S. maize producers, Pilcher et al. (2002) found that the percentage of growers that had decreased pesticide use to control European corn borer doubled between 1996 and 1998 (from 13 to 26%). Growers who reduced their insecticide use increased their share of Bt acreage from <20 to 47%. In a survey of crop consultants in Kansas and Nebraska, Hunt et al. (2007) reported

Integrated Pest Management

Experiences with Implementation, Global Overview, Vol.4

Peshin, R.; Pimentel, D. (Eds.)

2014, LVI, 574 p. 89 illus., 55 illus. in color., Hardcover

ISBN: 978-94-007-7801-6