

When and where a seed mix refuge makes sense for managing insect resistance to Bt plants

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ABSTRACT

Planting of a separate structured refuge for Bt crops as part of an insect resistance management (IRM) strategy to delay resistance evolution is the most common method of refuge deployment but this strategy depends on growers planting a refuge. A seed mix refuge interspersed with a pyramided Bt product is an alternative strategy that addresses the risk of growers not planting a refuge. However, concerns exist regarding how larval movement between Bt and non-Bt plants might influence resistance evolution in a seed mix field. To understand when seed mixes are an appropriate IRM strategy, a deterministic model run probabilistically was used to examine the evolution of Bt resistance in seed mix and structured refuges under varying levels of Bt efficacy, pest fitness, refuge size, larval movement, movement penalty and grower compliance. Results from modeling simulations show that the addition of a second and third Bt toxin can delay resistance evolution longer than a single toxin, making a seed mix refuge strategy a viable option where refuge compliance is a concern. In seed mixes, resistance was shown to evolve faster compared to a responsibly implemented structured refuge and evolved fastest in seed mixes when larval movement rates were high. However, when mortality from larval movement was included in model simulations, the selection pressure from Bt was reduced and two or three Bt-pyramids with a 5% seed mix refuge were at least as durable as the same products with a 5% structured refuge, depending upon refuge compliance. These simulations show that, across a range of conditions, seed mix refugia provide an effective alternative IRM tactic for delaying resistance evolution. Under some conditions use of seed mix refugia may be a superior IRM tactic leading to longer delays to resistance, and greater durability, compared to structured refugia and is a risk adverse tactic in situations when no refuge is planted.

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1. Introduction

Global adoption of crops expressing plant incorporated protectant (PIP) *Bacillus thuringiensis* (Bt) toxins has grown dramatically over the last decade from 44 million ha to 148 million ha (Peng, 2011). In the United States alone the Bt corn acreage has increased from 5.6 million ha in 2000 to 20.6 million ha planted in 2010 (NASS, 2000, 2010). Extended exposure to Bt toxins in the field without appropriate management can lead to resistance evolving in pest populations. To prolong the effectiveness of Bt crops like Bt corn, it is essential to develop a comprehensive insect resistance management (IRM) strategy to delay evolution of pest resistance to Bt toxins. At present, a high-dose/refuge strategy is considered to

be one of the more effective IRM strategies for delaying resistance evolution to Bt toxins (Bates et al., 2005). This strategy is based on the assumptions that Bt toxins, singly or in combination (pyramids), individually are highly efficacious against the same insect pest, that resistance is functionally recessive in the pest population, and a refuge of non-Bt plants is available to provide a source of susceptible individuals to mate with any survivors from the Bt crop (Alstad and Andow, 1995; Bourguet et al., 1996; Gould, 1998; Roush, 1997, 1998; Zhao et al., 2003). In the United States, a planted refuge is mandated for all Bt corn hybrids as part of a comprehensive IRM strategy (US EPA, 1998). However, the effectiveness of structured refuge in delaying the evolution of Bt resistance depends on growers complying with refuge requirements that can be complex and costly. Recent reports by Jaffe (2009) indicate approximately 25% of United States corn growers planting a Bt hybrid were not fully compliant with refuge requirements raises concerns that the risk of resistance evolving may be higher than previously thought.

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Furthermore, there is considerable uncertainty about the nature of grower compliance with refuge requirements outside the United States where refugia implementation may be voluntary rather than mandated. Therefore, it is reasonable to assume that in regions where little or no refuge may be grown, the risk of Bt resistance evolving in insect pests will be higher (Gould, 1998, 2003). Thus, in countries where refugia compliance is poor and/or IRM infrastructure is still evolving, it is more difficult to regulate Bt crops, monitor pest populations and deploy appropriate remedial actions to mitigate pest resistance to Bt crops should it occur.

An alternative to the high-dose/refuge strategy that offsets the risk associated with growers not planting refuges would be use of pyramided Bt toxin seed mixes that already contain non-Bt seed, thus transferring the responsibility of refuge implementation to the company providing the technology (Kennedy et al., 1987; Gould, 1996). Use of a seed mix ensures that an appropriate amount of a suitable refuge variety is planted in each Bt field and also distributes refuge plants relatively uniformly within Bt fields, lowering the probability of mating among Bt resistant adults compared with a separate block refuge. Furthermore, since manufacturing of seed mixes shifts the burden of compliance from the grower to the seed provider, the convenience of planting seed mixes for growers should increase adoption of pyramided Bt varieties, thereby reducing potential vulnerabilities from co-occurrence of pyramids with single Bt toxin products (Bates et al., 2005). Although use of seed mix refuge can provide additional benefits to an IRM strategy compared to structured refuge, seed mixes are not without risk and there are valid concerns about how larval movement between Bt and non-Bt plants might influence evolution of pest resistance in seed mixes of Bt and non-Bt plants (Mallet and Porter, 1992). Larvae not receiving a lethal dose that move off Bt plants onto non-Bt plants, and movement of larger less susceptible larvae from non-Bt to Bt plants, could increase heterozygote fitness and increase selection for resistance. In addition, movement of susceptible larvae off non-Bt plants onto Bt plants reduces refuge efficiency by lowering the number of susceptible insects produced by non-Bt plants. The impact of reduced refuge efficiency likely will be greatest for Bt plants with single proteins exposed to pests with highly mobile larvae, i.e. lepidopteran pests (Halcomb et al., 1996; Davis and Onstad, 2000). As a result of these concerns, the originally approved IRM programs for Bt crops in the U.S. included structured refuges and specifically excluded seed mix refuges (U.S. EPA, 1998).

However, incorporating pyramided Bt products (that combine several effective Bt toxins) into a seed mix with non-Bt refuge lowers the likelihood that larvae moving to or from Bt plants will be able to survive. Furthermore, while increased mortality of susceptible larvae moving onto Bt plants reduces the number of susceptible individuals available to mate, the guaranteed compliance and improved mixing of adult insects coming from Bt and non-Bt plants should partially offset the loss of susceptible individuals and benefit IRM (Murphy et al., 2010). Nevertheless, seed mix refuges are not a silver bullet and would not be an appropriate strategy under all conditions. Knowledge of crop composition, crop pest complex and associated pest ecology, pest pressure and IPM compatibility are necessary to determine whether a structured or seed mix refugia strategy is preferred.

To better understand when structured or seed mix refuges are an appropriate IRM tactic, a probabilistic model was used to simulate evolution of Bt resistance in seed mix and structured refugia under varying levels of Bt efficacy, pest fitness, refuge size, larval movement, and grower compliance. Unlike previous modeling (Peck et al., 1999; Davis and Onstad, 2000; Ives et al., 2011), this model explicitly examines larval movement in seed mixes by allowing larvae to move freely back and forth between

non-Bt and Bt plants and explores the effect of natural and genotype-specific movement and post-movement larval mortality on resistance evolution.

2. Materials and methods

A three-locus probabilistic model, implemented using Java SE runtime environment (v1.6.0.16) and capable of examining the impact of up to three insecticidal toxins and their corresponding resistance alleles, was used to evaluate resistance evolution in lepidopteran pests that vary in their susceptibility to Bt toxins from highly to moderately susceptible. The model was a three-compartment, random mating, non-random oviposition model, with random mating occurring separately within refuge compliant and non-compliant compartments. The model used a beta-PERT distribution (Project Evaluation and Review Technique) with new parameter values randomly selected for each model run based on estimated minimum, maximum and most likely values, with the most likely value (mode) weighted 4-times higher than the minimum or maximum (Vose, 2000). Thus, over many model runs, the model provided a measure of uncertainty by evaluating a range of values for all important model parameters.

Model scenarios examined the evolution of resistance to one, two and three Bt toxin products in a landscape consisting of only the Bt product being modeled, with no natural refuge or alternative host species. A range of fitness values for homozygous susceptible individuals was selected to create generic high-dose (99%–99.9% efficacy) and low dose scenarios (95%–85% efficacy) (Table 1). Similarly, fitness values for heterozygotes was determined using a range of fitness values, with the modal value being approximately 5-times that of susceptible individuals (Table 1.). Depending on the value selected for homozygous susceptible individuals, heterozygous fitness can be more than 40 times higher. Initial resistance allele frequency in all scenarios also was examined across a range of low to high starting frequencies. In some scenarios, the impact of non-compliance with structured refuge was examined with pest populations allowed to move (mix) between compliant and non-compliant compartments. In all scenarios, a single diallelic locus was assumed to determine resistance or susceptibility for each Bt toxin. Resistance was assumed to be complete with no fitness costs. Structured refuge was assumed to be 20% for single Bt toxins and 5%

Table 1

Model values used for the probabilistic model PERT distribution to examine one, two and three Bt scenarios.

Scenario	Model parameter	Min	Mode	Max
High efficacy	Wss ^a	0.001	0.005	0.01
	Dominance	0.001	0.02	0.04
	Allele frequency	0.0001	0.001	0.01
Low efficacy	Wss ^a	0.05	0.10	0.15
	Dominance	0.05	0.40	0.60
	Allele frequency	0.0001	0.001	0.01
Structured refuge	Non-compliance	0	0	0
		0.50	0.50	0.50
Seed mix	Mixing	1	1	1
	Base larval movement	0.10	0.10	0.10
		0.50	0.50	0.50
	Larval movement rounds	3	3	3
	Larval movement ratio ^b	0	0	0
		0.75	0.75	0.75
One toxin	Movement penalty	0.50	0.50	0.50
One toxin	Structured refuge	0.20	0.20	0.20
One toxin	Seed mix refuge	0.04	0.10	0.20
Two and three toxins	Structured refuge	0.05	0.05	0.05
Two and three toxins	Seed mix refuge	0.05	0.05	0.05

^a Survival (fitness) of susceptible insects.

^b Larval movement ratio is AsymmMoveAdj in the movement equation.

for two and three Bt toxins. Model scenarios also considered the impact of improved refuge compliance that would come from using a seed mix refuge rather than structured refuges.

2.1. Non-compliance with structured refuge

Grower non-compliance with structured refuge was modeled by creating separate compliant and non-compliant compartments with the compliant compartment having a user-defined percentage of refuge and the non-compliant compartment having no refuge. Recent reports indicate that on average approximately 25% of all growers are not complying with one or more refuge requirements (Jaffe, 2009). Therefore, it is likely that there are localized areas where growers are fully compliant and other areas where growers are planting little or no refuge. The influence of non-compliance on resistance evolution was examined by fixing non-compliance in the high and low dose efficacy scenarios at 0%, 50% or 100%. Mixing between compliant and non-compliant compartments was controlled through oviposition patterns with populations allowed to mix randomly across compartments each generation (complete mixing between compliant and non-compliant fields).

2.2. Seed mix refuge and larval movement

Seed mix refuges were simulated at 20% for a single Bt toxin and 5% for two or three Bt toxin products. Compliance was assumed to be complete based on modern manufacturing practices ensuring that there will not be less than the desired amount of refuge present. Larval movement was modeled by spreading movement and survivorship for susceptible and heterozygous individuals across a user-specified amount of time and conservatively assuming that mortality occurs each day before dispersal (Eq. 1 and 2).

$$\text{Daily survivorship} = \frac{\text{Days of larval movement}}{\sqrt{\text{Genotype fitness}}} \quad (1)$$

$$\text{Daily mortality} = 1 - \text{Daily survivorship} \quad (2)$$

Two types of movement, base larval movement (BLM) and genotype-specific movement (GSM), were assumed to be acting on the population. BLM (Eq. 3) represented the proportion of the population that would normally move even in the absence of Bt. GSM (Eq. 4) was movement by homozygous susceptible or heterozygous individuals off Bt plants and represented Bt toxin influence on movement. For GSM, the rate of movement was proportional to the fitness values for homozygous susceptible or heterozygous individuals. Therefore more homozygous susceptible individuals moved as Bt efficacy increased and heterozygote movement rates were determined by the dominance value and fell between the susceptible and resistant homozygotes.

$$\begin{aligned} &\text{Base larval movement rate} \\ &= 1 - \left(\frac{\text{Days of larval movement}}{\sqrt{1 - \% \text{movement}}} \right) \end{aligned} \quad (3)$$

$$\begin{aligned} &\text{Genotype specific movement} \\ &= 1 - \text{Daily survivorship of genotype} \end{aligned} \quad (4)$$

Movement of individuals that started on Bt plants (Eq. 5) was calculated on a daily basis and included a larval movement ratio (AsymmMoveAdj) that allowed a user-determined proportion of the population to undergo GSM.

$$\begin{aligned} &Bt_{\text{move}} \\ &= 1 - (1 - (1 - \text{dailysurvive}) \times \text{AsymmMoveAdj}) \\ &\quad \times (1 - \text{BaseLarvalMove}) \end{aligned} \quad (5)$$

Thus, $(1 - \text{dailysurvive})$ was the proportion of larvae that underwent GSM and $(1 - (1 - \text{dailysurvive}) \times \text{AsymmMoveAdj})$ was the adjusted proportion of larvae that underwent GSM. The proportion of larvae not undergoing GSM was $(1 - \text{BaseLarvalMove})$. Therefore $(1 - (1 - \text{dailysurvive}) \times \text{AsymmMoveAdj}) \times (1 - \text{BaseLarvalMove})$ was the proportion of larvae that did not move, while the proportion of larvae moving off Bt plants was $1 - (1 - (1 - \text{dailysurvive}) \times \text{AsymmMoveAdj}) \times (1 - \text{BaseLarvalMove})$. Therefore, under GSM, an adjusted proportion of homozygous susceptible and heterozygous individuals are moved each day. Homozygous susceptible individuals are more likely to move than heterozygotes or homozygous resistant individuals. All remaining individuals not moving in a genotype-specific manner are moved using BLM. In these simulations, two rates of BLM representing a species with relatively sedentary larvae versus one with relatively mobile larvae were examined with and without GSM. In addition, scenarios were run with and without a movement penalty applied post-movement to account for larval mortality during interplant movement (Table 1).

3. Results and discussion

3.1. Impact of number of toxins in a pyramid on resistance

Results of 1000 model simulations for each scenario were used to create a cumulative probability curve representing the time for 50% of the population to become resistant. Examples of typical curves for 1, 2 and 3 Bt toxins are shown in Fig. 1. The 10th, 50th and 90th percentiles from the probability distribution were used to assess the risk associated with each scenario for single and multiple Bt toxins using a structured or seed mix refuge (Tables 2 and 3). The lower 10th percentile of the probability represented 'worst-case' combinations of parameter values found in each scenario (low efficacy, high resistance allele frequency and high heterozygote fitness). Overall, resistance evolved fastest when no refuge was planted regardless of the number of Bt toxins present in the pyramided product. In all scenarios, the time to resistance increased non-linearly as the number of Bt toxins was increased and, regardless of refuge type, resistance always evolved faster for single Bt toxin products than two or three Bt toxin products under either high or low dose scenarios (Tables 2 and 3). Refuge non-compliance increased the rate at which resistance evolved but this effect was slowed with each new Bt toxin added. The time to resistance also was influenced by the interaction between dose (efficacy) of individual Bt toxins and the number of Bt toxins, with the slowest resistance evolution observed for high-dose products and the impact of increasing toxin number greatest for high-dose products (Tables 2 and 3). The value of increasing toxin number in delaying time to resistance was much less for low dose Bt toxin products (Tables 2 and 3). Overall, while going from low to high-dose provided measurable gains in delaying resistance, the impact of increasing Bt toxin number on slowing resistance evolution was far greater.

3.2. Seed mix refuge and larval movement

The primary vulnerability of Bt-pyramids is refuge compliance. Because resistance will likely be a local event, it is reasonable to assume that even in geographies where non-compliance is less than 25% there would be localized areas where non-compliance is much higher (>75%). As compliance decreases, the durability of Bt products decline (Tables 2 and 3) with the general impact to single Bt toxins being greater than for two and three Bt toxin products. Furthermore, when refuge is not planted, the advantage provided by Bt-pyramids is lost, resulting in rapid resistance evolution (Table 2).

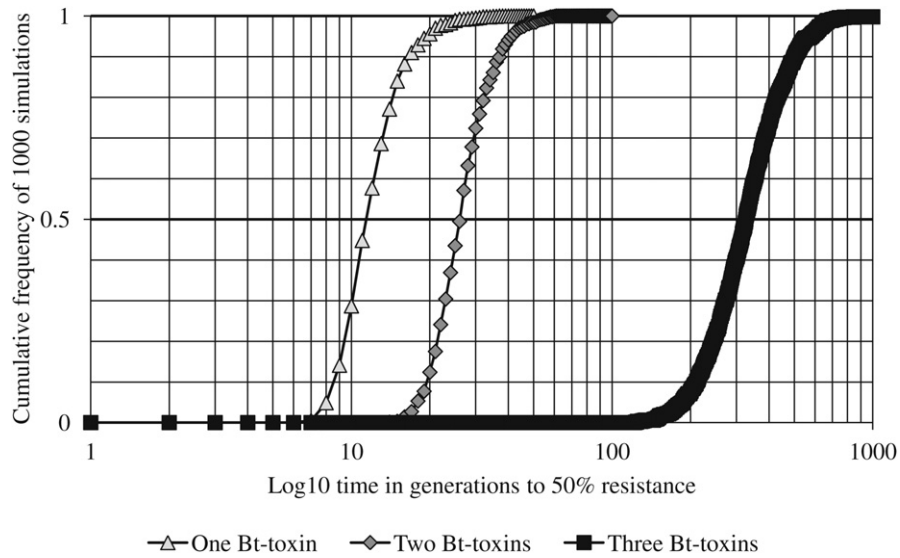


Fig. 1. Cumulative percentage from 1000 model simulations of the time in generations that it takes for 50% of the pest population to become resistant to one, two and three Bt toxins using low dose scenario assumptions.

These results show that a seed mix refuge can provide a risk-averse strategy to address refuge non-compliance. Simulations that included a range of larval movement scenarios found that even single Bt toxin seed mixes can effectively delay resistance compared to when non-compliance is high, 50% or greater (Tables 2 and 3). While resistance evolved rapidly in single Bt toxin seed mixes, the durability of two and three Bt toxin seed mixes was much greater even under extreme movement assumptions (Tables 2 and 3). Thus, depending on the situation, even deploying seed mix products containing pyramids of lower dose Bt toxins may be appropriate, especially under conditions of high refuge non-compliance. Similar to results from prior modeling of seed mix refuge (Peck et al., 1999; Davis and Onstad, 2000; Ives et al., 2011), larval movement caused resistance to evolve faster compared to equivalent fully compliant structured refuge and evolved fastest when movement rates were high as larvae exposure to Bt plants increased (Tables 2 and 3). The addition of GSM to BLM further decreased durability because this type of movement effectively stimulates additional homozygous susceptible and heterozygote

movement from Bt plants that would not normally be expected to occur off non-Bt plants. Furthermore, the impact of larval movement on resistance evolution relative to equivalent structured refuge increased as the number of toxins increased (Tables 2 and 3). Based on a comparison between a seed mix refuge with high larval movement and an equivalent structured refuge at 50% non-compliance, a seed mix refuge delayed resistance longer than a structured refuge.

Importantly, when interplant movement was penalized to account for movement-related mortality, resistance evolution could be delayed twice as long compared to movement only scenarios (Table 3). For single Bt toxin scenarios, including a movement penalty actually increased product durability in seed mixes relative to fully compliant structured refuge (Tables 2 and 3). Essentially, the majority of homozygous susceptible and heterozygote individuals on Bt plants that moved according to their genotype underwent additional non-selection related mortality that proportionally reduced the influence of the Bt component on resistance evolution thus increasing the time it takes for resistance to evolve. Given the sensitivity of the model to the movement penalty parameter, care must be taken in selecting a representative value for post-movement mortality since this tends to reduce selection pressure by Bt.

Also, because individuals undergoing BLM included homozygous resistant individuals, as pest mobility increased so did movement-related mortality. This increase in movement-related mortality tended to delay resistance compared to movement only scenarios (Table 3). This is especially evident in single toxin products where the additional mortality can result in additional delays of 19 and 9 generations for high-dose scenarios (Table 3). In effect, when modeling, movement should not be considered in isolation from post-movement survival because interplant movement effectively reduces the effective refuge size (and shortens durability) while post-movement mortality reduces the selection impact of Bt (and increases durability).

Overall, these results show that a seed mix refuge can delay resistance evolution longer than a structured refuge when high non-compliance is included but generally will not delay resistance as long as a responsibly implemented structured refuge. As determining the nature of non-compliance from year to year is a difficult problem, a seed mix refuge provides a more risk-averse strategy that ensures refuge is planted in situations where structured refuge

Table 2

The 10th, 50th and 90th percentile for generations to 50% of the population becoming resistant obtained from the cumulative probability curves for one, two and three Bt toxin high and low dose scenarios using a 20% or 5% structured refuge.

Toxin	Efficacy	Structured	Non-compliance	10th percentile	50th percentile	90th percentile
One	High	20%	0%	25	35	60
			50%	10	16	26
			100%	2	3	4
	Low	20%	0%	7	9	13
			50%	5	7	9
			100%	3	5	6
Two	High	5%	0%	653	1027	1765
			50%	206	430	807
			100%	3	4	5
	Low	5%	0%	10	13	16
			50%	6	9	12
			100%	4	5	6
Three	High	5%	0%	>6000	>6000	>6000
			50%	>6000	>6000	>6000
			100%	3	4	5
	Low	5%	0%	46	62	85
			50%	28	44	65
			100%	4	5	7

Table 3
The 10th, 50th and 90th percentiles for generations to 50% of the population becoming resistant obtained from the cumulative probability curves for one and two Bt toxin high and low dose scenarios using a 20% or 5% seed mix refuge.

Toxin	Efficacy	Seed mix	Base movement	Genotype movement	Movement penalty	10th percentile	50th percentile	90th percentile		
One	High	20%	10%	0%	0%	22	32	55		
				75%	0%	20	28	45		
				75%	50%	27	41	68		
			50%	0%	0%	15	21	33		
				75%	0%	15	20	32		
				75%	50%	21	30	51		
	Low	10%	20%	0%	0%	7	9	13		
				75%	0%	7	9	12		
				75%	50%	7	9	12		
		50%	0%	0%	6	8	11			
			75%	0%	7	9	12			
			75%	50%	7	9	13			
		Two	High	5%	10%	0%	0%	447	650	981
						75%	0%	141	185	251
						75%	50%	289	383	524
50%	0%				0%	155	210	293		
	75%				0%	91	118	160		
	75%				50%	201	263	359		
Low	10%		5%	0%	0%	10	12	16		
				75%	0%	10	12	16		
				75%	50%	14	17	24		
	50%		0%	0%	8	10	13			
			75%	0%	8	10	13			
			75%	50%	11	14	19			
	Three		High	5%	10%	0%	0%	>6000	>6000	>6000
						75%	0%	1036	1303	1649
						75%	50%	2112	2638	3399
50%		0%			0%	1526	1958	2528		
		75%			0%	658	831	1048		
		75%			50%	1419	1793	2321		
Low		10%	5%	0%	0%	42	56	76		
				75%	0%	34	43	55		
				75%	50%	72	93	120		
		50%	0%	0%	28	35	44			
			75%	0%	25	30	38			
			75%	50%	50	64	82			

compliance cannot be reliably assumed. Previous modeling and research have pointed out some vulnerabilities of seed mix refuge related to larval movement and subsequent survivorship that can lead to faster resistance evolution, especially for single Bt toxins (Mallet and Porter, 1992; Davis and Onstad, 2000), but many of these concerns are partially overcome in the case of multiple effective Bt toxins, especially when the Bt toxins approach a high-dose. Nevertheless, unless non-compliance is high or larval mobility is low or costly, results for the two Bt toxin low dose scenario (Table 3) suggest that seed mixes for two Bt toxin low dose products may be unacceptably risky. However, the addition of a third toxin in the low dose scenario delays resistance evolution for much longer and would be less risky in seed mix compared to a similar sized structured refuge under moderate to high amounts of refuge non-compliance.

3.3. Bt-corn examples

These results can be related to real world examples using Bt-corn products commercially available in the United States that express one, two or three Bt toxins. Two products, YieldGard VT and Herculex RW, express Cry3Bb1 and Cry 34/35 respectively and are an example of efficacious products that have been used successfully for corn rootworm control but are not considered high-dose. Genuity SmartStax with a 5% seed mix refuge combines these two coleopteran Bt toxins into a single product with efficacy that should increase product durability compared to each single Bt toxin. This product should fit the modeled two Bt toxin scenarios where seed mixes can provide as much as a two-fold increase in

durability (17–24 generations) compared to structured refuge (7–9 generations) under high levels of non-compliance (Table 3). Another example involves the sequential deployment of the lepidopteran resistant products, YieldGard Corn Borer (Cry1Ab), Genuity VT Double Pro (Cry1A.105/2Ab2), and most recently Genuity SmartStax (Cry1A.105/2Ab2, Cry1F), in the United States. In this case, a single Bt toxin product, YieldGard Corn Borer, with 20% refuge was planted commercially for many years with no documented cases of field failure. YieldGard Corn Borer was phased out and replaced by a two Bt toxin product, Genuity VT Double Pro, that resembles the modeled high-dose two Bt toxin scenarios with 5% refuge. The recent addition of multi-toxin products like SmartStax with 5% refuge provides a high-dose three Bt toxin product against lepidopteran pests, especially stalk boring pests, and should have greatly improved durability compared to either a one or two Bt toxin product as indicated by the results from the three Bt toxin high-dose scenario (Table 2). These examples show how the addition of a second and third Bt toxin make a seed mix tactic a viable IRM option in the US Corn Belt especially in areas where non-compliance is much greater than nationally assumed.

While larval movement in seed mixes can increase the rate at which resistance develops, results show that a seed mix refuge for two and three Bt toxins is capable of ensuring that Bt products provide comparable or better delays to resistance compared to structured refugia, particularly at higher doses and when movement-related mortality is considered. Therefore, seed mix pyramids need to be given global consideration when determining the most appropriate IRM strategy to use. In particular, there are

many agricultural systems, such as small holder agriculture in Asia and Africa, where planting of structured refuges by growers may not be practical and, a two or three Bt toxin seed mix refugia represents a risk-averse strategy (Tables 2 and 3). While implementing seed mix refugia in areas dominated by small holder farms also presents challenges to manufacturing such as, hybrid matching and uniform seed color to prevent separation of refuge seed, a seed mix refugia can be a reasonable tactic for small holder farms that helps to ensure product longevity.

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